The Karthala Caldera, Grande Comore *

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Abstract

The active Karthala volcano is found on Grande Comore, the most westerly of four volcanic islands comprising the Comores Archipelago, between northern Madagascar and Mozambique. The caldera, roughly elliptical in outline, is 4 km long and 3 km wide, with outer walls around 100 m high. It is dominated by a large central pit crater, Chahale, which is 1300 m long, 800 m wide, and 300 m deep. A smaller cylindrical pit crater 250 m in diameter and 30 m deep, Changomeni, is found one km north of Chahale. The vertical walls of both pit craters show excellent sections of the ponded flows which form the caldera floor, and the minor faults and intrusions which affected these flows. The youngest lava on the island was produced on July 12th, 1965, as single aa basalt flow emitted from a fissure halfway between the two pit craters. Small fumaroles are still active on this flow, as well as in the pit craters and at several small cinder cones in the caldera.

Alignment of pyroclastic cones and fissure eruptions forms a radial pattern centering on Chahale pit crater, suggesting that these radial fissures are locally controlled. Location of the caldera at the intersection of two regional fissure systems implies that its location is controlled by regional stresses. The present size and form of the caldera is a result of the coalescence of at least four smaller calderas. Although the visible walls of these smaller calderas do not show any outward dip, the theoretical considerations of Robson and Barr (1964), if applicable, require that at depth these are outward-dipping ring dyke type of fractures.

England, Sept. 1969.

Introduction

The four principal Comores islands form a west-northwest chain extending over some 270 km between East Africa and northern

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Madagascar (Fig. 1). All islands are volcanic, but Grande Comore, at the western end of this chain, is the only site of present activity.

Grande Comore is formed by the coalescence of two alkali basalt shield volcanoes, La Grille in the north and Karthala in the south (Fig. 2). The Karthala volcano reaches 2560 meters in altitude, and with its average slopes of 15°, is steeper than most other shield volcanoes. Above an altitude of 2000 meters the volcano is capped by a steep dome, on the top of which is found the Karthala caldera (Fig. 3).

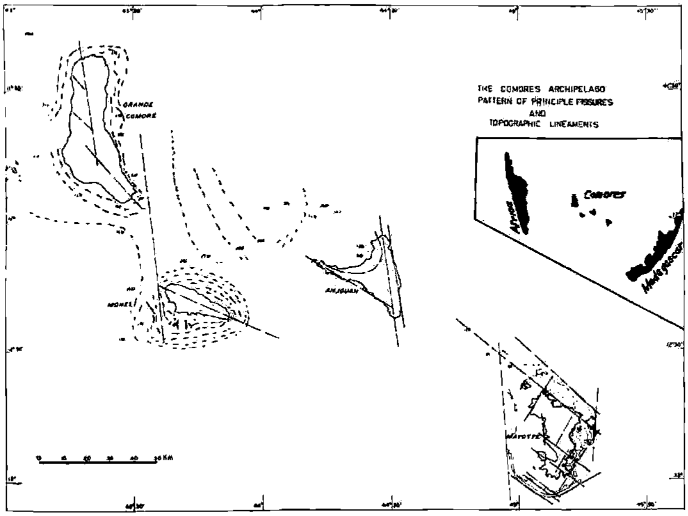

FIG. 1 - Principal fissures of the Comores Archipelago. The Karthala caldera occurs at the intersection of two regional fissures on Grande Comore. Insert shows location of the Archipelago relative to East Africa and Madagascar.

The caldera has been briefly described by numerous authors, the more notable of which are VOELTZKOW (1905), LACROIX (1938), POISSON (1948), and DE SAINT OURS (1960). These descriptions, although excellent in themselves, are presently inadequate because *a*) the caldera has been continuously changing since they were written, and *b*) these authors (except De Saint Ours) did not have the benefit of the superb topographic maps and aerial photographs which are now available, and *c*) these brief studies were not made in conjunction with a more comprehensive investigation of the whole volcano.

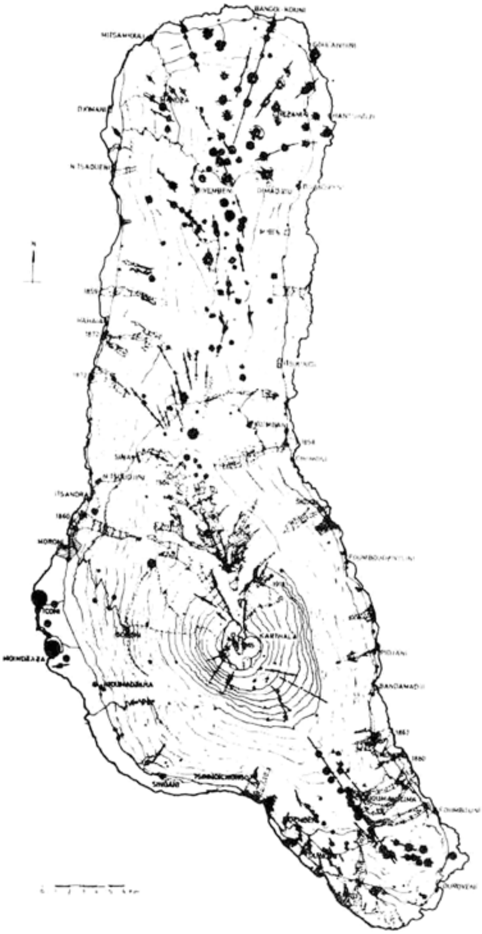

FIG. 2 - Geological map of Grande Comore, showing historic flows, radial fissures on La Grille and Karthala volcanoes, and location of the caldera on the domed top of Karthala volcano.

Geological Setting of the Caldera

The geology of the Comores archipelago as a whole is described by ESSON, *et al.* (in press). Two important features are that the islands become progressively younger westwards to the active Karthala volcano, and that there are two regional fissure systems, one trending north-south and the other northwest-southeast (Fig. 1). These fissure systems are particularly evident on Grande Comore, an island consisting of northern and southern limbs parallel to the north-south and northwest-southeast fissure systems respectively. The Karthala caldera is found where the two limbs meet, at the intersection of the fissure systems (Fig. 2).

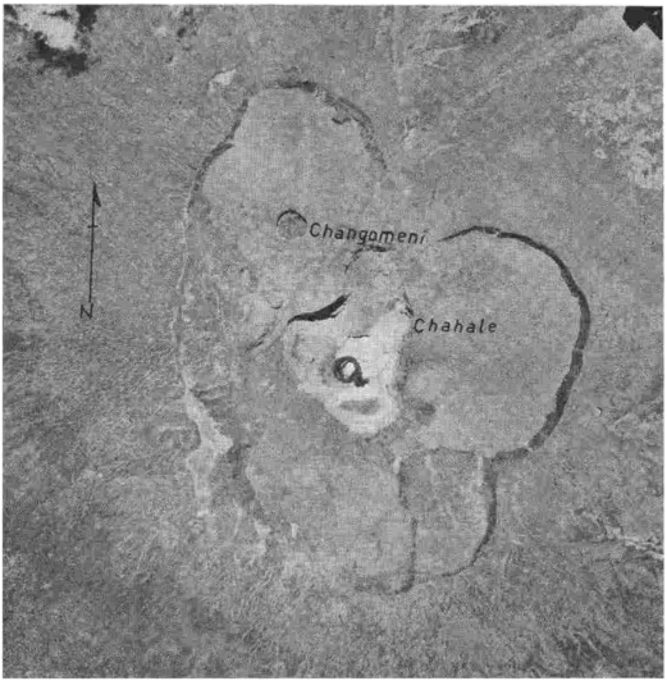

FIG. 3 - Aerial photograph of the caldera. Outstanding features are the steep outer walls, Chahale and Changomeni pit craters, and the radial fissures outlined by cinder cones.

In addition to the regional fissures there occur two local sets of radial fissures, outlined by coalescing cinder cones. One such set radiates in a zone between northwest and northeast from the summit of La Grille volcano which, however, shows no evidence for the existence of a caldera. The other set radiates in all directions from the summit of Karthala volcano, the site of the Karthala caldera, and extends for horizontal distances of 15 km away from the caldera (Fig. 2).

FIG. 4 - Circles show postulated location of the small calderas which are believed to have collapsed in the order *a* to *h*, and coalesced to form the greater caldera. Straight lines show the graben type fractures along which collapse also took place.

Description of the Caldera

a) CALDERA MARGINS

The caldera is grossly elliptical in outline, with a north-south axis of 4 km and an east-west axis of 3 km (Fig. 3). Closer observation shows that several independent features combine to give it this form. Firstly, at least four smaller calderas are clustered together to form the greater caldera, and account for the generally scalloped appearance of the caldera walls (Figs. 3 and 4). Secondly, the linear fissures, faults and straight walls impart a rhombic pattern to the caldera, the sides of the rhomb being parallel to the two regional fissure systems (Fig. 5). One might note that in both of these features the caldera is similar to the Santorin caldera, Greece (see WILLIAMS' summary, 1941).

FIG. 5 - Regional fissure pattern superimposed on a map of the caldera, showing how its form has been influenced by these fissures.

Except for the « Porte d'Itsandra », the outer walls of the caldera form steep cliffs dipping from vertical to 75° inwards, and up to 100 meters high (Fig. 6). The Porte d'Itsandra (Fig. 6*b*) represents an area where the walls were particularly low and have been frequently breached by flows emanating from the caldera, the 1860 flow being the most recent example. Slight differences in degree of erosion and vegetation of the walls, *e.g.* the small gorge in the outer west wall (Fig. 3), make possible some estimation of their relative ages of formation. There are four large benches as remnants of incomplete collapse along the outer walls, two in the west, one in the south, and one in the northeast (Figs. 3 and 6). The outward dip of lava beds in these blocks may be a reflection of their original dips, or they may indicate that during collapse the outer parts were lowered more than the inner parts.

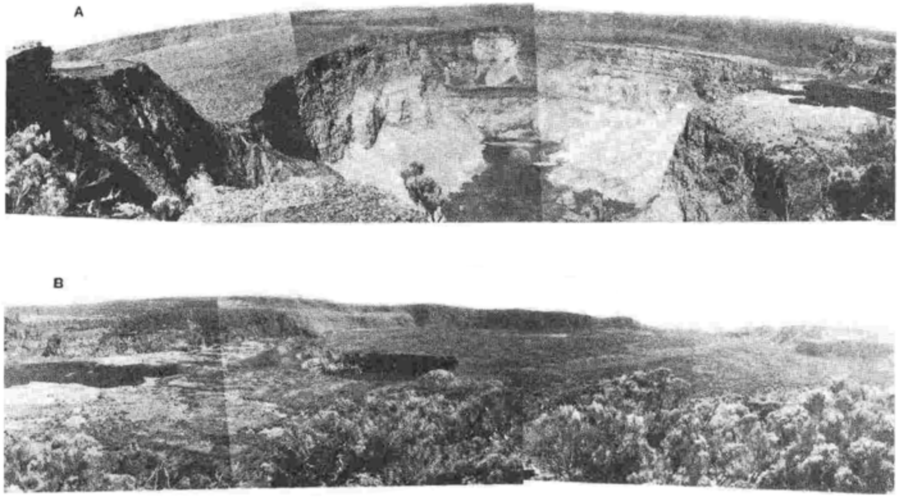

FIG. 6 - Panorama of the caldera including about 300 degrees of the compass, and showing most of the features described in the text. Figure 6*a* overlaps the left side of figure 6*b*.

b) PIT CRATERS

The two most striking features inside the caldera are the large southern pit crater, Chahale, and the smaller northern one, Changomeni (Figs. 3 and 6). Chahale pit crater is presently 1300 meters long, 800 meters wide, and 300 meters deep from the highest point on its northeast rim. From the caldera floor on its southern rim it is about 170 meters deep. Its walls are clearly vertical down to the first 100 meters and, although mostly hidden by talus below this, several bare areas show that they continue to be vertical downwards (Fig. 6*a*).

The floor is covered mostly by talus, which has in turn been partly covered by the 1965 lava flow (Fig. 6*a*). This 1965 flow is pierced by a smaller lava cone at the base of the south wall of Chahale (Figs. 6*a* and 7), and older cinder cones occur around the southern and southeastern rims of Chahale (Fig. 6*a*). What must have been the conduit of the southern cone is marked by a lighter zone in the wall of the pit crater (Figs. 6 and 8), reminiscent of the « wine glass » of Crater Lake, Oregon (WILLIAMS, 1942). A large platform at the bottom of this lighter zone (Fig. 6*a*) marks the level of the pit crater floor in 1900 (Fig. 9).

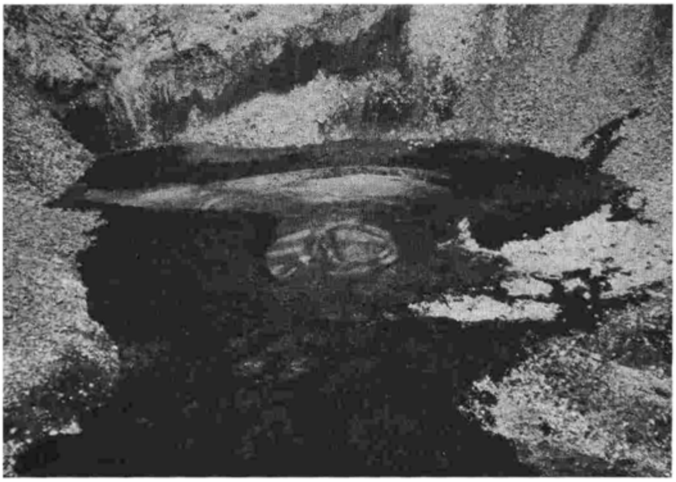

FIG. 7 - The 1965 lava flow on the floor of Chahale pit crater, cut by a later small lava cone.

A valuable aspect of the Chahale walls is that they provide a section through a substantial thickness of lava flows and illustrate the sequence of events to which these walls were subjected. In the west wall (Fig. 10) one sees a vertical fault scarp along which the southern side has been lowered during the formation of the small caldera *d* (Fig. 4). After this lowering, thick lava flows ponded against the scarp, covering the lowered surface and filling in the depression, and eventually covering and obliterating all surface traces of the scarp. Exposed in the eastern wall (Fig. 11) is a scarp which is similar to the above except that it dips about 75° southwards. It was also formed by relative lowering of the southern side during collapse of the small caldera *e* (Fig. 4). Against this scarp were ponded the same lava flows as against the western scarp, indicating that both have coexisted for a substantial time interval, *i.e.* that the small calderas *d* and *e* were connected during deposition of these flows. Minor displacements of the overlying flows along the eastern fault (Fig. 11) suggests that it may be the younger of the two, and therefore that caldera *e* is more recent than caldera *d*. The thickest of the ponded flows at its contacts with these scarps, and particularly the eastern one (Fig. 11), shows excellent examples of the orientation of cooling joints perpendicular to the surface against which it was cooled (Fig. 11 *b*).

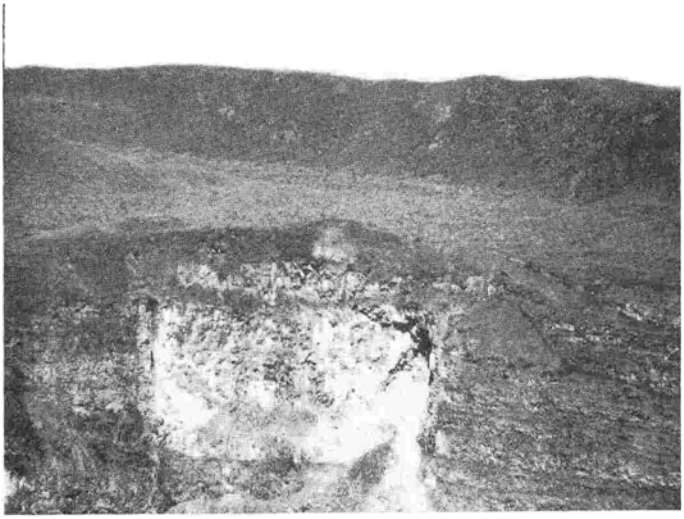

FIG. 8 - Vent exposed in the south wall of Chahale pit crater.

The most important historic changes in the Chahale pit crater were caused by the 1918 eruption. A good description of this eruption and its geomorphic effects has been compiled by LACROIX (1938, pp. 43-47), a summary of which is given below (authors' translation).

« This caldera had once been covered by continuous sheets of lava ponded against the foot of its walls, and these were later cut by a pit which in 1905 measured about 500 meters in diameter with vertical walls 100 meters high. The bottom of this pit was then covered by a horizontal sheet of lava which was cut by small cinder cones.

« The eruption of 1918 began suddenly in the night of August 11-12, with intense light flashes signalling the opening of a crevasse on the north flank of Karthala at an altitude of 1980 meters, about 600 meters above the source of the 1904 eruption. This crevasse was not more than 80 meters long, outlined by three conelets about 10 meters high; lava flowed from it northward for three days.

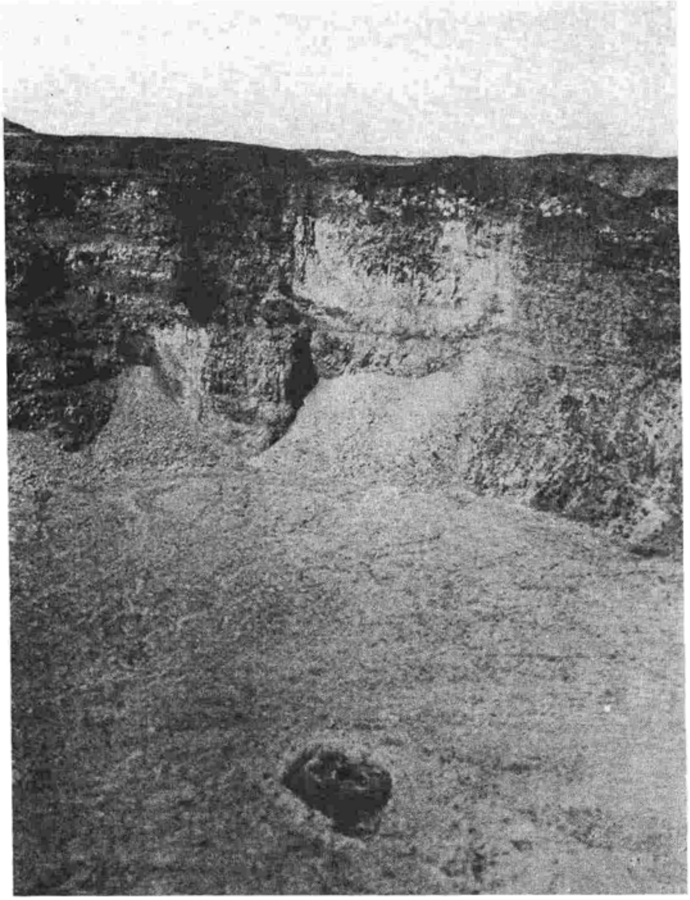

FIG. 9 - Floor of the Chahale pit crater showing the level of the floor in 1900 (after VOELTZKOW, 1905). Compare to fig. 6*a*.

« Small shocks were felt on the flanks of the volcano until August 23, the day on which a violent shock was felt on all of Grande Comore and the neighbouring island of Moheli. More prolonged shocks were felt on August 25, when at 7.30 A.M. an enormous column of vapour and cinders rose in rapid puffs above tha caldera, steadily increasing in size for about ten minutes. The same thing happened a 4.25 P.M. on August 26, the column reaching a height of about 5,000 meters above the caldera. Minor shocks were repeated until the end of the month, accompanied by very minor vapour emission.

« M. Legros visited the caldera in October, and found that the dimensions of the pit crater had been sextupled; from circular it had become elliptical and its floor covered with debris. Also, a new vent (Changomeni pit crater) had been opened in the caldera, a little to the north (of Chahale pit crater). This new pit was circular, about 300 meters in diameter, and had the same structure as the larger one ».

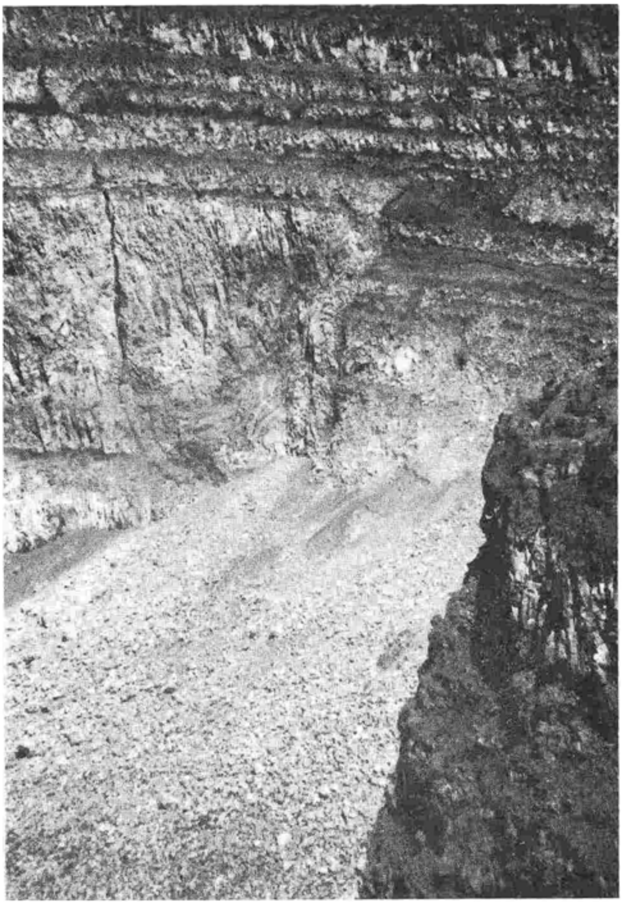

FIG. 10 - Fault scarp exposed in the west wall of Chahale pit crater. The thick flow was ponded against this scarp, and later extrusion along the contact produced the thin overlying flow with its feeder dyke clearly visible.

It appears to the present writers that the dimensions given by Lacroix for the Chahale pit crater cannot be correct, for the photograph shown in VOELTZKOW's plate *71* (see Fig. 9) suggests a diameter greater than 500 meters, and even the present dimensions are not six times larger than this. It does appear, however, that the

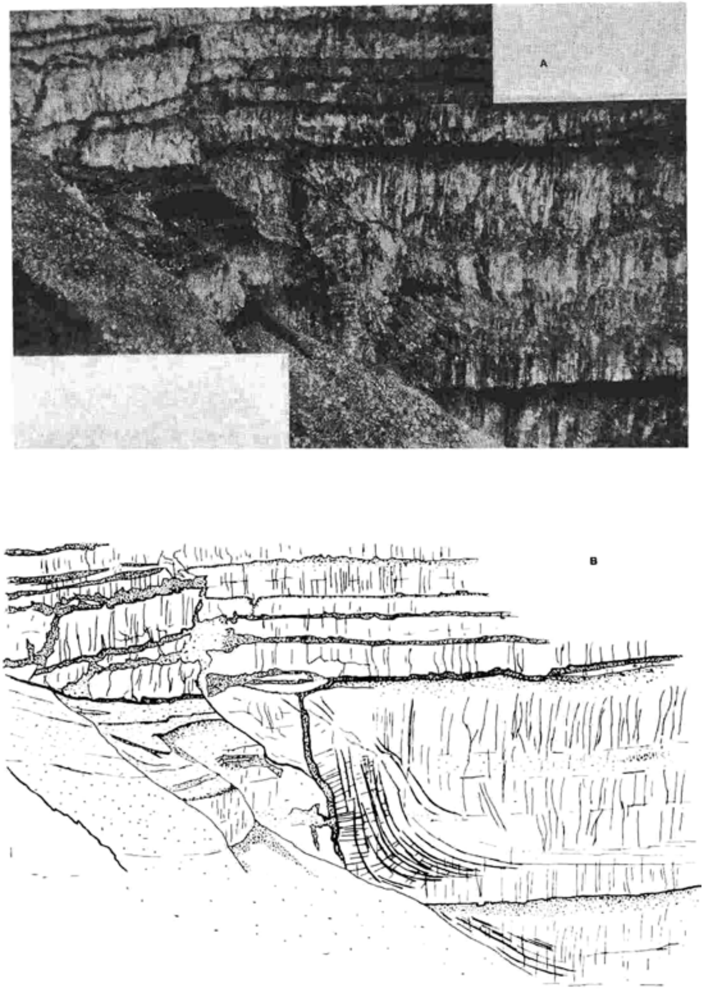

Fig. 11 - Fault scarp exposed in the east wall of Chahale pit crater, with the same thick ponded flow as in Fig. 10. Note how the cooling joints have rotated at the scarp contact, shown more clearly in the sketch in Figure 11 b.

nature of his description is correct. That is, Changomeni pit crater having formed, and substantial enlargement and lowering of the floor of Chahale pit crater having taken place during the 1918 flank eruption. The enlargement of Chahale probably took place through the formation, by explosion, of the pit in its northeastern corner (*g*, Fig. 4), now filled by lithic pyroclastic debris.

Changomeni pit crater, one km north of Chahale (Figs 3 and 6), is cylindrical in form, with a diameter of 250 meters, and vertical walls 30 meters high. Like those of Chahale, these walls show sections through the overlapping caldera flows. These flows vary in thickness and show an alternation of columnar jointed massive centers and scoriaceous tops and bottoms, and are cut by thin vertical dykes which branch into the scoriaceous zones before reaching the surface (Fig. 12). Changomeni pit crater is floored by ponded lava which is scoria-topped in the central part of the floor and broken into thin slabs where piled up against the walls. Fumaroles are found in a small crater on the northern part of the floor, where sulphur is precipitated, and at the base of the walls on all sides, where they deposit white amorphous material on the walls. Cinder cones are found on the north and south rims (Fig. 6). Changomeni pit crater was the site of the August, 1948 strombolian type eruption, during

FIG. 12 - The eastern wall of Changomeni pit crater. Note the fumarole on the right rising from the base of the wall, and the thin vertical dyke on the left. Note the thinning and overlapping of the upper flows in the central part of the picture. There is very little talus at the foot of the walls, as compared to the Chahale pit crater.

which large blocks were thrown hundreds of feet into the air (POISSON, 1948).

c) CALDERA FLOOR

The remainder of the main caldera floor is covered by horizontal lava flows showing some very smooth flat areas amongst the generally slaggy surfaces. Pyroclastic material covers less than five percent of the floor area and is concentrated around the two pit craters, especially the northeast part of Chahale, and the five or so isolated cones.

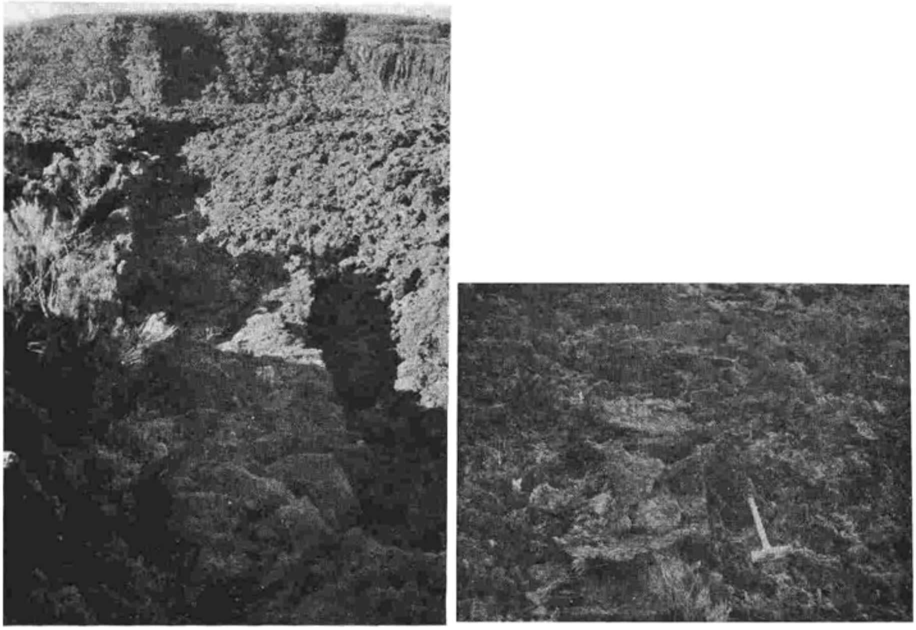

FIG. 13 - Surface expression of the « caldera » *i* (see Fig. 4). Figure 13 (left) shows its northern part as a tensional crevasse, and figure 13 (right) shows the southern part as a pressure ridge of piled up lava slabs.

A large linear feature transects the caldera floor from a point near the west rim of Chahale pit crater, through Changomeni pit crater, and northward to the outer wall of the caldera east of Porte d'Itsandra (Figs. 3 and 4). At several places along its length one sees minor vertical displacement, with the east side lowered (Fig. 6). This feature is essentially a tensional fissure. From this fissure, about halfway between the two pit craters, emanated the 1965 lava flow, which flowed southwards over the walls of Chahale pit crater to cover the lower part of its floor (Figs. 6 and 7). Its eruption, on July 12, 1965, was heralded by a large black cloud of vapour and cinders rising from the caldera floor and visible at Moroni, 15 km to the west.

An additional point of interest in the caldera floor is a circular feature about 250 meters in diameter, about 800 meters northwest of Changomeni (*i*, Fig. 4). This feature, clearly visible on the 1948 aerial photographs (Fig. 3), is seen on the ground as a small semicircular crevasse about one meter deep on its northern half (Fig. 13*a*), and an opposing semicircle on its southern half in the form of a pressure ridge of piled up lava slabs (Fig. 13*b*), these meeting on the east and west sides in an area of relatively flat topography. This feature might mark the site of a filled ancient pit crater, but the present writers regard it as an « incipient » pit crater, with fractures not yet deep enough to permit collapse or tap any source for pyroclastic cones analogous to those which apparently preceded the collapse of Chahale and Changomeni pit craters. Thus, we may have a circular piston which is slowly sinking, the northern part at a faster rate than the southern part, to produce the crevasse and pressure ridge.

Summary and Discussion

As a result of eruption along north-south and northwest-southeast regional fissure systems, the two volcanoes Karthala and La Grille began to form more or less simultaneously. Favourable location of Karthala at the intersection of the fissures allowed it to outstrip La Grille in rate of formation, with eventual build-up of the steep-sided dome-capped shield. After completion of the dome, the north-south fissures influenced the orientation of initial fractures *1* and *2* (Fig. 4) along which graben type collapse occurred. The increase of upward pressure relative to horizontal pressure (stress) caused radial and circular fractures to develop.

Eruptions following the development of these fractures presumably emptied the underlying magma chambers, removing support, and causing collapse along the circular fractures. This resulted in formation of the small calderas in the order *a* to *e* (Fig. 4). Although these caldera walls dip mainly inwards, one cannot assume that they represent the original fractures. The inward dips may be a result of erosion, and the vertical walls of the two most recent « calderas » *f* and *h* (Chahale and Changomeni pit craters) suggests that this is most likely the case. The collapse of these calderas was probably not a sudden engulfment, but rather a stepwise and irregular collapse, as evidenced especially by the benches remaining in calderas *a* and *b* (Figs. 3, 4, and 6). One might note that this type of collapse would be necessary for inward-dipping (conical) fractures, a fact emphasized by Reynolds (1956). The calderas *b* to *e* would have intersected at their margins, but these appear to have merged with *a* by graben-type collapse along fractures *3*, *4*, and *5*. « Caldera » *f* (Chahale) was then formed, exposing the faults along which *d* and *e* collapsed. During the flank eruption of 1918, the « calderas » *h* (Changomeni pit crater) and *g* were formed by collapse and explosion respectively. One may expect eventual collapse of *i* to form another pit crater similar to Changomeni.

As these regional fissures, radial fissures, grabens, and circular fractures represent a striking combination of the features discussed by ROBSON and BARR (1964), it is pertinent to try and interpret the stress system in the light of their theoretical predictions. In applying these predictions to the Karthala caldera, we might best assume that throughout the development of these features there was a vertical stress (P_{max}) which was greater than either of two horizontal stresses (P_{min} and P_{int}), a reasonable assumption since a very considerable force is needed to transport the magma upward to the surface in the first place. We must then assume that at the beginning of volcanism via the regional fissures, P_{int} was much greater than P_{min}. This also seems perfectly reasonable because otherwise the fissures would not have formed at all. As the Karthala shield volcano grew, P_{int} appears to have approached P_{min} in value, which could have taken place by an actual equalization of these regional stresses, or more probably by a local equalization due to increasing difficulty in transmitting stress through the growing pile of lava. Associated with this equalization of stresses was an increasing tendency for central type eruptions to take place, resulting in build-up of the dome. After formation of the dome, however, there must have remained sufficient difference in these horizontal stresses to cause the initial graben type collapse and influence generally the overall form of the caldera. When the stresses were more or less equal, the small circular calderas and radial fractures were formed. We thus see that, using the theoretical considerations of ROBSON and BARR (1964), reasonable assumptions about the stress environment can be made to explain the features observed. With these same assumptions about the changing stress environment, we may thus go on to a more detailed application of their predictions to try and deduce something about the deeper structure of Karthala volcano.

ROBSON and BARR (1964, pp. 326-327) consider that when P_{max} is vertical and applied at a depth greater than 4.7 km, and $P_{int} = P_{min}$, shear failure should occur in the form of inward dipping fractures, with the resultant caldera about 4 km in diameter and increasing in diameter with greater depth of the magma chamber. The walls of the Karthala caldera appear to fit this requirement, and some of the widespread radial fractures also appear to require a very deep source of upward pressure. We have seen, however, that the Karthala caldera results from the clustering together of individual smaller calderas which, according to the theories of Robson and Barr, are too small to have formed by shear failure from a deep source of upward pressure.

The other possibility discussed by ROBSON and BARR (1964, pp. 326-327) for shallow magma chambers, *i.e.* at a depth less than 4.7 km with P_{max} vertical and $P_{int} = P_{min}$, shows that the stress can be relieved by vertical tension cracks radiating from the center of stress, or by a single arcuate tension crack dipping outwards at an angle greater than 60°. In the latter case the arcuate cracks would form segments of a circle which comprises a ring dyke. As we have seen above, the walls of the small circular calderas that are visible at the surface are vertical in the two cases where very recent and uneroded, and therefore possibly have been so in all cases. They may thus be the surface expression of ring dyke type of fractures expected from shallow magma chambers. Although Robson and Barr do not make any statement concerning the relationship between diameter and depth of magma chamber for this fracture type (except that the magma chamber is less than 4.7 km deep), the present writers feel that the Karthala calderas are most likely to have resulted from ring dyke type of tensional fractures rather than shear failure along inward-dipping cone-sheet type of fractures.

Acknowledgements

The writers are grateful to Dr. K. G. Cox for helpful discussion and criticism of the manuscript, and to Dr. B.G.J. Upton for criticism of the manuscript. The research was supported in part by the National Research Council of Canada and the U.K. Natural Environment Research Council.

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Manuscript received Oct., 1969