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Investigation of the origin and magnitude of debris flows from the Payhua Creek basin, Matucana area, Huarochirí Province, Perú

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ABSTRACT: The small city of Matucana (population 5800), Province of Huarochirí, Perú is located on the flood plain of Rimac River in Andes Occidental, approximately 75 km east of Lima at an elevation of 2390 m (area of 11° 50.489' S, 76° 22.857' W). Adjacent ridges and mountain peaks rise to 5000 m. Matucana shares a 300 m wide valley bottom with two transportation arteries: Carretera Central, the only highway in Perú connecting the Amazon basin to the Pacific Coast and Ferrocarril Central, the highest standard gauge railway in the world which services mines and communities in the Andes. The present course of Rimac River is controlled by a dike and fill for the highway and railroad. These structures confine it to the northern portion of its flood plain. Consequently, parts of Matucana are lower in elevation than the bed of Rimac River. Payhua Creek (PC), a steep, debris-flow-prone tributary to Rimac River, has built an extensive fan at the upstream end of the city. Debris flows from PC has dammed Rimac River and diverted it into Matucana. This type of disaster occurred 1959 and 1983 when heavy precipitation occurred in the normally arid Andes Occidental. The 1959 event was particularly notable as it destroyed 90% of Matucana with loss of life. Although these events were not well documented, investigation of the PC fan and documentation of 1983 deposits on the fan indicate that the 1983 debris flow had a volume in the 0.12×10^6 to 10^6 m^3 range. Investigation of surficial and bedrock geology including mapping of all landslides in PC basin was carried out in 2004. A landslide complex immediately west of Payhua village is the most significant source of debris flow sediment in the basin. Incision of an unfavourable succession of andesite flows overlying a pervasively fractured tuff is responsible for the concentration of landslides in the Payhua village area. The area affected by landsliding in this area has increased by a factor of five since 1951. The PC basin upstream from Payhua has been a relatively small source of debris flows during the past 600 to 800 years based upon archaeological evidence. Exposures of debris flow deposits in the PC fan indicate that debris flow events larger than those of 1959 and 1983 have occurred in the recent geologic past. Matucana has also grown significantly since 1983 and has further encroached on the Rimac River flood plain and the PC fan. As a result, if debris flows of the magnitude of those in 1959 and 1983 occur, direct burial of the upstream area of Matucana by debris flows is likely.

1 INTRODUCTION

1.1 *Geoscience for Andean Communities*

The Multinational Andean Project: Geoscience for Andean Communities (MAP:GAC) began June 28, 2002 and includes Argentina, Bolivia, Canada, Colombia, Chile, Ecuador, Peru, and Venezuela. The project goal is to contribute to improving the quality of life for the people of the Andes by reducing the negative impact of natural hazards (earthquakes, landslides, and volcanoes). Through the project, updated and integrated geoscience and geospatial information on natural hazards will be provided for land use planning and, natural hazard mitigation. As a part of this project, one or more pilot study areas were selected in each country. These areas contain natural hazards that are typical of those that face Andean peoples in their respective countries. Investigations of hazards within the pilot areas develop geotechnical skills, methodologies and insights that are easily applied in similar environments throughout the Andes of the participating country. Inundation by channelized debris flows and debris-flow-induced hydrological flooding in the small city of Matucana in Andes Occidental are typical of hazards faced by communities throughout this region. Debris flows from the adjacent small mountainous drainage basin of Payhua Creek (*Quebrada Payhua*), diverted Rimac River (*Río Rimac*) through. Matucana in 1959 and 1983. They present a continuing hazard to the community. On this basis, Matucana and Payhua Creek basin were chosen as a pilot study area as a part of MAP:GAC. This paper reports the results of fieldwork and accumulation of documentary evidence in the project area up to December 2004.

2 PHYSIOGRAPHY AND SETTING

2.1 *Matucana area*

Matucana (population 5800) is located in Huarochirí Province, Perú (Fig. 1) approximately 75 km east of Lima at an elevation of 2390 m above sea level (a.s.l.) (area of 11° 50.489' S, 76° 22.857' W). Matucana is situated on a 300 m wide flood plain along the floor of the deep and steep-sided Rimac River (RR) canyon in Andes Occidental. Adjacent ridges and mountain peaks rise to 5000 m within ten kilometres of Matucana. It shares the valley bottom with two strategic transportation arteries: Carreterra Central, the only highway in Perú connecting the Amazon basin to the Pacific Coast and Ferrocarril Central, the highest standard gauge railway in the world which services mines and communities in the Andes to the east. The present course of Rimac River is controlled by a dyke and fills for the highway and railroad. These structures confine the river to the northern portion of its flood plain. Consequently, parts of Matucana are lower in elevation than the bed of RR.

2.2 *Payhua Creek basin*

Payhua Creek (PC) basin lies immediately to the north of Matucana. It is an elongate basin 6.1 km in length and less than 3 km in width at the widest point with a total area of 14.9 km^2. It rises to 4760 m a.s.l. PC lies within a narrow to gorge-like valley. Its overall gradient is 21°. However, its profile is marked by numerous waterfalls along nearly vertical reaches of the channel, particularly along the lower 2 km. Slopes along the gorge are commonly 50°–70°. The basin is underlain by andesitic to rhyolitic flows, breccias and pyroclastic complexes of Cenozoic age (Instituto Geologico Minero y Metalurgico 1995). The basin is asymmetric from west to east reflecting a general dip of flow complexes to the east and south. Scarp slopes along the east side of the basin average around 50° to 60° over elevation-changes of 1000 m. Dip slopes along the western margin of the basin are in the 35° to 40° range over elevation-changes of about 1000 m. However, nearly vertical outcrops of 50 to 100 m can be found throughout the basin and rockfall is a problem along the bases of many slopes.

Figure 1. Location of Matucana/Payhua Creek project area.

2.2.1 *Neotectonism and surficial geology*

Andes Occidental is a tectonically active mountain belt. It is experiencing rapid uplift and fluvial incision. Incised relict alluvial fans are present in the basin hundreds of m above the floor of RR valley. Although there are no quantitative estimates of uplift rates for the study area, uplift rates in the order of 0.2 to 0.3 mm/yr since the Miocene have been determined for the adjacent central Andes (Gregory-Wodzicki 2000).

2.2.2 *Land use in Payhua*

Mountainsides in PC basin have been extensively terraced for farming and grazing for more than 1000 years. These terraces extend to ridge-tops in many parts of the basin. The terraced fields are irrigated up to about 3500 m and support a variety of crops. Terraced fields above the limits of irrigation presently serve as small pastures.

2.2.3 *Climate and debris flow activity*

Climate at the elevation of Matucana is temperate and dry: average temperature ranges from 27°C during the summer (mid December to March) to 19°C during the winter (mid June to September). Temperature decreases progressively with altitude: below-freezing temperatures occur every night at elevations above about 4200 m. Total annual rainfall averages 239 mm at Matucana. About 70 percent of it falls between January and March. Rainfall patterns are disrupted by El Niño climatic events in the equatorial Pacific Ocean and atmosphere. These events have occurred roughly four years apart in recent years. They bring intense rains to the RR basin and commonly trigger debris flows in the region (Kuoiwa 2002).

2.2.4 *Payhua Creek fan*

PC has built an extensive fan at the upstream end of Matucana where PC joins RR (Fig. 2). It is about 400 m

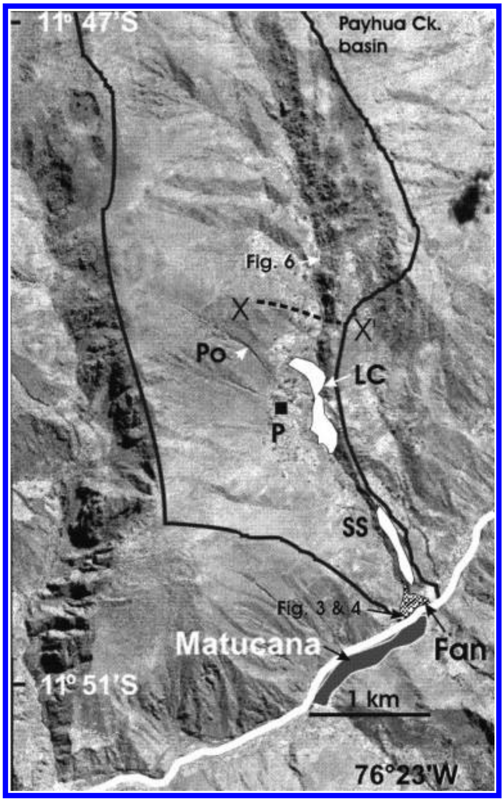

Figure 2. A Quickbird satellite image of the Payhua Creek area, Aug. 13, 2004: X-X′- boundary between upper and lower basin, P- Payhua village, Po- *Patipunco* ravine, LC- Payhua landslide complex, SS-sagging slope block, white line-Rimac River (Ferrocarril Central and Carratera Central). Payhua Creek joins Rimac River and the extreme southwest point of the fan.

Figure 3. Bouldery debris flow diamicton near the confluence of Payhua Creek with Rimac River. Oval indicates a man standing next to a 2 m stadia rod.

Figure 4. Looking up the channel of Payhua Creek in the opposite direction from Fig. 3. The channel is deeply incised into Payhua fan. Circle indicates a 1.5 m tall man. Cross sectional area of the channel is approximately 300 m^3. The 1983 debris flow exceed the capacity of the channel.

in length from apex to its southernmost extent. Its overall surface slope is approximately 9° (it has been extensively modified into terraced fields for agriculture). It terminates in a cliff bank created by incision of the fan by RR. The fan is almost entirely underlain by bouldery debris flow diamicton sediments. Poorly sorted bouldery gravel beds, associated with muddy turbulent stream flow, are locally interstratified with diamictons. Boulders 1 m in diameter are common within the diamictons. Individual boulders up to 3 m are present (Figs. 3–4).

3 PREVIOUS WORK

The physiography, geology, climate and hydrology of the Matucana area including past debris flows and floods from PC, are summarized in a report prepared for District of Matucana in 2000 (Martinez Vargas & Medina Rengito 2000).

4 THIS STUDY

4.1 *Objectives*

Field investigations in Matucana and the PC basin in September, 2004 with the objectives of:

1. Mapping of the distribution of surficial sediments and landslides within QP basin with the ultimate goal of understanding the origin of debris flows in the basin.
2. Determination of the past scale and frequency of debris flows in the basin and estimation of the volume of future events.

3. Comparison of the present area of landsliding in the basin with past distributions based upon archival air photo coverage.

A draft terrain inventory map PC basin was completed using a terrain inventory legend scheme modified from Howes & Kenk (1997). This included the location of all active landslides within the basin and an inventory of areas affected by rapid mass movement. A Quickbird satellite image (1 m resolution) of the basin that was taken on Aug. 13, 2004, was used as a base for mapping at a scale of 1:10 000 (fig. 2). The final, digital version of the map will be prepared following the generation of a digital elevation model (DEM) and detailed topographic map of the basin to be completed in 2005. Residents of Matucana and the mountain village of Payhua were interviewed in order to reconstruct debris flow events back to 1959 and arrive at order of magnitude estimates of volumes and maximum discharges of past debris flow events. Archaeological techniques were used to determine the long-term stability of fans and terraced hillsides. These included the use of widespread pottery fragments from the pre-Inca period (pre-1400 AD) and distinctive construction of retaining walls from the same period to document absence of debris flow activity on terraced fields (retaining walls destroyed by debris flows during the post European contact period were rebuilt in a different manner). Major landslides within the basin were investigated in order to determine the geological and geomorphological conditions that led to the failure. Sections of the channel of PC containing sediment were surveyed in order to estimate quantities of sediment contained in the channel and along its margins that could be mobilized into future debris flows following the general methodology of Hungr et al. (1984). Estimates of the magnitude of future debris flows based upon this data will be presented in a future paper.

5 PREVIOUS DEBRIS FLOW EVENTS

5.1 *Historic debris flows*

The knowledge base with respect to previous debris flows from PC largely consists of oral accounts of local residents and limited newspaper coverage. As noted above, debris flows from PC blocked RR diverting it through Matucana in February, 1959 and March, 1983. The 1959 event resulted in several deaths was particularly destructive because adobe brick was extensively used for construction at that time. Many buildings were literally washed away by the flood. A smaller event that only affected terraced agricultural fields on the PC fan occurred in 1941. Reliable records of debris flows prior to 1941 do not exist. Local weather records are not available for the debris flow events. Consequently, antecedent conditions are not known beyond the 1983 event occurring during an El Niño year. Many debris flow events occurred during that year in the Matucana area. RR is confined to an incised channel with near vertical walls between the PC fan to the north and the fan of Huaripachi Creek (*Quebrada Huaripachi*) immediately to the south. Topography dictates that diversion of RR in both cases took place at the downstream limits of the fans where the deeply incised channel of PC joins in the RR. No part of Matucana, which was considerably smaller in area at the time of those events, was directly buried by debris flows although the Ferrocarril Central tracks were buried. It is reasonable to assume that the railway fill acted as a protective dyke for Matucana to some degree. Investigation of terrace fields on the PC fan determined that retaining walls were reconstructed following the 1983 event. Accounts vary as to the limits of the 1983 and 1959 flows on the fan. Some accounts indicate that the entire 4.8 ha fan was covered.

5.2 *Granulometry and clay mineralogy*

Granulometric analysis, determination of Atterberg limits and clay mineralogy of two debris flow matrix samples from the fan and a third sample from higher in the PC basin indicate them to be low plasticity to a non-plastic silty sands ranging from SC to SM in the Unified Soil Classification scheme. The mineralogy of the small clay-size fraction, as determined by X-ray diffraction, is dominated by clay-size, non-clay minerals such as quartz, plagioclase, augite, calcite, muscovite and hematite. True clay minerals such as chlorite or montmorillonite make up only one or two percent of clay-size particles. The mineralogy reflects rapid erosion and predominance of physical weathering over chemical weathering in a tectonically active and arid drainage basin.

5.3 *Estimates of historic debris flow magnitudes*

An order of magnitude volume estimate for the size of the 1983 debris flow (the 1959 event is assumed to be of similar magnitude because of similar effects) can be made based upon field observations in and around the channel of PC. The channel incises PC fan to a depth of about 14 m over a total distance of approximately 400 m. Its mean cross-sectional area is about 300 m^2. In order for a flow to spill out on to the fan surface, it would fill the channel and would consequently have a minimum volume of about 120,000 m^3. Assuming similar incised channel dimensions, this volume was exceeded during the 1983 event with the burial of adjacent fields on the fan surface. Such a discharge would be sufficient to dam and divert RR. However, filling of the PC fan channel to overflow represents the peak discharge of an event with an extensive discharge of debris into the RR channel prior and subsequent to maximum peak discharge. Numerous authors have demonstrated proportionality relationships between debris flow maximum instantaneous discharge (Q_{max}) in m^3/s and total discharge (Q_{total}) in m^3 so that $Q_{total} \sim n\, Q_{max}$ where n can range from 10 to 80 s or more depending on the study, e.g. Hungr et al. (1984), Jakob & Jordan (2001), and cases cited therein. Unfortunately, there is no data on the velocity of either the 1959 or 1983 debris flows. Consequently, 120,000 m^3 is a minimum estimate of the volume of the 1983 debris flow. The maximum volume is likely less than 10^6 m^3 because a flow larger than that volume would likely have been large enough to bury parts of Matucana.

5.4 *Magnitudes of pre-historic debris flows*

Any estimates of historic debris flow magnitudes must be tempered by evidence of prehistoric event based upon exposures of sediments comprising the PC fan. Exposures along the channels of PC and RR reveal only massive debris flow diamicton that commonly contain boulders exceeding 1 m in length (Figs. 3–4) and lacking obvious flow boundaries or breaks in sedimentation. Based on these observations, the fan has largely been built by debris flow events that covered parts of the fan to depths of 3 m or more and greatly exceeded the volumes of the historic ones. The lack of buried soils or other indicators of long term breaks in debris flow deposition and the rapid uplift rates in the region suggest that the debris flow deposits that have built the fan are geologically recent i.e. hundreds or thousands of years old. At the regional rate of uplift, deposits tens or hundreds of thousands of years old would likely have been deeply incised and would presently form terraces.

6 GEOLOGY OF PAYHUA CREEK BASIN AND ORIGIN OF DEBRIS FLOWS

6.1 *Division of PC basin based on geology and landslide activity*

The PC basin is divisible into a lower and upper basin based upon the types and density of landslides and landslide activity that occurs within in them. These in turn reflect differences in underlying geology. It will be shown that landslide activity is directly linked to debris flow activity.

6.1.1 *Lower basin*

The lower basin stretches from the area of the mountain village of Payhua to the head of the PC fan. Surficial deposits include erosional remnants of debris flow fans. Assuming uplift rates 0.2 to 0.3 mm/yr, the 400 m elevation of some of these fan remnants would date then as middle Pleistocene. At the elevation of Payhua village, the bedrock of the basin is overlain by active debris flow fans and rockfall aprons from bedrock ridges north and west of Payhua village (the village lies within an active rockfall fan and it is impacted by large blocks several times a year). Underlying bedrock consists of extensively jointed and fractured andesitic or dacitic flows, breccias and pervasively fractured pyroclastic rocks. Vertical succession of lithologies along the PC canyon suggest that these volcanic rocks dip in the general direction of PC basin drainage.

6.1.2 *Landsliding in the lower basin east of Payhua*

The most active and continuous areas of landsliding in PC basin occur along the reach of the PC canyon adjacent to the village of Payhua about 2.2 km north of and 1000 m in elevation above Matucana. This will subsequently be referred to as the Payhua landslide complex (Fig. 2, LC). Approximately 16 ha of active rock and debris slides, rockfall and complex landslides that include old debris-flow-fan remnants and portions of active debris flow fans border on approximately one kilometre of the channel. This reach contributes the greatest amounts of coarse and fine sediment to the PC channel in the basin. These landslides have locally dammed PC in the past and may have the potential to create breakout floods. Furthermore, several rapidly expanding ravines within talus slope/debris-flow cone complexes above Payhua village have produced debris flows that directly entered PC during the 1959 and 1983 debris flow disasters. A debris flow from the largest of these ravines (*Patipunco*) may have been the ultimate source of the 1959 debris flow according to longtime Payhua village residents (Fig. 2, Po).

6.1.3 *Stratigraphic and structural architecture and slope instability*

The ultimate cause of failure along the approximately 70 m deep canyon of PC is the incision of the inherently unstable configuration of pervasively fractured red tuff that is overlain by more coarsely jointed andesitic lava flows (Fig. 5). The red tuff is approximately 40 m in thickness. Incision of this resistant over recessive succession leads to undermining of the andesite flows and rock falls along near vertical canyon walls or rotational or translational type failures with the failure plane(s) seated within the red tuff. The latter varieties are expanding rapidly into slopes immediately east of Payhua village.

6.1.3.1 Documentation of increasing landslide activity

Comparison of 1951 air photographs with 2004 satellite imagery indicates that landsliding has increased

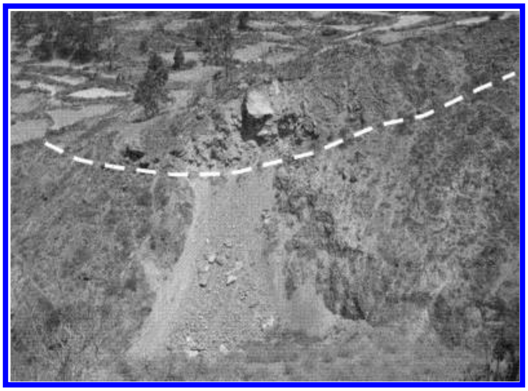

Figure 5. Dashed line indicates the contact between a coarsely jointed andesitic flow unit and the underlying pervasively fractured red tuff unit. The slope is about 70 m high. The rockfall occurred within the past 20 years and continues to grow as the failure in the red tuff undermines the andesite flow. Bouldery debris from the rock fall blocks the channel of Payhua Creek.

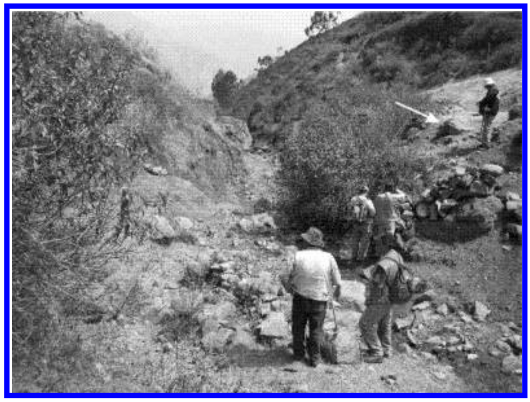

Figure 6. Channel of Payhua Creek near the downstream limit of the upper basin (see Fig. 2). Arrow indicates a bouldery levee marking the upper limit of debris flow deposits. Compare channel cross sectional area to the fan channel in Figure 4. The boulder indicated by the arrow is about 3 m above the floor or the channel.

by a factor of five and *Patipunco* and adjacent ravines have expanded in width and depth over the intervening 54 years. The cause of this acceleration is not known. Fields along both sides of the PC canyon are irrigated. The addition of irrigation water to the slope has been suggested as a contributing factor by some residents. However, a cause and effect relationship cannot be demonstrated with currently available data.

6.1.3.2 Sagging of the east side of the PC canyon

One other area of extensive but presently very slow moving or semi-stable slope failure is present in the lower basin. Below the landslide complex adjacent to Payhua village and immediately upstream of the head of PC fan, a 1 km section of the east side of the PC canyon wall has apparently detached from the adjacent upland and has moved into PC canyon. (Fig. 2, SS). Its movement appears to be slower than the landslides immediately east of Payhua. It shows no evidence of past damming of the canyon. Details of its velocity or other aspects of its movement are not known. It is regarded as a sagging mountainside or slow moving rotational failure and requires further study and monitoring.

6.1.4 *Geology and landslide occurrence in the upper basin*

The upper basin (Fig. 2) is underlain by massive cliff-forming andesite flows or flow complexes that apparently overlie the recessive rocks of the lower basin. Agricultural terracing extends to ridge crests along the east side of the basin. Archaeological evidence and historical changes coincident with the arrival of the conquistadors in the 1530s date these structures as pre-Columbian and likely pre-Inca (ca. 1200 to 1400 AD or older). The preservation of these terrace structures across slopes and tributary ravines indicates that they have been stable for the past 600 to 800 years. Landslides in the upper basin are confined to rock falls and rock slides where the massive andesite cliffs have failed along jointing planes or flow boundaries. These can be dated to the past 600 to 800 years where they have removed or buried agricultural terraces. Three such major failures dating from this period are present in the upper basin.

6.1.4.1 Agricultural terraces and debris flow activity

Agricultural terraces have been built to within about 5 vertical metres of the channel bottom of PC in the upper basin. The highest debris flow levees are about 3 m above the channel floor in this area. Debris flow deposits are distinctive in the basin because they contain clasts from all lithologies occurring in the basin up-stream from any given point. These polymictic deposits are absent from pre-Inca agricultural terraces immediately above the channel. Therefore, the uppermost levees define the upper limits of the largest debris flow event during at least the last 600 to 800 years in the upper basin. They define a channel cross-section less than one-tenth the area of the cross section of the PC channel across the PC fan. Consequently, more than about 90% of the volume of the 1983 debris flow that reached the PC fan apparently had its origin farther downstream in the PC basin.

7 PRELIMINARY CONCLUSIONS

Debris flows from PC basin have been a recurring hazard to Matucana, Peru. These events have dammed RR diverting it into this small city with loss of life and extensive damage. Several conclusions can be reached with respect to historic and future events:

1. A 1 km reach of PC immediately east of Payhua village receives sediment from the greatest density of active landslides in the PC basin. This reach is the greatest source of debris flow sediment in the basin. The upper basin is a minor contributor to debris flow volume by comparison.
2. A minimum volume estimate for the debris flows of 1959 and 1983 is 120,000 m^3. However, evidence from fan stratigraphy suggests that prehistoric events may have greatly exceeded the volumes of the historic events.
3. The Payhua landslide complex has increased five-fold in area during the past 54 years. In addition, the *Patipunco* ravine complex, which contributes debris flows directly to PC, has also enlarged and become more active. Consequently, sediment that could be mobilized into debris flows has become more abundant. Landslides are very active in this area and are capable of blocking PC with the potential to trigger an outburst flood and debris flow. Therefore, future debris flows on the scale of the 1959 and 1983 events or larger should be expected.
4. Matucana was significantly smaller in 1983 and 1959. Although no part of the city was directly impacted by debris flows during those events, newly built areas adjacent to the PC fan are likely to be directly impacted by future debris flows of similar magnitude.

Note: Geological Survey of Canada Earth Sciences Sector contribution number 2004398.

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