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Deaths and injuries in the eruption of Galeras Volcano, Colombia, 14 January 1993

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Abstract

Six volcanologists and three tourists were killed in the crater of Galeras Volcano, Colombia, when it erupted without warning. The scientists were attending the United Nations International Decade for Natural Disaster Reduction Workshop which had been convened to improve monitoring, research and disaster mitigation at Galeras, at the time the most active and one of the most hazardous volcanoes in South America. Information on the events surrounding the eruption was obtained by sending a questionnaire to twelve scientists who had been inside the caldera at the time of the eruption or who had assisted in the search and rescue operation. The autopsy reports on the five corpses, and the few pieces of equipment and clothing retrieved from the crater area, were also studied. The main causes of death and injury were the forces at the eruptive vent and the bombardment by hot rocks ejected in the first 15 min of the eruption, ranging from blocks over 1 m in size to pea-sized lapilli which fell last. Some conclusions can be drawn for the future safety of volcanologists working in craters at high altitude. Hard hats would protect against concussion from blows to the head during escape from the danger area, and a lightweight, heat-resistant and water-repellent coverall would limit the skin burns and the risk of clothing being ignited from contact with incandescent, falling ejecta. The coverall could also be life saving by protecting immobilised casualties from hypothermia due to the rain and wind whilst waiting to be rescued, especially as the volcanic activity, cloud cover or nightfall could curtail rescue efforts. Work in hazardous craters should be strictly limited to essential tasks and periods of good visibility, and a climbing team should leave the area at least four hours before nightfall in case rescue is needed. Tourists must be warned against visiting active crater areas.

Keywords: deaths; pathology; eruption; Galeras volcano

1. Introduction

The United Nations International Decade for Natural Disaster Reduction (IDNDR) Galeras Volcano Workshop held at Pasto, Colombia, in 1993 will be remembered for the six volcanologists and three tourists who were killed whilst on a field excursion to the crater when the volcano erupted without warning at 1.43 p.m. local time on 14 January. The Workshop had been convened to advance monitoring, research and hazard mitigation at Galeras which had reawakened in 1988 after more than 40 years of dormancy (Muñoz et al., 1993). The volcanologists were in a group led by Dr. S.N. Williams, one of the

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convenors of the Workshop, which went to collect gas samples from fumaroles located inside, and on the outer slope, of the crater and to make microgravity measurements. At the time of the eruption, other groups of scientists attending the Workshop were on field excursions on the volcano's flanks.

In this paper we summarise the main physical impacts of the eruption on those persons who were killed or injured. The hazards of monitoring active volcanoes are becoming an increasingly important issue for volcanologists. More volcanologists are working on active volcanoes than ever before and, since 1979, fifteen have been killed by eruptions (Tilling and Lipman, 1993). With growing pressure to improve volcano monitoring, an important question is whether any methods can be devised to protect volcanologists, other than limiting the amount of time they spend physically monitoring in areas of high risk. This analysis of the tragic accident at Galeras is, therefore, an attempt to identify those factors which determined death or survival and to learn ways of improving the future safety of scientists and tourists visiting active volcanoes.

2. Background

The active crater of Galeras is located 7 km west of Pasto, a city of about 300,000 inhabitants. Galeras had been designated as a Decade Volcano by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and as such warranting special study by international scientists. On the day of the field excursions the scientific groups met at the summit of Galeras (4270 m) at around 9 a.m. before dispersing to leave Williams and his group to descend into the caldera and make their way to the inner crater. The caldera is a U-shaped structure open to the west and approximately 1700 m across at its widest point (Fig. 1). The crater cone is about 400 m wide and 150 m above the floor of the caldera, with Las Deformes fumaroles located on the south west slope of the cone. The vent of the crater had been plugged by a lava dome which was emplaced in late 1991. Most of the dome had been ejected in an explosive event on 16 July, 1992. Cloud cover prevented the crater area being inspected from the Police Station observation post (Fig. 1) where the excursion groups met but, the day before, Professor G. Brown, three Colombian geologists and one of the authors (PJB) obtained a glimpse from the summit after establishing a series of sites for microgravity readings along the road which led up the volcano (Fig. 2). Fumarolic degassing was observed, and no unusual features of the crater were noted (Fig. 3).

At 1.41 p.m., the field groups on the flanks of the volcano heard a sound like a loud peal of thunder

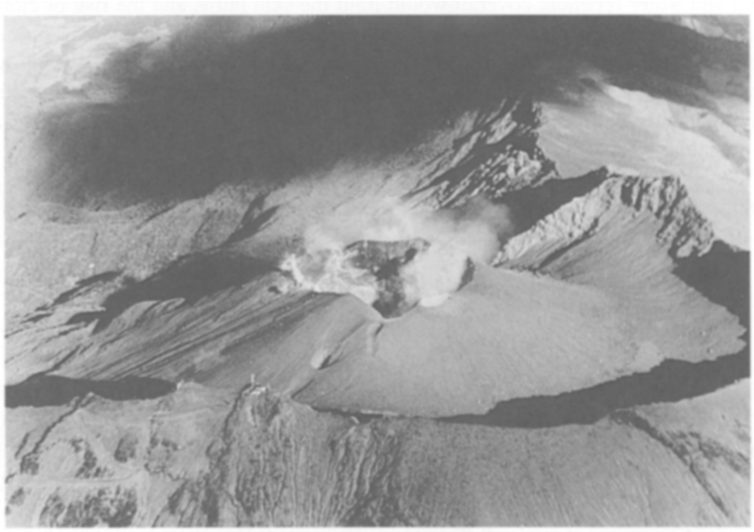

Fig. 1. View looking west of Galeras caldera and inner active cone. The Police Station, with its communications mast, is visible in the foreground (Courtesy Pasto Observatory).

Fig. 2. Professor G. Brown (left) and three Colombian volcanologists working with a gravimeter on 13 January 1993. Fernando Cuenca (2nd from left) was killed with Brown next day.

which rang out around the volcano, and residents came out of their houses to obtain a view of the summit which was, however, still shrouded in cloud. The group in the crater was finishing its work, with some of its members already walking out to leave the caldera. Brown and the two Colombian volcanologists he was training were still continuing their work because the crater completed the line of micro-gravity stations which they had followed that morning from the bottom of the summit road. Nine deaths occurred within seconds of the eruption in a bombardment of incandescent ejecta from the vent. Aware

Fig. 3. The last glimpse of the active cone on the afternoon of 13 January before the excursion group descended through the cloud next day.

that a terrible accident may have befallen their colleagues, the field groups returned immediately to Pasto whilst the volcano periodically continued to vent a plume which rose to an estimated 3 km in height and produced a fine ash fall over 325 km^2 (Muñoz et al., 1993). The eruptive activity continued for about four hours, during which time most of the survivors were helped or carried out of the caldera by rescuers.

By nightfall, all the injured scientists had been admitted to the main hospital in Pasto. In the following three days search parties scoured the caldera and retrieved five corpses which were sent to the hospital for autopsy examination. No trace was found of the bodies of four of the scientists who had been working close to the vent at the time of the eruption.

3. Methods

A questionnaire (Appendix) was sent to twelve scientists who had been in the crater at the time of the eruption or had joined search and rescue parties afterwards; all questionnaires were returned. Autopsy reports and photographs of the five bodies which had been found were also obtained. The questionnaire asked for information on the events surrounding the eruption, aspects of search and rescue and the injuries which the individuals had received. The harrowing experiences of all those involved at the incident meant that the documentation of the events and the injuries was less than ideal at the time. Nevertheless, it is possible to compile a reasonably accurate account even though many details may be questionable. The information gathered on the questionnaires and the autopsy findings were drawn together to study the nature of the injurious impacts.

4. Results

4.1. Events surrounding the incident

Sixteen people (thirteen scientists and three tourists) formed the excursion group to the crater. One of the scientists, Subject 6, carried a radio and communicated frequently with the Pasto Volcano Observatory whilst the party worked in the crater area. The cloud cover continued to obscure visibility for much of the time. Just before the eruption the fog was obscuring the higher parts of the crater rim, but a good view could be obtained of the interior of the crater from its rim.

At about 12.30 two scientists, subjects 15 and 16, had finished their work and had begun their walk out of the caldera. Approximately one hour later, and 10 min before the eruption, Williams advised the remainder of the party to begin to leave to ensure an early return to Pasto whilst the weather remained good. Subjects 6, 7, 8 and 9 proceeded up from Las Deformes fumaroles and along the crater rim, followed by subjects 12 and 13 about 10 m behind, and subjects 10 and 11 another 10–15 m behind them (Fig. 4). They had gone about 100 m along and 20–30 m down the outer slope of the crater when Williams felt the crater shake and heard rocks falling; he started to shout out to everyone to leave as fast as possible when the eruption occurred.

The survivors of this departing group reported that the sound of the eruption was loud but not ear shattering, rather like close thunder or a sonic boom. The explosive sound was accompanied by a fusillade of rocks from the shattered lava dome with a black eruptive cloud emanating from the vent. Subjects 6, 7, 8 and 9 at the head of the group were killed in the initial blast of rocks whilst they were running away. The middle two subjects, 12 and 13, ran as fast as they could, and Subject 13 was struck almost at once on the head over the left eye by a missile which left him conscious but sufficiently concussed that he could not walk steadily. He ran and fell at least twice down the slope until finding a boulder to hide behind. From there he watched bombs and blocks falling out of the sky, the blocks at first being over 1 m across which shattered on impact and sprayed shrapnel glowing hot inside which hissed when the fragments lay on the ground. After two minutes the missiles were football to baseball size, and ash-laden rain also began to fall. He ran on until coming across subjects 10 and 11. Subject 12 was hit on the head and knocked to the ground soon after he started running; he got up and after running for about another 10 m was felled by a rock which shattered his right leg. He dragged himself behind a boulder for shelter and watched the blocks and ash falling. A good proportion of the rocks and ash was incandescent. His jacket and trousers caught fire as missiles landed on and around him, and he had to roll about to extinguish the burning. He lay there conscious until being rescued two hours later.

Further behind were subjects 10 and 11 who ran and took cover in a depression about 1–2 m deep behind some small boulders 20–30 cm high. They watched for 2–4 min as blocks were falling from the eruption column with many striking them. There was a smell of sulphur but it was not overwhelming. Subject 10 was hit repeatedly by rocks, and whilst protecting his head his right hand was injured when a rock struck it. When the falling rocks had stopped, they thought it was safer to run away. They ran 20–25 m, passing one of the dead subjects, noticing that his clothes were on fire. They soon met Subject 13 who, they reported, was reeling around and looking dazed.

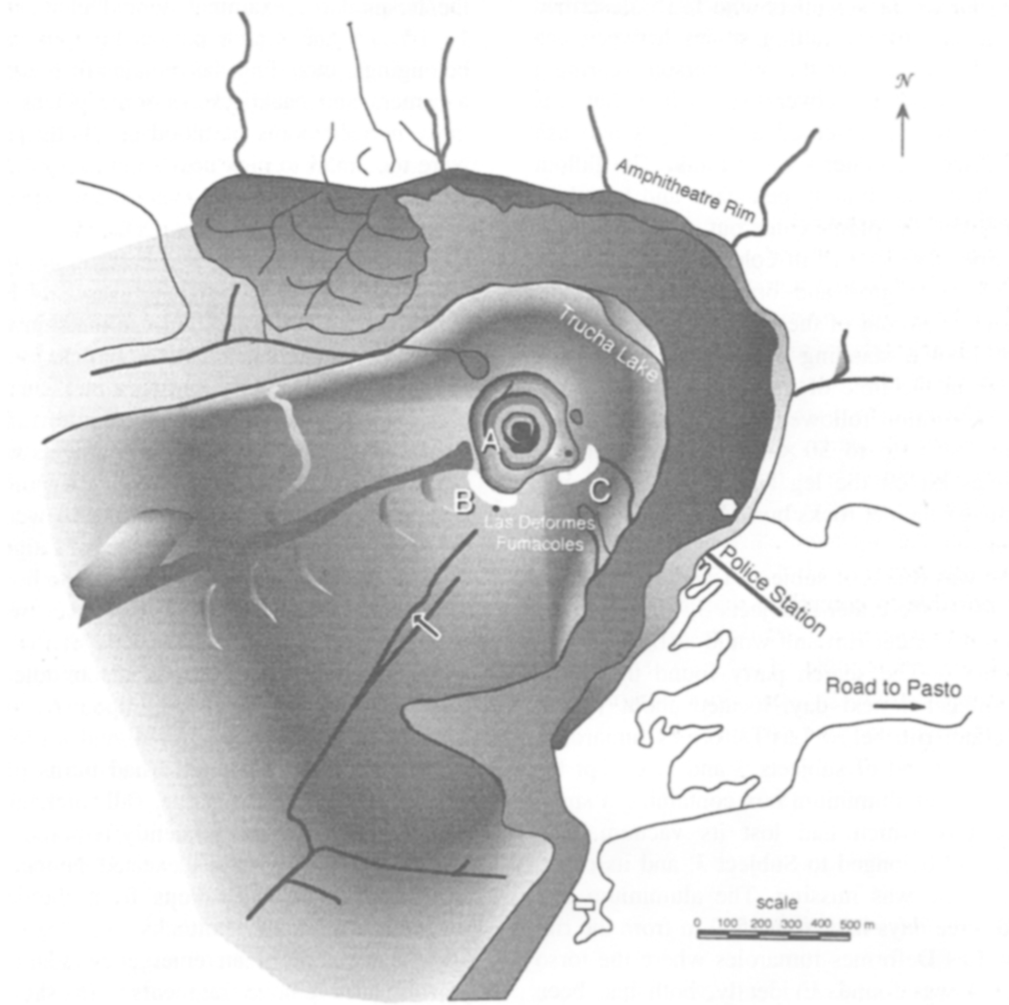

Fig. 4. Diagram of the caldera and active cone showing approximate location of main party members at the time of the eruption. Key: $A = 1, 2$; $B = 3, 4, 5$; $C = 6–13$. The arrow points to where the gravimeter was found.

The ash column which was incandescent in its lower part continued to rise from the crater with occasional explosions over the roar of outgassing. Ash-laden rain began to fall. All three subjects walked to the way up the caldera wall. Subject 10 tried to climb up using the rope but had to be aided by Subject 14. Subjects 11 and 13 had both been badly bruised by the impacts of rocks and had to be lifted out on stretchers by rescuers.

Meanwhile, subjects 15 and 16, who had been the first to leave the crater area an hour before the eruption, were beginning to ascend the caldera wall when the eruption occurred. They heard a blast, then a bubbling and rolling sound, and instantly took refuge in the caldera wall. Subject 15 described being hit repeatedly by falling stones between pea and baseball size. He was the only person wearing a hard hat and protective coveralls; his hard hat was hit many times. He observed a small gas and ash flow roll down the crater's outer flank. The fallout from the plume was mainly pea-sized and lasted 15 min, after which the plume came out in pulses which they described as varying in colour: black, yellow, white, red-brown, grey and orange. Both subjects were able to climb out of the caldera unaided.

Subject 14 was standing between the crater and caldera wall at the time of the eruption. He felt an earthquake sensation followed by the explosion. Incandescent rocks up to 50 × 60 cm fell where he was. He was hit on the leg but was not seriously injured, though the hot rocks burnt holes in his jacket and trousers.

No trace was found of subjects 1 and 2, who were last seen inside the crater. Subjects 3, 4 and 5 were together on the crater rim and would also have been killed instantly. The search party found the upper torso of Subject 4 next day, located about 100 m from the crater rim below Las Deformes fumaroles. No trace was found of subjects 3 and 5, except for the remains of an aluminium box containing a small gravimeter box which had lost its vacuum. The gravimeter had belonged to Subject 3, and its outer, glass fibre, case was missing. The aluminium box was found three days later some 500 m from the rim and below Las Deformes fumaroles where the torso of Subject 4 was found. Evidently, both had been flung away from the crater by the force of the eruption.

5. Rescue

Scientists and rescue workers began to reach the summit at about 2 p.m. local time, and they began their descent into the caldera about an hour after the eruption started. Subjects 10, 11 and 13 were carried out on stretchers and taken to the hospital by road ambulance. Subject 12 was the most severely injured, but despite his head injury he did not lose consciousness. It took about three hours for him to be removed from the caldera on a stretcher and to be transported by helicopter to the hospital in Pasto.

Over the next two days the bodies of the deceased victims were retrieved and taken to the mortuary in the hospital for examination and identification. On 17 January the search parties brought back a few belongings, including the remains of the gravimeter, a camera and backpack. In some places the search party noticed pools of blood and body parts which were too small to pick up.

6. Injuries of survivors

All the survivors had burns to the skin where they had come into contact with hot rock. Burns to the hands were especially troublesome: survivors had tried to scramble over the ground after falling, coming into contact with hot rock fragments which were scattered around. Gases were not a problem. The light rain and ashfall were enough to wet and dirty the skin, adding to body cooling and fatigue.

Four survivors were admitted to the hospital. The most badly injured was Subject 12, who had a depressed fracture of the left side of the skull, jaw and temporal bone (affecting the middle ear). The right leg had sustained a compound, comminuted fracture of the tibia and fibula, and a rock had also fractured the left fibula. He had burns of the legs, arms and hands and a large, full thickness burn on the back. His legs subsequently required skin grafting and the back burn was excised. Numerous contusions and minor lacerations from the impacts by rocks on the back, buttocks and legs were also present. That night an emergency craniotomy was performed to remove fragments of his skull bone and a small subdural haematoma. He was flown out of Pasto to his home country by air ambulance two days later and underwent numerous reconstructive surgical operations to the right leg and skull for over a year afterwards.

Subject 13 had been concussed by a rock striking his left forehead. In addition, he suffered a severely sprained left ankle, badly sprained right knee with severe contusions on the right leg, all caused by impacts from flying rocks. Numerous superficial burns were present on the hands, arms, scalp, ears, back and legs, especially the right leg which was badly swollen. The burns on the hands healed very rapidly. On return to his home country he spent over a week on crutches until the marked swelling of the right leg gradually subsided. The left ankle was temporarily supported by a plaster cast.

Subject 10 fractured one of the metacarpals of the right hand which was treated by open reduction in his own country. In addition he suffered minor lacerations and numerous contusions to the shoulders, arms, legs, thigh and back where he had been struck by flying rocks. Two small full thickness skin burns were subsequently treated with skin grafts.

Subject 11 also had numerous superficial burns and severe contusions of the body, especially to the legs which were initially badly swollen and thought to be fractured. He was flown to his home country by ambulance.

None of the wounds of any of the injured subjects, including the compound fractures of the skull and both legs sustained by Subject 12, became clinically infected.

7. Autopsy findings

The autopsy findings are briefly summarised below to show the main injuries and modes of death.

7.1. Subject 6

The main cause of death was destruction of the skull and exposure of the brain. The skin bore numerous partial and full thickness burns over about 32% of the total body surface area (TBSA). There was blackening of the lower legs, findings resembling the soot deposits seen in the victims of fire. The hair was burned in the right temporoparietal region. The lungs were also noted to be pink in colour which suggested that the victim had inhaled air containing carbon monoxide. It was concluded that he had been hit on the right side of the face and head by a curved hot rock which had set his hair on fire as well as causing the comminuted fracture of the cranium. Before dying he was able to take a few breaths of air which probably contained carbon monoxide. Combustion of the clothes of one of the victims was noted by a survivor, and this could also have contributed as a source of carbon monoxide here. The skin burns were caused by hot rocks falling on his legs as he lay on his left side with his face down.

7.2. Subject 7

He sustained open wounds of the skull (fronto-parietal region), with lacerations over the face, right knee and left pretibial region. He had full thickness burns of the abdominal wall, anterior left thigh, right elbow, right thigh and dorsum of the left foot. The thorax was deformed by multiple fractures of the spine. Subcutaneous emphysema of the neck was present. There was also blackening of the legs as in Subject 6. Internal examination revealed a large fronto-parietal subgaleal haematoma, a diffuse subdural haematoma and severe cerebral oedema. He had sustained comminuted fractures of the lower cervical and upper thoracic vertebrae, with the spinal cord sectioned at C7-T1. There were multiple fractures of the ribs with flattening of the thoracic cage. The parietal pleura had been ruptured by fractured ribs. The trachea and bronchi were ruptured with detachment and rupture of both lungs. The heart was detached and the pericardial sac ruptured. The thoracic aorta was ruptured. There was a slight peritoneal haemorrhage with rupture of the spleen. It was likely that a rock struck the victim on the front of the head causing a hyperextension injury of the neck. He was flung through the air against a hard rock surface with the internal rupture injuries being caused by rapid deceleration. Rocks scraped the skin causing lacerations and the hot temperatures caused burns.

7.3. Subject 8

This subject also sustained severe skull injuries, including left fronto-parietal and right parietal open wounds. There were full thickness burns of the left shoulder, right arm, right gluteal region, and the palm of the right hand. There was a closed fracture of the left femur. Internally, he had a right occipital subgaleal haematoma, a diffuse subdural haematoma, severe cerebral oedema and brain stem haemorrhage. There was a large haemothorax and associated multiple rib fractures and injury to the lower lobe of the left lung. These injuries were sustained when he was hit on the head by flying rocks and then fell on his knees on to hot rocks. Another rock hit him in the scapula area, resulting in fractured ribs and the rupture of the lung, whilst he was on his knees with his hand outstretched on to a hot rock. The large subdural haemorrhage was the result of forces to the head from the fatal blow.

7.4. Subject 9

This victim also sustained fatal injuries from rocks striking the skull and chest. There were open wounds of the right frontal skull region with a fracture of the supra-orbital ridge. There were also fractures of the left pre-auricular temporal bone, occipital bone and right forearm. Full thickness burns were present on the left pectoral, right axillary and right scapular areas; behind the neck and left shoulder, left forearm, right gluteal region, right lumbar region and behind the right leg. The left foot had sustained a partial traumatic amputation. Third degree burns extended over 18% TBSA. There was an open fracture of the left tibia and fibula. Internally, a fronto-parietal subgaleal haematoma was found, as well as a depressed fracture in the occipital and right temporal regions. There was a diffuse subarachnoid haemorrhage over the whole surface of the brain. The upper lobe of the left lung was ruptured and was associated with a massive left haemothorax but no fractured ribs. It was concluded that the victim died from the effects of flying rock hitting his head, causing the subdural haemorrhage, and the subarachnoid haemorrhage was due to shaking of the brain in association with this. The rupture of the lung suggested an explosive blast injury but, as there was no evidence of a blast wave associated with the eruption, it was more likely to be due to the impact of a flying rock. Hot flying rocks caused the other injuries.

7.5. Subject 4

This victim was in the party taking microgravity measurements on the crater rim when the eruption occurred. Only the upper torso and head was intact, with the lower limbs separated from the trunk. The entire body remains were cooked, but not desiccated or charred as in fire victims. The dentition was, nevertheless, well preserved indicating that the temperature undergone by the body had not attained 500–800°C. Some of the hair had been protected from the heat. The facial features were indistinguish-

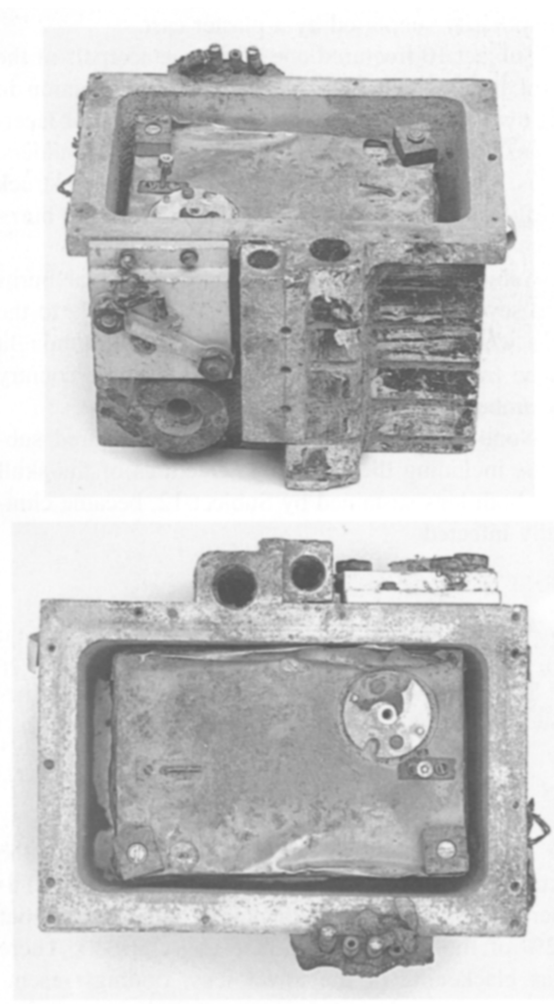

Fig. 5. Aluminum box (2.2″ × 3.6″ × 2.7″) containing inner gravimeter sensor was the only remnant of Brown's personal gravimeter.

Fig. 6. A backpack, camera with case and film, torch and book were amongst the few items retrieved by search parties. All show thermal damage.

able. There was a palpable comminuted fracture of the skull. It was concluded that he had been flung face downwards and a large rock had fallen on him and cut him in two. The body had then been subject to heat from radiation or convection producing a temperature which was possibly high enough to ignite body fat (500–600°C). It was possible that the body remains had been covered by a hot ash and gas flow down the crater side and of the type observed by Subject 15. As the body was found 500 m from the crater rim, it is unlikely that radiation from the plume would have been sufficient to have caused the thermal changes.

8. Objects found around the crater

The aluminium box containing the gravimeter box was found with its lid missing (Fig. 5). The lid had been made of thick aluminium and was held on with twelve brass machine screws. The outer glass fibre housing of the gravimeter was missing. The force required for the screws of the lid of the aluminium box to fail was estimated from an examination in the Dept of Engineering, University of Cambridge, and it was concluded that a rise of temperature of at least 200°C was needed to have produced sufficient pres-

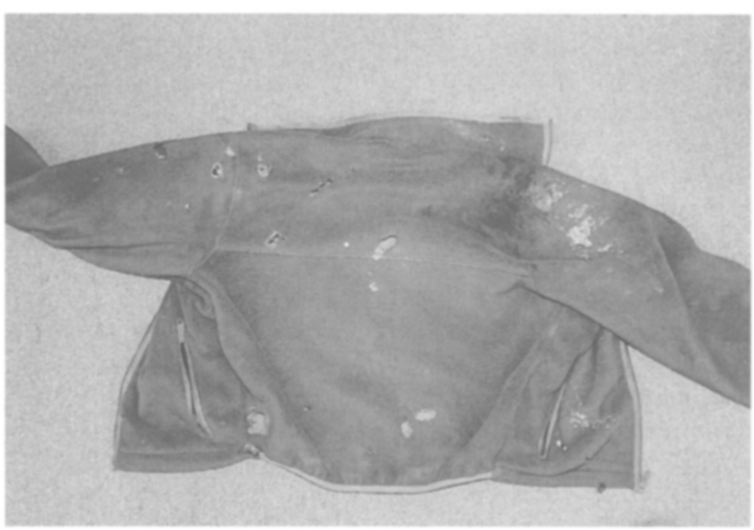

Fig. 7. Synthetic fleece with holes worn by Subject 12.

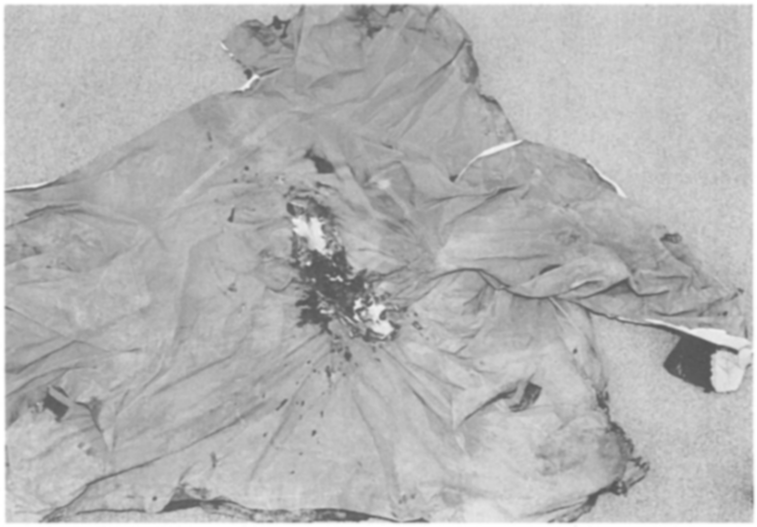

Fig. 8. Gore-Tex anorak worn by Subject 12: the polyester outer lining melted when it came in contact with a hot rock.

sure to cause the seams to open. Plastic materials also melted over 200°C, as evidenced by the effects of hot rocks on the retrieved backpack, camera and torch, as well as the fleece and anorak worn by Subject 12, and gas mask cartridge (Figs. 6–9).

9. Discussion

Small volcanic eruptions of the type which occurred at Galeras occur without leaving any geological record, but they have devastating effects on people located at close range of the vent. The risks of small explosions occurring without warning from lava domes or plugged volcanic vents are well known to pose lethal hazards to volcanologists and others who visit the crater rims of active volcanoes. Nine tourists were killed whilst standing near the edge of the Bocca Nuova crater of Mount Etna when they were struck by rocks in an explosion in 1979; many others were injured, some standing as far as 400 m away from the crater edge (Chester et al., 1985). At

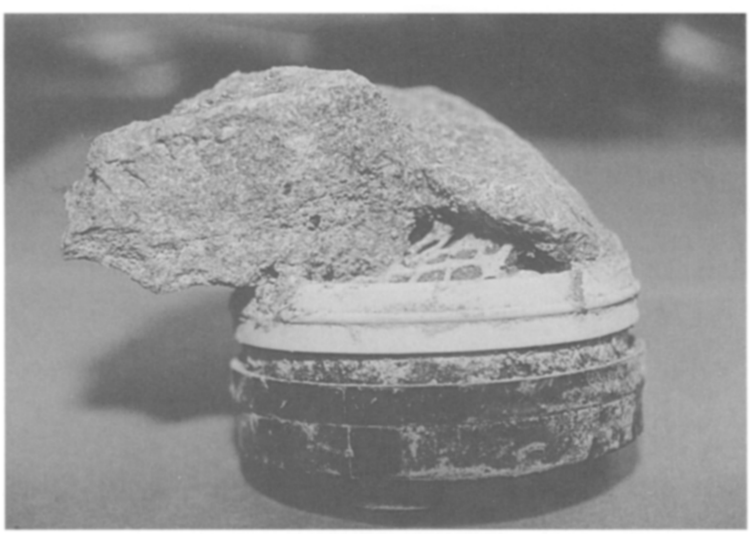

Fig. 9. A hot rock fused on to the plastic casing of a gas mask cartridge.

Yasur Volcano, Vanuatu, two visitors to the crater rim died in 1994 when they were struck by a 15-kg bomb ejected from the vent (Smithsonian Institution, 1995). Only two months after the Galeras eruption, the battered bodies of two more volcanologists killed by a phreatic explosion were found at the crater rim of Guagua Pichincha Volcano, Ecuador (Fink, 1995).

A possible mechanism for these eruptions is extreme gas pressurisation causing the rock to fail (Stix et al., 1997). Whether there are any consistent seismic or other precursors to these explosions is not clear at the present time, but they are likely to be difficult to anticipate in real time with current monitoring techniques. At Pichincha, the two scientists were reported to have received a warning based on seismicity an hour before their deaths (Fink, 1995). The cause of such explosions is most likely to be the steady build up of pressure below a plug formed of cooled juvenile material, or a mixture of this material and debris from earlier explosions; or, at the commencement of the eruption, it may be the pre-existing old rock. The pressure rise may be due to the collection of magmatic gas, or heating and partial vaporisation of ground water (a phreatic or steam eruption). Ejection velocities of between 200 and 300–400 m/s have been observed in Vulcanian explosions, which are the type of activity that most closely resembles the small eruptive explosions described here (Wilson, 1980). The rocks may be very hot and capable of causing full thickness skin burns. The heat of the eruption column may be 800–1000°C which could also pose a hazard from radiation, and also from small gas and ash flows descending from it or flowing over the crater rim.

The mass and velocity of the rock fragments may be so great as to inflict body displacement and/or the effects of blunt or penetrating trauma, resulting in head injury, rupture of the liver, spleen and kidney, heart and great vessels. The threshold of lethality to humans applies to missiles having over 80 J kinetic energy (TNO, 1992). Thus for fragments weighing 0.5 kg, or the weight of an average single lens reflex camera, a 90% probability of death exists if the impact velocity is greater than 20–30 m/s. For fragments weighing 10 kg the critical velocity is much less, about 6–13 m/s. Clearly, these figures are likely to be exceeded near the source of the eruption and for even low energy releases; at the Etna explosion of 1979, the impact velocities were 15 m/s or more (Chester et al., 1985). The chance of being hit will depend upon the number of fragments and the location of individuals at risk of being struck by a laterally ejected rock or rocks falling out of the air. It is most unlikely that blast waves are generated in these eruptions, as the energy release from a fragmenting volcanic plug will be much slower in comparison to the detonation of a chemical explosion, especially as the ejection velocity is below or just above the speed of sound (approximately 330 m/s). The absence of a blast wave was confirmed by the accounts of the survivors and the other pathological findings.

We have concluded that the main cause of death and serious injury was the fusillade of flying and falling hot rocks which continued for about 15 min after the onset of the eruption with the size of the missiles ranging from boulder (> 1 m) to pea size and diminishing as the eruption continued. Blocks were found as far away as 1 km beyond the caldera rim. The impacts of the rocks were capable of causing devastating injuries to the skull and the rest of the body. Close to the vent few, if any, body remains were to be found. In survivors, severe injuries can be caused by fractures to the skull, chest, spine and long bones, as well as full thickness burns from contact with flying or stationary hot rocks.

As happened to one survivor, the effects of concussion by a relatively minor impact of a rock to the head was sufficient to impede his ability to escape, as there was some evidence that he was dazed and had difficulty walking following this relatively minor injury. Escape was also made more difficult for all the survivors because of the falling hot rocks. In addition, the eruption caused a rainfall which was sufficient to wet the skin and contaminate wounds with ash. The damp and cool temperatures, especially if there were wind, could add to the risk of hypothermia in injured victims unable to rescue themselves. The arguments for wearing hard hats and a heat-resistant, water-repellent coverall seem compelling, both to facilitate escape and to reduce morbidity in survivors of such events, even though such clothing would offer little resistance to the more lethal ejecta. Only one member of the scientific group wore such clothing. In addition, tough boots and heat-resistant gloves should be included in a list of essential protective wear. Certainly, the conventional mountaineering wear of polyester type anoraks and fleeces offers no protection against hot rocks, as illustrated in this event, and although the Gore-tex membrane of the anorak retrieved in this incident (Fig. 5) stood up to the heat from a rock, and would have prevented ignition of clothing, it did not prevent the development of an extensive, full thickness, skin burn.

In this incident the release of asphyxiating gases such as carbon dioxide and hydrogen sulphide, or irritant gases such as sulphur dioxide, did not pose a risk in the crater area as there was forceful degassing upwards to form a plume. On the other hand, there were grounds for supposing that a small hot ash and gas flow (minor pyroclastic flow) did flow down the crater wall for a short distance at some stage; this would have been lethal to anyone lying injured in its path. Fortunately, this did not flow in the direction of the crippled Subject 12. There was no evidence for an explosive blast wave capable of displacing bodies or causing severe lung injury.

The accounts of the survivors give some justification to believe that it is better to shelter behind a boulder and watch out for flying rocks rather than to keep running from the crater area and be caught unawares. On the other hand, waiting too close to the vent area for very long might result in the survivor being caught in a bigger eruptive event, or even a minor pyroclastic flow, as suggested by the evidence above. The proximity of trained rescue services was clearly an important factor, as only one of the survivors caught in the eruption in the crater was able to climb out unaided up the caldera wall, with three of the four subjects requiring to be lifted up by stretcher. When night fell, the search and rescue mission was called off in accordance with a decision made at high government level because of the risk to the rescuers themselves. Any injured person left in the crater at that time would most likely have died overnight from hypothermia, as the temperature at the summit usually dropped below freezing point. It therefore behove volcanologists not only to be aware of a means of rescue in the event of a serious incident, but also to plan to leave hazardous crater areas well before nightfall and at the first indication of impending cloud cover and poor visibility. The risk will, of course, be seriously compounded for scientists working in volcanoes in remote areas, and detailed consideration needs to be given to safety when such expeditions are planned. In highly populated areas, such as Galeras, it can be justifiable for volcanologists to enter the craters of active volcanoes to advance monitoring methods, in which case a constant radio link with the local Observatory is essential, as was done in this field excursion.

A number of factors contributed to limiting the loss of life from this eruption. The number of scientists entering the crater was limited to those collecting gas samples or performing microgravity measurements. Two scientists left an hour before the others as soon as their work was finished. The scientists who were walking down the outer side of the crater at the time of the eruption were knowledgeable about what was happening to the volcano and the options available to them to save their lives; all were conscious that they could be killed at any minute by flying rocks or from an escalation of the eruption, but they also knew that a slim chance of surviving existed, and this drove them in their terrified state of mind to escape. The crippled Subject 12 remained conscious and was able to call out to rescuers, who could then identify his location. Two overriding factors were responsible for his survival: the courage of his rescuers who entered the caldera knowing that there was a possibility that the eruption could escalate, and the availability of skilled neurosurgical assistance at the hospital in Pasto.

In conclusion, volcanologists entering hazardous crater areas should undertake detailed risk assessments taking into account some of the considerations recorded here, and decide whether the scientific benefits outweigh the hazards. As far as tourists are concerned, there is never any justification for them to enter areas of obvious hazard, and careful consideration needs to be given to public access to observation points on active crater rims.

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This paper is dedicated to the memory of a friend and colleague of one of the authors (P.J.B.), Geoff Brown, and the Russian and Colombian volcanologists who died in the eruption. We thank the scientists and their co-workers who completed the questionnaires and are indebted to Arthur E. Timbs, Department of Engineering, University of Cambridge, for his study of the remains of the gravimeter, with advice from John Flett. The hospital in Pasto kindly supplied the autopsy reports, and we thank the staff of the Pasto Volcano Observatory for their assistance.

Appendix A

GALERAS WORKSHOP – CONFIDENTIAL QUESTIONNAIRE

Please supply as detailed answers as possible to these questions on separate sheets of paper.

A. GENERAL INFORMATION

A.1 Please mark on the map and figure where you were at the time of the eruption. Please also record where you last saw other scientists before the eruption, marking how long before the eruption it was when you saw them.

A.2 What were you doing immediately before the eruption?

A.3 What clothing were you wearing before and at the time of the eruption? Did it include any protective clothing, e.g. special headware, heat resistant overalls, Gor-Tex or heat/chemical-resistant outer layer?

A.4. What safety advice had you considered before visiting the crater?

A.5 What was your perception of the risk before the eruption? Has your perception altered since the eruption? If yes, in what way?

A.6 Please describe what happened to you after the eruption until you got back to Pasto. Please include times and the names of others with you and their actions also. Give details of heat, trauma, blast and other phenomena you experienced (.e.g. rocks, ash, gases).

B. INVOLVEMENT IN SEARCH AND RESCUE

Please give details of immediate actions after the eruption or any search and rescue involvement in the subsequent days. Please give locations of injured/dead/objects found and details of any other findings you may wish to include.

C. MEDICAL DETAILS

C.1 Were you in good health before the eruption (please state any conditions you have been under recent treatment for).

C.2 Were you injured in the eruption? Please summarise any injuries you received and subsequent treatment, including details of how you were rescued, if applicable.

C.3 Have you suffered any emotional disturbance since the eruption? If yes, please give details.

D. CONSENT TO DISCLOSE INFORMATION

Please include a sentence that you agree to your information being incorporated in a summary form in a report that may be prepared for scientific purposes. It is not intended to identify individuals. Medical and any other sensitive information will not be disclosed without your agreement.

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