STATISTICAL AND PROBABILISTIC APPROACH TO VOLCANIC HAZARDS FOR LOCATION OF GEOTHERMAL WELLS AND PLANT IN FOURNAISE ACTIVE VOLCANO (REUNION ISLAND, WESTERN INDIAN OCEAN)

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ABSTRACT

The Piton de la Fournaise (2,635 m) is the active basaltic shield volcano of Reunion Island (55°43′E, 21°17′S) in the western Indian Ocean. As with Kilauea Volcano, Hawaii, this active volcano built up on the western flank of an older volcano, Piton des Neiges (3,069 m), whose activity dates back 22,000 years B.P.

Geothermal investigations by BRGM (1978 to 1983) lead to a drilling program in 1985-1986 inside the last U-shaped caldera (8 x 13 km) called Enclos, beside the sea-shore, on historical lava flows (20 to 100 years old).

Careful archives investigations on historical volcanic activity for 3 centuries have been carried out since 1980 by the Indian Ocean Geological Survey (BRGM) in La Reunion to first evaluate the hazards to drilling and to future equipment funneling steam toward the geothermal plant, planned to be set up on the external rim of the caldera.

INTRODUCTION

Piton de la Fournaise (Fournaise), on the island of La Réunion in the Indian Ocean, is an active basaltic shield volcano growing in an intraplate environment. This volcano lies in a tropical climate that is characterized by an annual average rainfall of as much as 500 cm on the windward (southeast) flank. Moreover, it is built against and upon the south to southeast flank of a much larger basaltic shield volcano, Piton de Neiges, and has erupted hundreds of times within the past two and one-half centuries, providing abundant opportunities for direct observations and study of a variety of volcanic activity. Upton and Wadsworth (1965) and Ludden (1978) demonstrated a general parallelism in chemical composition of lavas of Fournaise and Kilauea volcanoes, although lavas of Fournaise are generally somewhat more alkalic than their Kilauean counterparts. Ludden (1977) concluded that the average rate of magma production has been nearly identical for the two volcanoes during recent historic time. Duffield, Stieltjes and Varet (1982) suggested a structural comparison on gravitational slumping of large parts of each volcano as an important mode of structural evolution.

The geothermal drilling program is planned for 1985-1986 within the caldera, in Grand Brulé (Figure 1). The abundant volcanic activity within this caldera during the past 3 centuries (Figure 2) lead us to carefully study the occurrences and evolution of volcanic activity this last decennary.

STRUCTURE OF FOURNAISE VOLCANO

The principal structural features of Fournaise are: (1) a summit caldera and adjoining downfaulted trough, (2) a family of broadly curving faults that are nested around the caldera, to the west, and (3) three rift zones (Figure 1). The caldera is an 8-km-wide collapse depression within which a roughly 400-m-high lava shield has grown around the principal intra-caldera vent. The top of this lava shield is indented by Dolomieu and Bory craters, nearly interconnected and roughly 1,000 m and 250 m wide, respectively. The caldera is breached on the east, where it connects with an 8-km-wide, east-trending, downfaulted trough that extends to the sea coast and presumably beyond. The walls of this composite depression range from

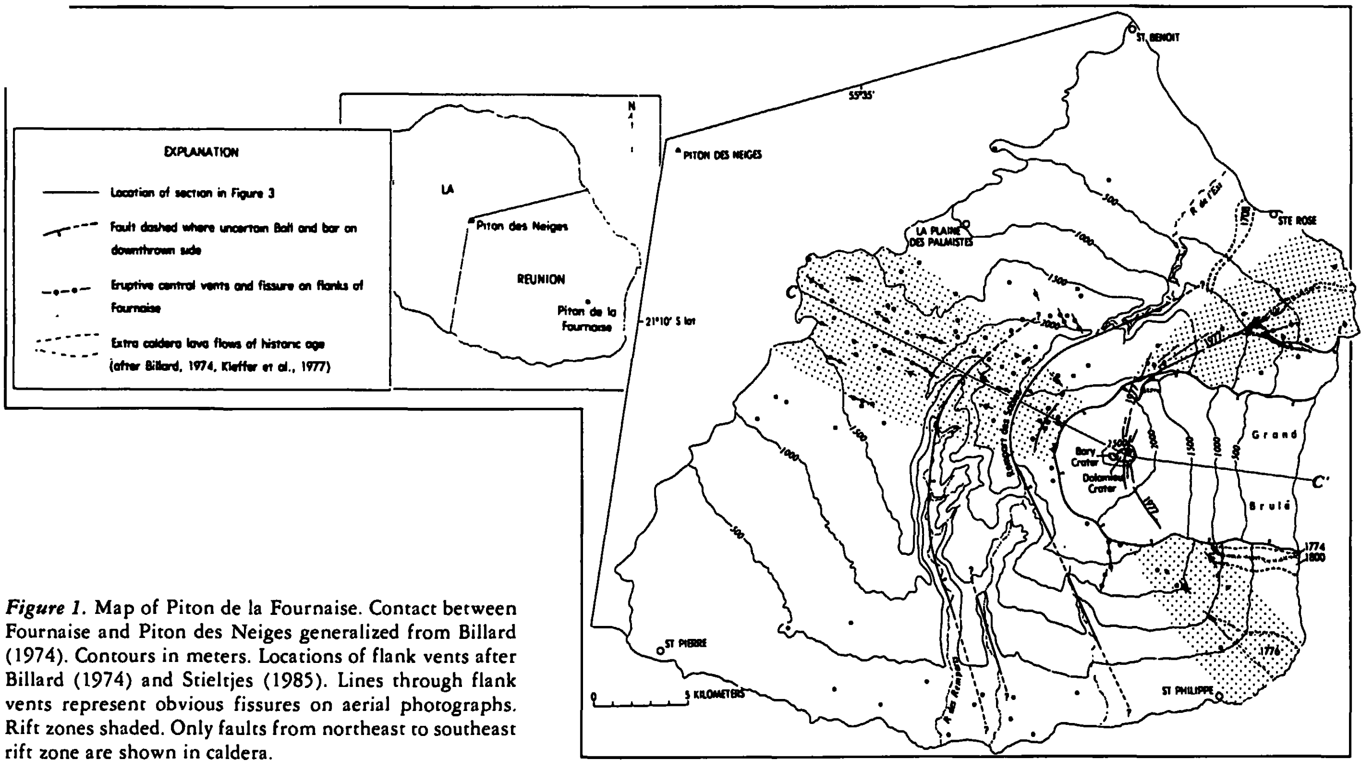

Figure 1. Map of Piton de la Fournaise. Contact between Fournaise and Piton des Neiges generalized from Billard (1974). Contours in meters. Locations of flank vents after Billard (1974) and Stieltjes (1985). Lines through flank vents represent obvious fissures on aerial photographs. Rift zones shaded. Only faults from northeast to southeast rift zone are shown in caldera.

about 100 to 300 m in height and have effectively contained all historic and recent prehistoric lava flows that originated within the caldera. The caldera is called the Grand Enclos, in reference to its part in enclosing many of these lavas; the name Grand Brulé is applied to the lower part of the east-trending trough, in reference to the burned, devastated character of the landscape that has resulted from repeated encroachment of young lava flows from the caldera.

The caldera is nested within a family of broadly curving, steep-walled canyons and inward-facing escarpments. The largest canyons, those of Riviere des Remparts and Riviere de l'Est are as deep as 1100 m and 800 m, respectively, and are characterized by outer walls that are notably steeper than the inner walls. The monotonous, homogeneous nature of the sequences of lava flows exposed in opposing walls has, to date, precluded any documentation of fault offset across the river canyons. There can be little doubt, however, that the rivers initially made their courses along the base of generally east-facing fault scarps because, except in their lowermost reaches, the rivers trend at a large angle to the direction of widespread consequent drainage developed on constructional slopes of the volcano. The lowermost reaches may parallel this consequent direction because of local river diversion due to burial of the original fault scarp by younger lava flows, or because the river reflects the original trace of the fault scarp. The geologic maps of Bussiere (1967), Bachelery and Chevallier (1982) and Stieltjes (1985) suggest the former possibility.

Previous workers have expressed divergent views about the existence of rift zones at Fournaise. Upton and Wadsworth (1970, p. 143) wrote that "... there is no trace of linear eruptive zones comparable to the rift zones of the Hawaiian volcanoes." Ludden (1978, p. 188), although not directly addressing the question of rift zones proposed a relatively "... well-developed system of feeder networks and magma reservoirs ..." to explain petrographic contrasts between some of the oldest and youngest lavas of Fournaise. Kieffer, Tricot and Vincent (1977, p. 959) described the 1977 eruptive fissure on the northeast flank of Fournaise as marking a zone of weakness "... of which the behaviour may have been that of a rift zone." We agree with this description and, moreover, propose the existence of three rift zones, trending approximately N.50° E. (northeast), N.135° E. (southeast), and N.45° W. (northwest), respectively. Each forms a constructional ridge that radiates from the caldera, direct evidence that relatively abundant lava has erupted and accumulated there compared with other parts of the flanks of the volcano. Moreover, these ridges are the loci of many fissures and parasitic vents along fissures, further evidence of their rift-zone character (Figure 1). Thus, while it is true that the rift zones of Fournaise are relatively underdeveloped topographically, compared for example to the east rift zone of Kilauea, they are, nonetheless, similar to Hawaiian rift zones in the sense that they are constructional ridges along which relatively large volumes of magma have been erupted. Their "underdeveloped" state, specifically that of the northeast and southeast rift zones, may in part reflect their relative youth, a theme that we elaborate upon in a following section.

The northwest rift zone forms a saddle ridge whose axis is essentially on line with the summits of Piton de la Fournaise and Piton des Neiges (Figure 1). Scores of cinder ridges and cones lie within this zone, many clearly localized along generally northwest-trending fissures. Only one eruption is known to have occurred in this rift zone during historic time (Stieltjes, 1985). There are ^{14}C dates from

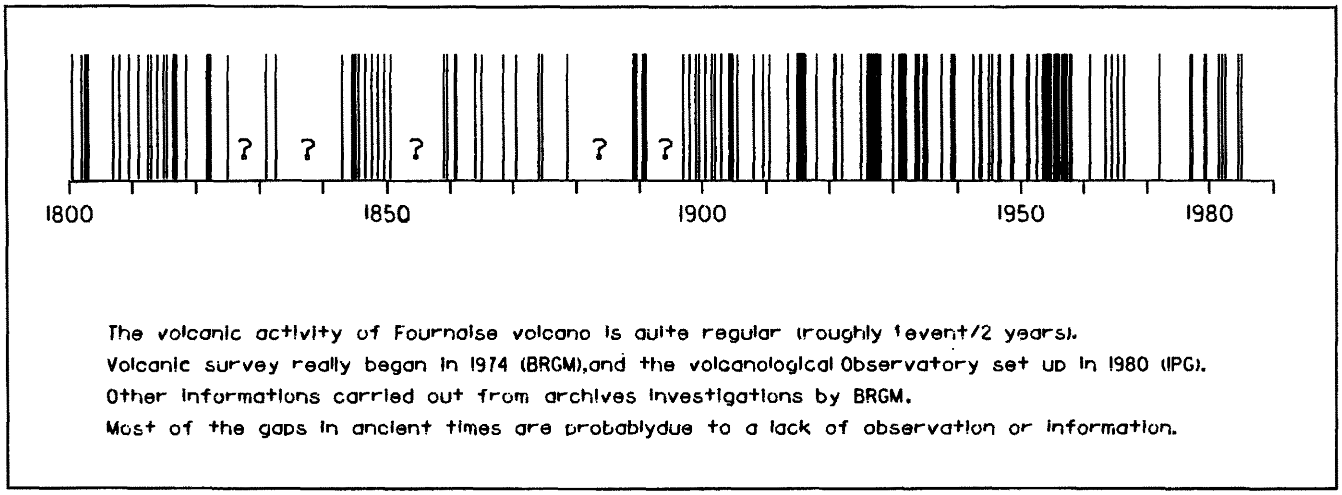

Figure 2. Frequency of volcanic events in Piton de la Fournaise volcano since 1800

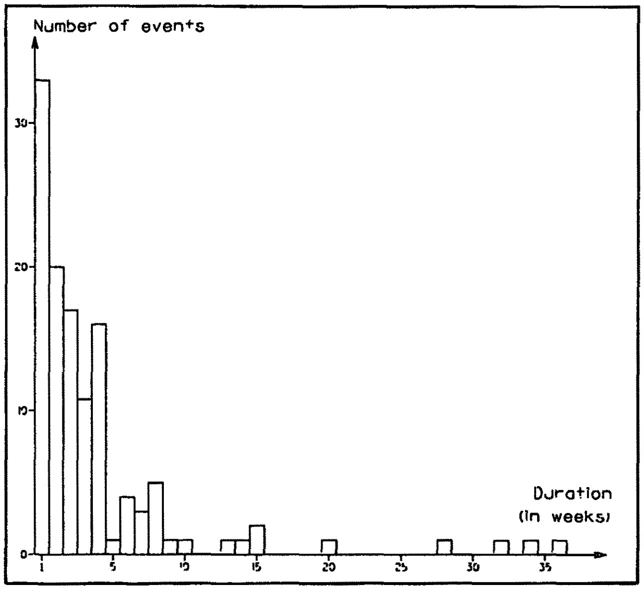

Figure 3. Duration of Piton de la Fournaise volcanic activity since 1844

Bachelery and Chevallier (1982, 1983) that date many of the cones in this rift between 2,000 and 9,000 years. McDougall (1971, sample RU 97) reported a K-Ar age as young as 0.029 ± 0.005 m.y. for basalt within this rift zone. Some of the lavas partly ponded against, flowed along, and overran scarps of the family of curved, nested faults west of the caldera; others cascaded northeastward over steep cliffs that probably represent preexisting walls of canyons eroded in underlying lavas on the windward side of Piton des Neiges (see geologic maps of Bussiere (1967); Billard (1974); Bachelery and Chevallier (1982); Stieltjes (1985).

The northeast and southeast rift zones form tapering ridges that plunge beneath and presumably extend well beyond sea level (Figure 1); no detailed offshore bathymetry exists to indicate their possible submarine extent along strike. Each is the site of many parasitic vents and cones, each has been the site of eruptions in historic time, and each forms a pronounced shore-line promontory, characteristic of relatively rapidly building coastlines in preferentially active zones. The most recent flank eruption of Fournaise occurred near the topographic axis of the northeast rift zone and fed a flow that built this promontory even further seaward (Kieffer and others, 1977). Of the four other historic extra-caldera eruptions, one occurred along the northeast rift zone in 1708, and three along the southeast rift zone, in 1774, 1776, and 1800 respectively (Figure 1).

FOURNAISE VOLCANIC ACTIVITY

Piton de la Fournaise is one of the most regularly active volcanos in the world (an average of one event every 18 months); moreover, its effusion rate increased for the last 30 years.

The oldest data on Fournaise's historical activity, given by seamen, date from 1644. Archives investigations by BRGM have brought to light 156 recorded events (Figure 2). Of the historical activity 97 percent occurred inside the caldera of Enclos (collapsed 2,300 years ago); for these last 3.5 centuries, only 5 eruptions occurred outside the Enclos (3 percent of the activity); the last one occurred in 1977, and basaltic lava flowed through the village of Piton Ste Rose to the sea, destroying several houses and overflowing the main road.

During the XIXth century, about 10 huge lava flows reached the sea shore (where geothermal drilling will be performed); only 4 lava flows of less importance have reached it during the XXth century.

The duration of eruptions is generally short: d< 3 months: 88 percent (Figures 3 and 4). The duration of eruptions considerably increased these last 50 years, which correlates with an increase in the effusivity rate. This seems to indicate an evolution in the recent volcanic activity since 1930, with a significant change about the 1950s.

The duration of intervals between eruptions varies from 2 weeks to 8 years. Some intervals (3 percent) are particularly long, 5.5 to 8 years, without any clear connection with the duration of previous activity or the volume of magma emitted.

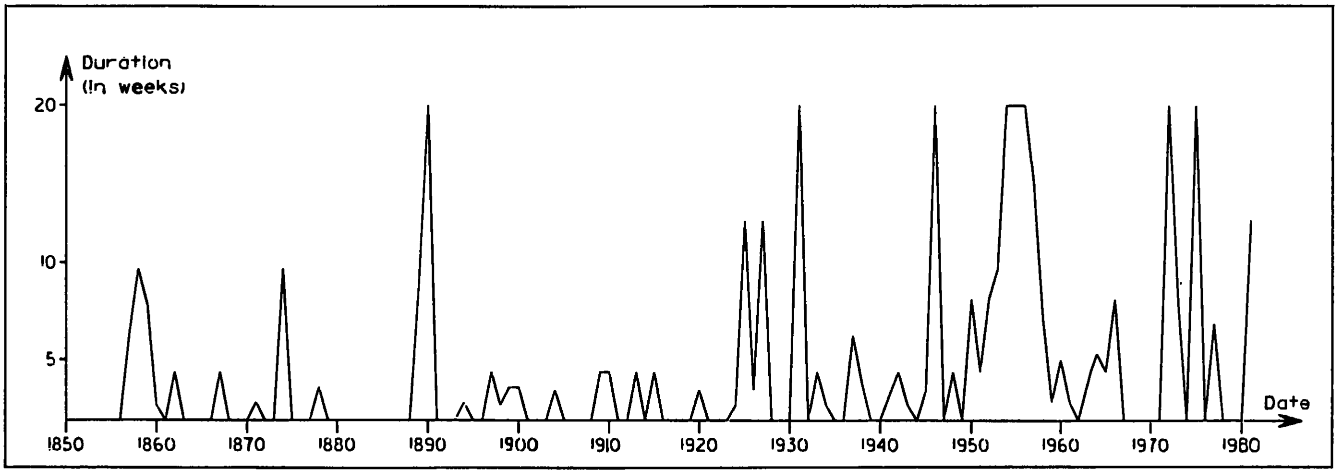

Figure 4. Duration of eruption, Piton de la Fournaise volcano. Peak heights limited at 20 weeks.

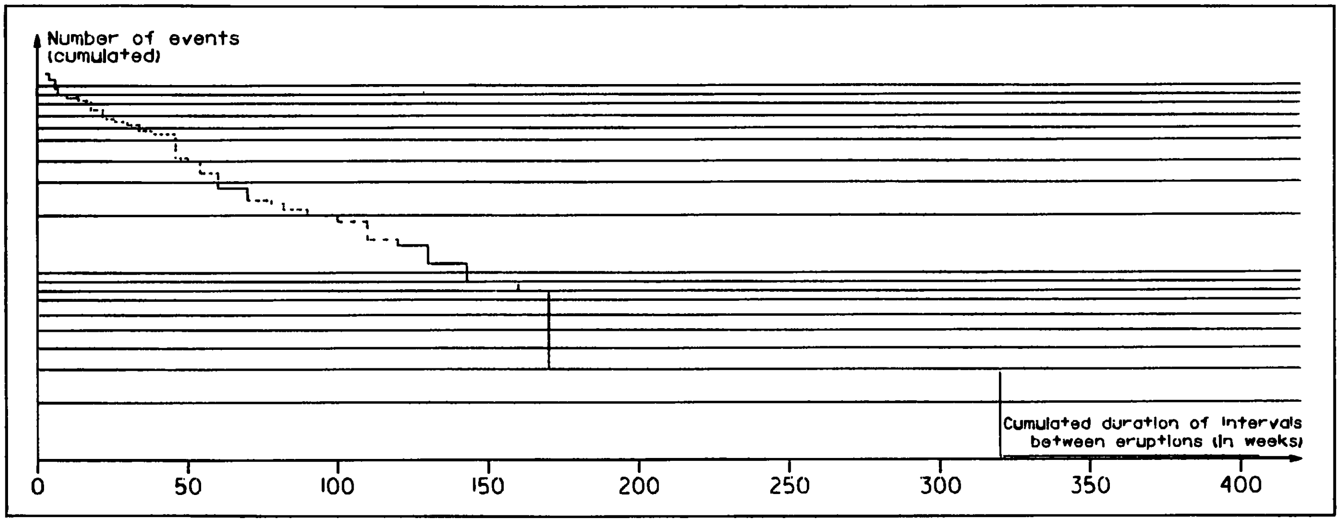

Figure 5. Cumulated intervals in volcanic activity of Piton de la Fournaise (semi-log Wickmann diagram)

IMPLICATIONS ON VOLCANIC HAZARDS IN GRAND BRULE FOR GEOTHERMAL WELLS AND SETTLEMENTS

Although the number of known events is great (156), it is insufficient for previsions or volcanic hazards. In terms of quality and precision of archives data, we only took into account the events of the last 140 years (the 1844 to 1984 period). It should be noted that the data collected are not exhaustive; numerous events, in particular shorter events, are not recorded.

The representation of intervals on a semi-log diagram shows that the eruptive phenomenon is not hazardous. The eruptive process of la Fournaise is neither a simple renewal process nor a superposition of point processes but a simple semi-markov process (Figure 5).

In spite of the fact that, for the whole historical period, this type of activity suggests an actual recharging of high level magma at a roughly constant rate, a detailed study of the succession of eruptions and periods of rest shows that the relations between them are not simple. We cannot consider we have the recharging of a single reservoir but probably several little reservoirs. Moreover, we cannot consider there is a single factor determining a volcanic eruption but several ones (and not only of recharging), which must interact to bring about such a phenomenon.

For the area of Grand Brulé, along the seashore where geothermal wells have to be drilled in 1985-1986, we may consider that the risk of being destroyed by a lava flow for this short period (16 months) is low, considering the concentration of activity along the tectonically active zone and the lower quantity of magma emitted for each eruption (since 1950, compared to the former century).

The geothermal plant and settlement have to be built out of the caldera. Volcanic hazards exist but may be compared to the duration of life of the industrial equipment.

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