GEOMORPHOLOGY OF THE MAYON VOLCANO AND ITS RELATION TO HAZARDS

by

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1. Introduction

Volcanism in the Philippines is generally thought to be subduction-related (Datuin, 1979; Punongbayan). Seven subduction zones, manifested by trenches, bound the Philippine Mobile Belt (see Fig.1). Running parallel and nearby these seven trenches are elongated, narrow zones of volcanoes. The seven volcanic belts consist of a total of 220 volcanoes.

The Bicol arc is composed of 12 active and inactive major cones (Fig.3.2). It belongs to the eastern volcanic belt which trends northwest. Volcanism is related to the westward subduction of the Philippine Plate along the Philippine Trench in the east. It is characterized by medium to high calc-alkali rock suite of basalts, basaltic andesites and andesites. A shift in the eruptive activity through time has been observed in the Bicol arc where activity migrated from north to south (BMG, 1981).

A review of existing literature materials on Mayon Volcano yielded three significant studies focusing on the different eruption products of Mayon, those of Ruelo (1988), Punongbayan and Ruelo (1985) and Newhall (1977). In Ruelo's (1988) "Composite Hazards Zone Map", the four most frequent hazards associated with Mayon have been identified and discussed descriptively. His hazard mapping depended on geological mapping activities, knowledge of the topography, analysis of meteorological records around Mayon and a "complete" understanding of the eruptive behavior of Mayon. A discussion on the influences of the distribution of the different eruption products on the seven-slope-segment profile of Mayon is given in Punongbayan and Ruelo's work (1985). Newhall (1977) also attempted to map out the different eruption products but focused more on the lava flows. Nevertheless, these studies remained descriptive and a little bit too general for a quantitative analysis of the distribution of products. With the introduction of geographic information systems in volcanological applications semi-quantitative and quantitative studies on product distribution can now be easily facilitated

Primarily, this study aims to perform a systematic inventory of volcanic hazards in Mt. Mayon and consequently produce susceptibility maps for lava flows, pyroclastic flows and lahars using the combination of geological-geomorphological mapping techniques and geographic information systems. To achieve this general objective, the following specific objectives have been formulated:

- To identify the different volcanic processes and hazards through geological-geomorphological mapping using multi-scale and multi-temporal aerial photographs and through field checks.
- To produce a systematic inventory map of volcanic hazards together with its pertinent attribute database in a geographic information system.

Some of the limitations encountered in the course of the study include the following:

- Difficulty to place lava flow deposits in a sequence of relative ages using the law of superposition due to:
    - the shape of the volcano, which distributes lava flows around 360 □, complicating morphostratigraphic correlation,
    - unreliability of the forest cover density criterion due to the effects of later pyroclastic flow and airfall processes as well as due to human activities, and,
    - the lack of firmly established stratigraphic sections upon which relative datings could be reckoned from.
- Individual lahar deposits could hardly be reconstructed according to dates of deposition, even for the more recent ones, because they tend to overtop previous ones.
- Lack of topographic map updated after the 1993 eruption which is necessary for more detailed studies along the Bonga Ravine.
- Data on rheological properties are not sufficient to draw empirical laws which could be used as a basis for factor analyses

2. Mayon's Eruptive History

Mt. Mayon is one of the youngest, if not the youngest, volcanoes in the Bicol volcanic chain. But, its precise age has not been determined as yet. The oldest exposed sample that was taken by Meyer in 1985, has been dated about 5,000 years of age (Villarta, et.al.,1985). The rest of the older deposits are either buried underneath recent ones or rendered undatable.

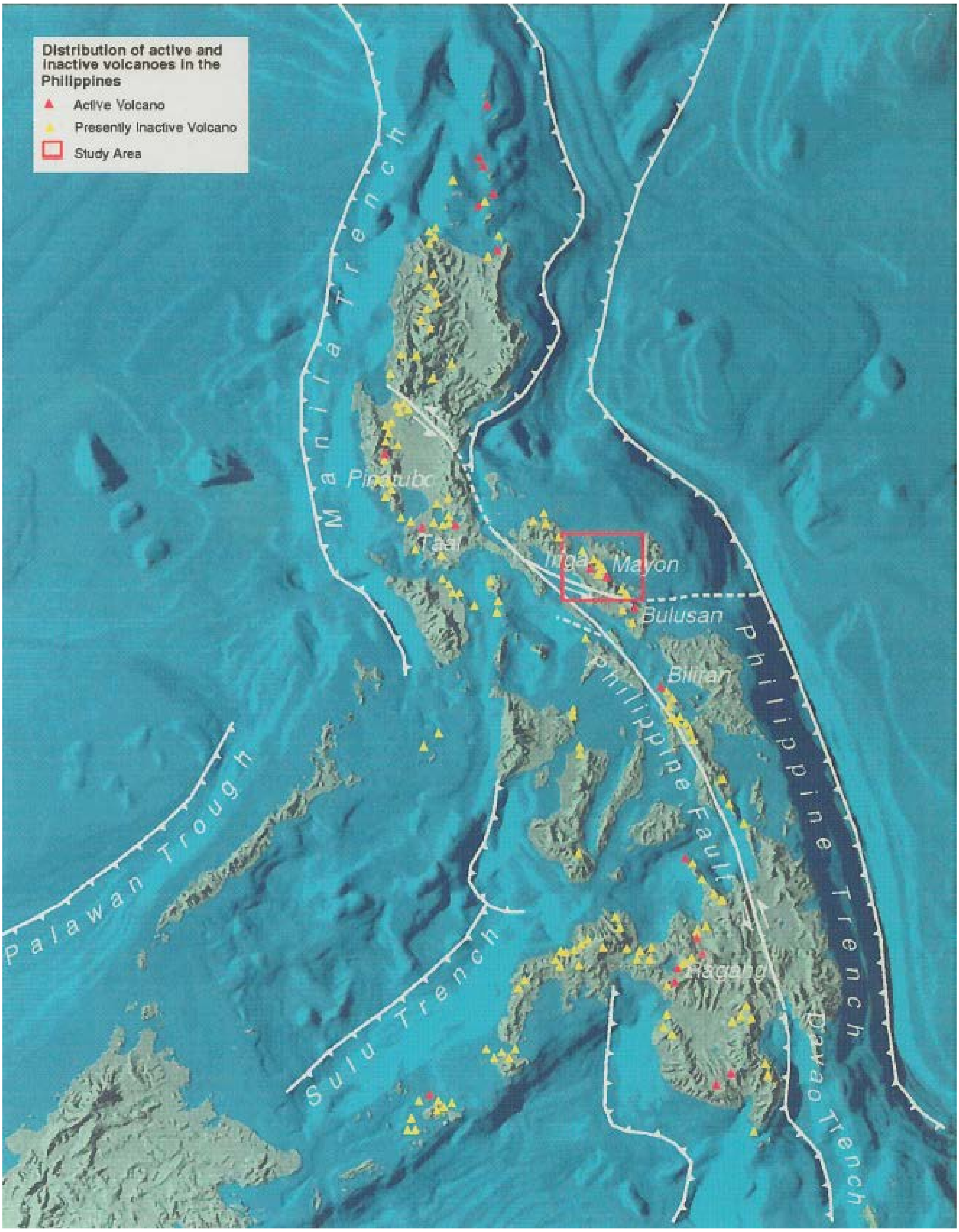

Fig..1. Distribution of volcanic belts in relation to the trenches found in the Philippines (after Punongbayan, 1988).

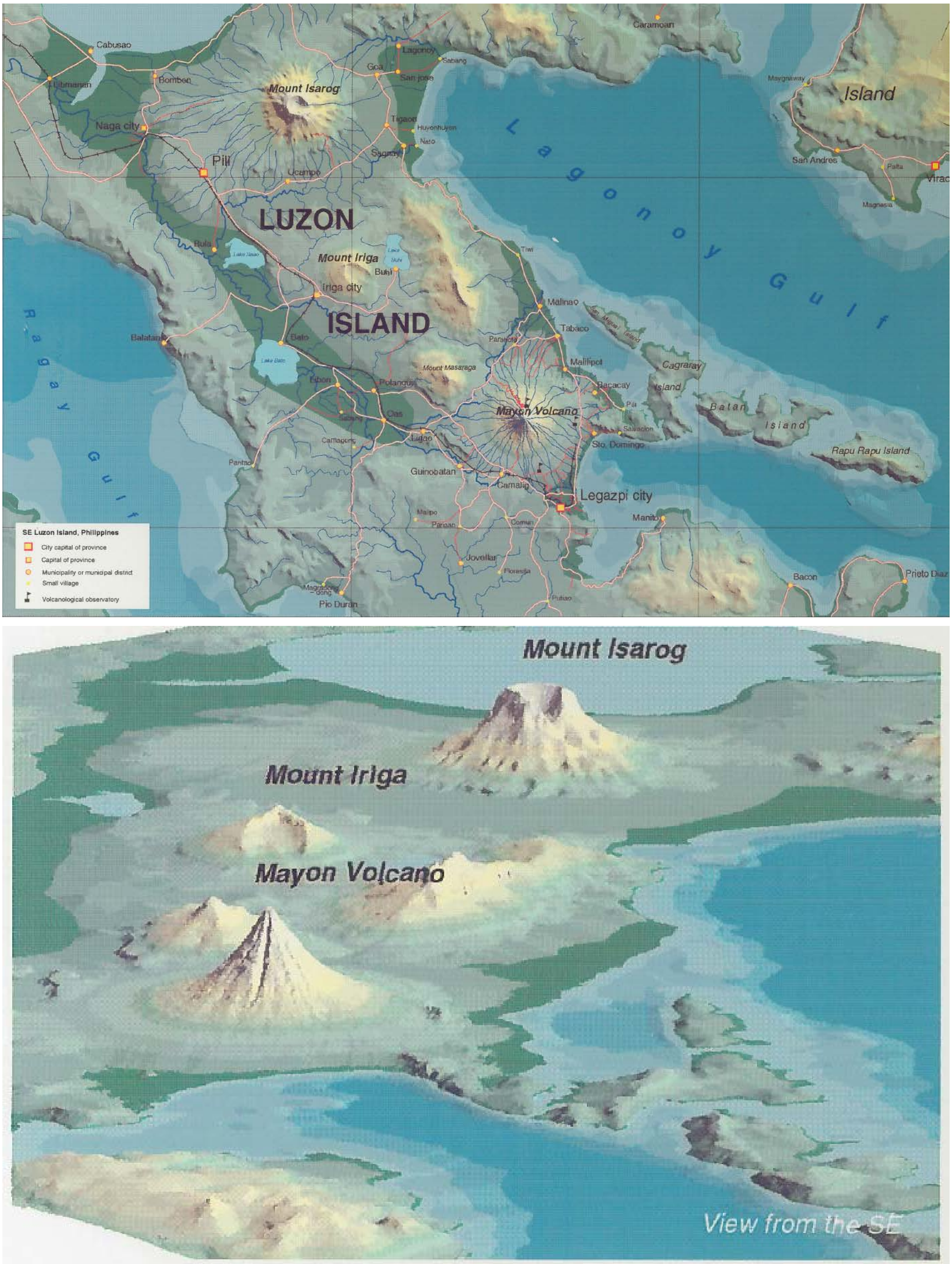

Fig.2. Volcanic cones in the Bicol arc (modified after Villarta et.al. (1985) & Knittel-Weber & Knittel (1990).

The first recorded eruption of Mayon dates back to 1616. This consisted of a very limited account of this particular event by de Bry. Since that year, the volcano has had 45 recorded eruptions, the latest of which was in February-March, 1993.

In a span of 378 years, the eruptions varied from minor to major eruptions. Minor eruptions consisted of weak ash and steam ejections. Moderate to major eruptions include: Strombolian eruptions, which occur from time to time; Vulcanian eruptions which are the most common and the Plinian type, which rarely happened. A summary of the historical eruptions of the volcano is given in Table 3.1.

Age estimation for Mayon was attempted by Newhall in 1977, using three different methods which gave him three different results. By averaging the rate (92.5 x 10^6 m^3 average from 1928 and 1968 eruptions) at which new volcanic products are added to the cone, and then dividing this into the total volume of the cone (1.01 x 10^{11} m^3), he arrived at 5,500 years.

The other method he used was extrapolation downward from a C^{14} date to an assumed base level of the cone. This C^{14} date of 1480±85 years B.P. was given for a charred wood taken 7.9 m. below the surface at elevation 370 m.. By assuming the base of Mayon to be at sea level and the 7.9 m to represent 1480 years of cone construction, he was able to arrive at 69,000 years. Villarta et.al. (1985) calculated its age to be 25,000 years by backward extrapolation using the recent growth of the cone (4 x 10^6 m^3/year since 1902) over the total volume of the cone (1 x 10^{11} m3). Punongbayan (1985) calculated the range of age of Mayon between 14,000 years and 52,000 years. The first value was based on the minimum number of major eruptions (1730 eruptions) multiplied by the short repose period (7.9 years). The second value was obtained by multiplying the maximum number of eruptions (3780 eruptions) by the long repose period (13.7 years). But, when he considered Newhall's cyclical behavior of relatively large eruptions, he finally arrived at an age of 24,000 years for the volcano.

Note that the first method used by Newhall and the method used by Villarta et.al. are the same and yet very different age estimates were obtained. This is because they used different average growth rates for cone construction and different volumes of the cone. On the other hand, Villarta et.al. and Punongbayan used different methods but came up with closely similar results.

In this paper, calculation of the volume of the cone was done using a GIS. The pre-Mayon hills were first masked out from the DTM map. Assuming a 0 base level before the growth of the cone, the total volume was calculated to be 1.054 x 10^{11} m^3. Backward extrapolation using an average growth rate of 4.9 x 10^6 m^3 (from 1928 to 1993), the age of the cone is estimated to be 22,000 years old.

Some studies of previous workers disclosed cyclical variations in the eruptive activity of the volcano. Punongbayan (1985) inferred five cycles based on the trend of repose periods of Mayon. Each cycle or batch consists of 41 to 47 years. Within each batch a generally decreasing repose period is shown, and, in between these batches are relatively longer duration intervals. He concluded that major eruptions occur at the end of each long duration interval.

Newhall (1979) observed a cyclical variation based on the modal and whole rock chemical analysis of fifty-one sequential Mayon lavas. Each of the two recent cycles observed: 1800 to 1876 and 1881 to 1979, consists of 1 to 3 basaltic flows followed by 6 to 10 andesitic flows. He explained that this "....chemical variation apparently results from the periodic influxes of basaltic magma from depth into a shallow magma system. Fractional crystallization of olivine, augite, hypersthene, calcic plagioclase, magnetite and pargasitic hornblende produces successively more andesitic lavas until the next influx of basaltic magma."

Likewise, a statistical analysis of the eruptive events from 1766 to 1984 by Lizardo (1986) disclosed the existence of two separate phases characterized by patterns of generally decreasing reposes expressed by and exponential model."

CYCLE/PHASE	PUNONGBAYAN (1985)	NEWHALL (1979)	LIZARDO (1986)
1	1800 - 1814	1800 - 1876	1800 - 1897
2	1834 - 1858	1881 - 1979	1900 - 1984
3	1871 - 1900		
4	1928 - 1947		
5	1968 - 1984		

Table 1. Observed cycles in the eruptive history of Mayon.

The cycles theorized by Newhall and Lizardo more or less fall in the same time frame, hence it is possible that Lizardo's phases in eruptive events could be explained by Newhall's cyclical variations.

3. Geomorphology

As the terrain is a key factor in the spatial distribution of natural hazards, geomorphological mapping seemed the most logical starting point in making an inventory of volcanic products in Mt. Mayon. It was undertaken using the ITC System of Geomorphological Mapping which was developed in 1967 by Verstappen and van Zuidam and Verstappen's (1988) analytical geomorphological method of volcanic hazard mapping. However, units were classified in a non-hierarchical manner for easier data capture and manipulation.

Using genesis as the major discriminant factor in the classification, seven genetic landform types were mapped on 1:50,000 scale (Fig 3). These are the following:

- Landforms of Volcanic Origin
- Landforms of Fluvio-Volcanic Origin
- Landforms of Fluvio-Volcanic-Denudational Origin
- Landforms of Fluvio-Structural Origin
- Landforms of Fluvial Origin
- Landforms of Fluvio-Marine Origin
- Landforms of Marine Origin
- Landforms of Denudational Origin

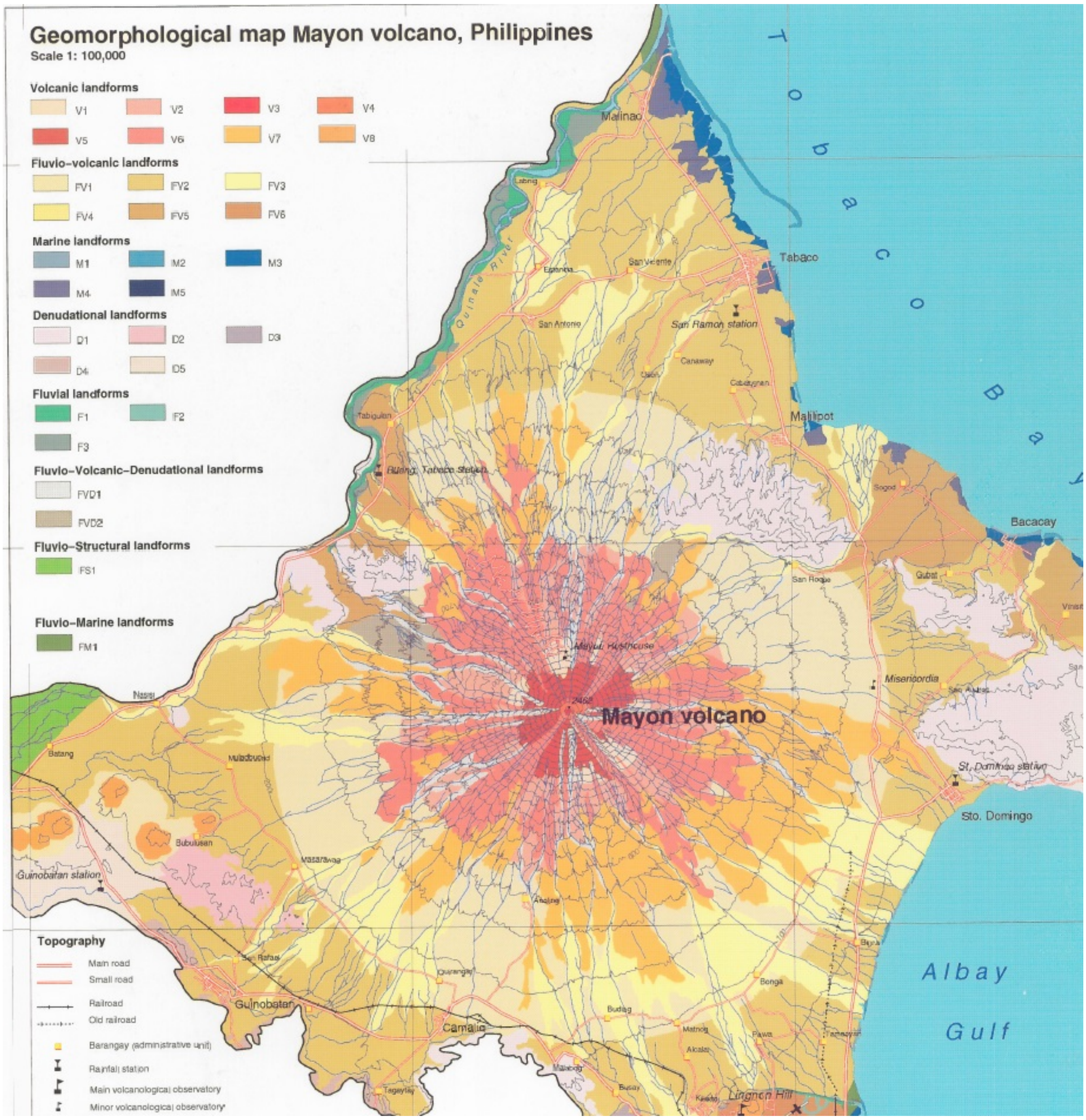

Fig 3. Geomorphological map of Mayon volcano

3.1 Volcanic Landforms

Mayon Volcano possesses a characteristic concave profile which reflects the interplay between erosion and eruption (Fig.3.). Becker (in Faustino, 1929) described its profile as a hyperbolic sine curve, a profile which he ascribed to ash tending to accumulate to its angle of repose but, balanced by the need to distribute the load of the cone over a broader area. So anything in excess of the angle of repose rolls down the slopes to rest at lower elevations or at lower slopes.

This present author divided the profile of the volcano into four main slope segment classes based on visual interpretation of slope steepness from air photos and contour map. These are: the very steep upper volcanic slope (V1), the steep middle volcanic slope (V2), the moderately steep upper volcanic footslope (FV1) and the gentle lower volcanic footslope (FV2). By overlaying this slope segment/class map with the digital elevation model (DTM) map and the slope segment/class map with the slope gradient map, the statistics of the four slope classes have been obtained (Table 2).

SLOPE SEGMENT	*SLOPE STEEPNESS*	*AVE. SLOPE GRADIENT (%)*	*PREDOM. GRADIENT (%)*	*MINIMUM ELEVATION (m)*	*MAXIMUM ELEVATION (m)*	*MAJORITY ELEVATION RANGE (m.)*
Upper Volcanic Slope	*Very Steep*	*75*	*67*	*946*	*2440*	*1179-2145*
Middle Volcanic Slope	*Steep*	*43*	*33*	*416*	*1515*	*514-1200*
Upper Volc. Footslope	*Mod. Steep*	*13*	*7*	*28*	*668*	*105- 484*
Lower Volc. Footslope	*Gentle*	*3*	*1*	*0*	*238*	*20- 160*

Table 2. Slope and elevation statistics of the four slope segment classes of Mayon. The majority elevation range consist of 95% of the DTM values for every slope class.

The polygenetic character of Mayon Volcano gave rise to different volcanic landform units formed by its episodic eruptions. Eight volcanic units (Fig. 3) have been delineated, these are: the Upper Volcanic Slope (V1), Middle Volcanic Slope (V2), Crater (V3), Young Lava Flow-Agglutinate-Tephra Complex (V4), Old Lava Flow-Agglutinate-Tephra Complex (V5), Lava Flows (V6), Pyroclastic Flow Fans (V7) and Cinder Cones (V8).

3.1.1 Upper Volcanic Slope (V1)

The very steep and straight upper slope (V1) of the volcanic cone consists of lava flows, loose deposits from ballistic projectiles, tephra fall from eruption clouds and agglutinates. The lava flows serve as armour and provide the upper slope the mechanical strength so that very steep slopes, as much as 100%, are sustained. Commencing from the crater rim, this unit radiates downslope until an average elevation of about 1179 m., where a nickpoint marks the lower limit of this geomorphological unit. Except for the rare grassy vegetation on its lower reaches on the northern side, this unit is generally bare.

The upper volcanic slope is moderately dissected by some of the major ravines and gullies that reach nearly up till the summit and more by the smaller gullies which radiate around the upper cone.

3.1.2 Middle Volcanic Slope (V2)

Majority of the steep middle volcanic slope (V2) lies between 514 m. and 1290 m. above sea level. This slope segment is straight-concave in form and is relatively less steep than the upper volcanic slope. Average slope steepness is 43%. It is characterized by intercalated deposits of lava flows and pyroclastic flows. Airfall deposits are found as thinner intercalations, whenever they are preserved from erosional processes.

The middle slope is moderately to highly dissected with rills, gullies and ravines. Rills often develop on the newly deposited pyroclastic flow and airfall materials. The gutters formed along lava flows, as well as the topographic depressions formed alongside them, usually develop into gullies which grow bigger in time as long as they are not covered with new volcanic deposits.

Vegetal cover on the northern and northwestern sides of the middle volcanic slope consists predominantly of moderately dense natural forests. The other sectors of the middle slope, which have been affected by 20th century eruptions, are covered with less dense younger forests or shrubs or grasses or they could also be bare.

3.1.3 Crater (V3)

The crater (V3) of Mt. Mayon is typical of simple cones (Francis, 1993), tiny for the size of the whole edifice. Its diameter before the 1993 eruption was not more than 200 m.. With the eruption in February, 1993, it has grown a bit in diameter to 250 m.. The latest eruption also left the southeastern crater rim directly open to the Bonga Ravine. This chute is a critical factor for deposition of subsequent lava flows and small to moderate pyroclastic flows.

Faustino (1929) described the crater floor to consist of sub-angular boulders, scoria, granulated fragments of lapilli and ash and volcanic sublimates. The volcanic sublimates of native sulfur and aluminum sulfate occur as encrustations in some of the rock materials. The crater walls are irregularly stratified, consisting of deposits of lava flows and pyroclastics.

3.1.4 Young Lava Flow-Agglutinates-Tephra Fall Complex (V4)

Confined around the immediate vicinity of the crater, this consists of most recent thin lava flows and loose and agglutinated airfall deposits and ballistic projectiles. As this unit falls within the upper volcanic slopes, it also possesses very steep slopes. As expected, this unit is bare of vegetation.

3.1.5 **Old Lava Flow-Agglutinates-Tephra Fall Complex (V5)**

Also within the limits of the upper volcanic slope, this unit likewise consists of similar, but older, thin, short lava flows and loose and agglutinated airfall deposits and ballistic projectiles. The surface is likewise clear of any vegetation.

3.1.6 Lava Flows (V6)

The lava flows (V6) are predominantly of the clinkery aa type which consist of a jumble of loose and irregularly shaped cindery blocks. Beneath the upper rubbly part is a lower massive layer consisting of solid lava which has cooled more slowly, insulated from the atmosphere by the upper layer. Gradations to block lavas as well as powdery components are also present.

Generally fed from the crater, the main lava flow usually follows notches made by ravines and gullies prior to eruption. Or, the main flow could be channelled along ravines and gullies which are "linked" to the crater upon collapse of the crater rim during explosive eruptions. Shorter lava flows could be directed anywhere around the volcano as in the 1978 lava flow deposits, although, the main flow during this eruption went down a pre-existing ravine in the southwest. In contrast to the 1978 lava flow deposits, the 1993 lava flows were all funnelled down the 350 m. wide and 250 m. deep Bonga Ravine, down to an elevation of 246 m. (Fig.4.3). The funnelling down of all lava flows into a single gully during an eruption depends on the enormity of the ravine, its capacity to accommodate all out-going flows and the way by which lava is extruded from the crater. Lava fountains can direct shorter flows in all directions. But, quiet lava effusions will follow gullies that directly open to the crater.

The presence of old lava flows (Fig.3) with abrupt upper termini could apparently give suggestions that these particular flows did not originate from the crater. Newhall (1977) suggests that these flows issued as viscous lavas from fissures as low as 1300 m. elevation. However, field check of some examples mentioned by Newhall yielded no uncharacteristically different or more viscous materials. Instead, this anomaly could have been the result of an abrupt change in gradient of the longitudinal profile of the accommodating ravine at the time of deposition. Then, due to subsequent aggradational processes, the upper stretches of the ravine could have been covered by later deposits burying with it the upper parts but, leaving the middle part of the flow conspicuously exposed. A clear example of this is the 1993 lava flow which flowed down the Bonga Ravine at a very steep gradient from the crater until elevation 1100 m.. However, with the sudden change in the gradient of the ravine at this elevation, the flow likewise abruptly changed to a lesser gradient (Fig. 3). Another possible explanation is that, since the upper volcanic slope is very steep and since lava flows have higher temperature and are relatively less viscous along this slope due to their proximity to the source, the lava will tend to leave thinner deposits which could be easily buried by later pyroclastic deposits. On the other hand, the continuations downslope which solidify along less steep gradients, would leave thicker and more morphologically distinct deposits.

Morphologically, most lava flows are steep-sided linear flows which either remain linear-lobate at the toe or bifurcated or "fan-type"or irregularly shaped. Linear lava flow fronts are shown by the 1993, 1984, 1947 and many other flows. The typical bifurcated toe is characteristic of the 1928 lava flow (Fig.4.5). Fan type flow fronts have been mapped in older flows in Buang, Buhian and Masarawag. Bifurcated and fan-type flows usually start to spread out at elevations 600 m. to 400 m.. These altitudinal locations correspond to the break in slope between the middle volcanic slope (V2) and the upper volcanic footslope(FV1). Widths of lava flows along their middle reaches vary from 75 m. to 450 m. while, widths at the flow fronts range from 125 m. to 2 km. The anomalously wide flow (2 km. wide) is located in Masarawag, Guinobatan.

Lateral ridges or "levees" are common in most lava flows (Fig.3). The gutters formed between lateral ridges could reach as much as 20 m. deep. The ridges are usually observed from the upper reaches of the flows but disappear close to their flow fronts. Flow fronts are instead characterized by minor morphological features like flow ridges and toe ridges. These features are distinct with the lava flows of 1978, 1947,1938 and 1886.

Mayon lavas consist of one or more flow units. Average maximum distances from crater and maximum altitudes reached by the mapped lava units are 4.524 km. and 448 m, respectively. A very old undated lava flow on the northern part of the volcano reached the farthest distance of 7.145 km. from the summit. Another lava flow situated in the southeast, reached the lowest altitude of 241 m. above sea level.

Newhall (1977) mentioned about impassable cliffs along lava channels. He attributed their presence to erosion by debris flows and fluvial erosion. While, Moore and Melson attributed their origin to erosion by pyroclastic flows. This present author believes that in addition to these causative factors mentioned by Newhall and Moore and Melson, collapse of the lava floor, as has been observed along the Buang Ravine, is also a reason for the development of cliffs along lava channels.Very old lava flows are vegetated by natural forests. Relatively recent ones are vegetated with trees, bushes, shrubs and grasses. A study of flora in the 1947, 1938 and 1928

flows by Newhall (1977) revealed that the flora of these flows are quite similar to each other. The 1928, 1938 and 1947 flows had 26, 20 and 19 species of vascular plants, respectively, then. Recent field check of what is left exposed of the 1968 lava flows showed that this is already moderately covered by a particular type of shrub (Ulmaceae family Trema species) which was mentioned by Newhall in 1977. Similarly, the 1978 flow has already started to slightly grow
the same type of shrub in addition to ferns and lichens. The 1984 flow is still sparsely grown with ferns and lichens. The 1993 flow is still bare as it is only a little over one year old.

3.1.7 Pyroclastic Flow Fans (V7)

Most of the mapped pyroclastic flow fan (V7) units are composed of two or more overlapping flow units formed either from the same eruption episode or from different eruption episodes. Block and ash deposits from Soufriere (St. Vincent) type nuées ardentes are the most common type of pyroclastic flow deposits (Newhall, 1977; Francis, 1993). These have developed from the collapse of eruption columns (see Chapter 5.2.2). Francis (1993), explained that "the formation of pyroclastic flows from an eruption column is a matter of density: an eruption column can only rise convectively if it is less dense than the surrounding atmosphere. If it is more dense, once the momentum imparted by the gas thrust runs out, it can only collapse downwards under gravity....As they fall, the potential energy they gained in the eruption column is transformed into kinetic energy, driving them at high velocity to the ground."

The nuée ardentes of Mayon usually follow pre-existing ravines and gullies and start to spread out from elevation 600 m. forming aprons around the base of the middle volcanic slope. The farthest distance reached by a mapped pyroclastic flow reached as far as 8.562 km. in Fidel Surtida, Sto. Domingo. But, Ruelo (1988) and Villarta et.al. (1985) cited that pyroclastic flows of the 1897 eruption reached as far as the coast of Sto. Domingo. However, morphologically, no traces of this deposit could be delineated in the aerial photographs.

Block and ash deposits consist of loose masses of ash and blocks of all sizes. The clasts consist of poorly vesiculated andesitic blocks or breadcrust bombs in an ash matrix. They have well defined flow fronts and margins. Flow fronts are sometimes lobate. But, more often, they are irregularly shaped. Linear trains of boulders are also exhibited by most of the younger pyroclastic flow fans like the 1947 and 1938 deposits (Fig.4.7). Transverse ridges of boulders were developed in a pyroclastic flow which is tentatively dated as 1928 near Maninila-Tumpa area. However, at present, this is already partly covered by the 1968 pyroclastic flow.

Along cross sections, block and ash deposits are usually unbeddded to thickly bedded, with thicknesses of individual layers ranging from 0.2 m. to 25 m.. Reverse graded deposits have been observed, but, normally these are ungraded.

Other pyroclastic flow fans could probably consist of block and ash deposits formed from the Merapi type nuées ardentes (see Chapter 5.2.2). Although this type of pyroclastic flow has
been described in the 1892 eruption (Newhall,1977)), deposits resulting from this process are hardly differentiable from deposits of the Soufriere type nuées ardentes.

Base surge and ground surge types of pyroclastic flows have also been cited in previous reports (Newhall, 1977). Base surge is a high velocity turbulent pyroclastic flow (Francis, 1993). Since it is a low density, dilute phenomenon, it is not constrained by topography. It has less momentum and thus, travels over smaller distances. The base surge deposit of February 2, 1993 partly covered the 1984 block and ash deposits. This deposit is thin, 30 cm. on its proximal part and 10 cm. near the distal parts of the deposit. It consists of fine-grained, planar bedded deposits. The fragments are poorly sorted lithic materials set in a yellowish-buff finer matrix.

Most pyroclastic flow deposits take a long time to re-grow a diverse set of plant species. In most cases, the pyroclastic flow deposits from the 20th century eruptions are only vegetated with cogon grasses. It even takes longer for the pyroclastic flow to sustain a wider range of plant species than the lava flows. In the case of the 1947 pyroclastic flow for example, it is only presently grown with cogon grasses and very minor other plant species, whereas, the lava flows from the same eruption are already moderately densely vegetated with at least twenty-six plant species (Newhall, 1977).

3.1.8 Cinder Cones (V8)

Seven cinder cones (V8) averaging 230 m. in peak height have been mapped on the southern and on the west-southwestern lower footslopes of Mayon. These consist of olivine-augite basalt. The pyroclasts rest at a moderately steep angle of repose of 34% around an average basal diameter of 710 m.. Gently sloping to moderately steep upper volcanic footslopes surround these cinder cones. Ramos, et.al. (1988) placed the age of these cinder cones to approximately 5,000 to 10,000 years old based on their erosional and weathering conditions.

3.2 Fluvio-Volcanic Landforms

Six units have been grouped under landforms of fluvio-volcanic origin. These are the upper volcanic footslope (FV1), lower volcanic footslope (FV2), active lahar channels and fans (FV3), inactive lahar channels (FV4), inactive/old lahar fans (FV5) and the pyroclastic plain (FV6).

3.2.1 Upper Volcanic Footslope (FV1)

The concave upper volcanic footslope (FV1) is primarily an accumulational slope segment which starts from around elevation 484 m. and reaches down to elevation 105 m.. It has sloping to moderately steep slopes averaging 13%. The dominant volcanic products found in this unit are pyroclastic flows, lahars and ashfall deposits. Some lava flows were also able to reach till the middle reaches of the upper volcanic footslope. Degree of dissection is slight to moderate for this slope segment. The gullies start to diminish in depth in this slope segment and turn into open, unentrenched drainage systems.

Predominant land use is coconut plantation. Grasses and shrubs predominate over areas recently covered with pyroclastic flows and lahar deposits.

3.2.2 **Lower Volcanic Footslope (FV2)**

The nearly flat to gently sloping lower volcanic footslope (FV2) has an average slope gradient of 3%. The majority of the lower footslope falls within an elevation range of 20-160 m. This slope segment extends from the coastline in the East to the nickpoint which marks the line between the lower and the upper volcanic footslopes. In the North, the lower reaches of this unit abuts with the slopes of Mt. Masaraga (D1). In the West, the distal margins of the lower footslope terminates at the base of the low lying sedimentary hills (D4). To the South, they end up at the base of the low hills underlain by dacite-rhyodacite-andesite rocks.

It is undissected to slightly dissected. It consists predominantly of lahar deposits and accumulations from slope wash deposits. Most of the lower footslope is cultivated, primarily with rice. Coconuts, fruit trees and cash crops are the most extensive associated land use. Areas covered with recent lahar deposits are either bare or grown with grasses.

3.2.3 Active Lahar Channels and Fans (FV3)

Mayon lahars could either be eruption-related (primary) lahars or non-eruption-related (secondary) lahars (Umbal, 1986; Ruelo, 1988; Arguden & Rodolfo, 1986). Source of water for eruptive lahars could come from the condensation of steam clouds generated by an eruption. Francis (1993) stated that major-ash-producing events often propagate torrential rainstorms, since the ash particles act as nuclei, around which water collects to form raindrops and the resulting deluges may initiate lahars. But, more important in the study area are the non-eruptive lahars which occur more often, triggered by heavy rainfall brought about by the monsoons and typhoons.

The blankets of ash that accumulate on the steep slopes during eruptions are easily eroded by surface run-off as they are loose, incoherent materials. Adding to that, there is sparse vegetation left after an eruption which could retard run-off. So, surface run-off flow directly from the watershed surfaces into the main channels. In turn, run-off along these gullies and ravines causes the highly erodible banks to slump, adding the newly dumped materials to the load of the run-off. Increased stream load also increases the rate of lateral erosion along these gullies until such time that lahars are generated. The erosive character of the stream is usually dominant along the middle volcanic slopes. But, once they reach that part of the proximal upper volcanic footslopes where the height of river banks decrease to about 2-3 m. high, the torrents of silt, sand, cobbles and boulders start to spread out across the adjacent lowlands.

Although the lahar deposits of Mayon consist of overprinted deposits from different lahar events, it was still possible to distinguish two main morphological types: the channel type and the fan type lahar deposits. Most channel type deposits are narrow, channel-confined and form tongue-like deposits at their distal parts (Fig.4.8). These are formed from considerably smaller lahar events. Most of them are found within the lower footslopes.

The fan type deposits are usually channel-confined along the distal reaches of the middle volcanic slope till the proximal parts of the upper volcanic footslope. But, once they overtop the confining walls, they spread out like sheet deposits with irregular, non-lobate flow fronts. Although Umbal (1986) described Mayon lahars as viscous flows, the irregular, non-lobate flow fronts suggest more fluid slurries at their terminal parts. Most flow fronts of these broad fan like sheets terminate close to the boundary between the upper and the lower volcanic footslopes.

The deposits from Mayon lahars are polylithologic in character consisting of a wide range of grain sizes. It has sand as the dominant size fraction. More boulders and other coarse materials are observed along the central parts of the lahar channels than on their sides. Boulders as big as 5-6 m. in diameter have been observed in the field. Newhall (1977) even stated that boulders as huge as 15 m. in diameter can be transported. Deposits are usually ungraded, unsorted and unstratified. However, laminated silty top layers are commonly observed in the field.Recent lahar events often leave barren wastelands.

3.2.4 Inactive Lahar Channels (FV4)

These units are slightly entrenched former lahar channels which has long been abandoned as indicated by the moderately dense vegetation growth along the channels themselves. Most of them have "died" as a result of the closing of the channel due to lava blockage. They are usually found along the northern lower footslopes.

3.2.5 Old/Inactive Lahar Fans (FV5)

Old fans developed from very old lahar deposits, found both on the upper and lower volcanic footslopes, are more difficult to delineate due to cultural influences. Nevertheless, the overall morphological expression could still de discerned.

3.2.6 Pyroclastic Plain (FV6)

This unit is a nearly flat terrain underlain by unconsolidated pyroclastic materials from Mayon. It is found in the south-southeastern part of the study area. The area is occupied by the concentrated settlements of Legazpi City and Daraga. Associated land use is rice cultivation.

4.4 Fluvio-Volcanic-Denudational Landforms

Two geomorphological units having a combination of fluvial, volcanic and denudational origins are found on the slopes of the volcano. These are: the steeply-sided ravines and gullies (FVD1) and the highly dissected pyroclastic complexes (FVD2).

3.2.7 Steeply-Sided Ravines and Gullies (FVD1)

Major ravines and gullies play an important role in the distribution of products of future eruptions since they serve as channel ways for them. Hence, mapping them is necessary.

There are numerous steeply-sided ravines and gullies that radiate around the slopes of Mayon. But, only those with widths of 50 m. or more, and therefore, large enough to be mappable on a 1:50,000 scale have been included in the geomorphological map.

Majority of significant gullies and ravines have gully heads traceable on the upper and middle slopes. The Bonga Ravine, which is presently the widest and deepest, directly lead to the crater floor as a result of the breaching of the southeastern crater rim during the February 2, 1993 explosion.

These units usually have U-shaped cross sectional profiles along the upper and middle volcanic slopes. However, these change into box-shaped profiles as they reach the upper volcanic footslopes and finally turn into open, unentrenched streams as they reach the lower volcanic footslopes. These changes in the cross sectional profiles can be attributed to:

- the difference in types and characters of processes which affect the different slope segments - gully erosion by pyroclastic flows in the upper and middle volcanic slopes while, erosion by lahars and fluvial processes on the upper volcanic footslope.
- the different types of materials they erode upon in each of the slope segment classes- lava flows, airfall and pyroclastic flows predominate on the upper and middle volcanic slopes while, pyroclastic flows and lahar deposits predominate on the upper volcanic footslope.

3.2.8 **Highly Dissected Pyroclastic Complexes (FVD2)**

Thick deposits of pyroclastics, which are densely dissected, are found on the northern middle volcanic slopes and upper volcanic footslopes. These consist of airfall and pyroclastic deposits, but mostly, the latter. The overall fan-shaped morphology, characteristic of recent pyroclastic flow fans, is still distinguishable. Their presence on the northern slopes indicates again that this slope sector has not been affected by 20th century eruptions except close to the summit.

3.3 Fluvio-Structural Landform

One unit has been mapped under this genetic group, the **fluvio-structural basin (FS1)**. This unit is but a small part of the southern terminus of the Albay Basin, a corridor formed along the Legazpi Lineament in its interaction with both the Philippine Fault and the Philippine Trench. The whole basin unit extends beyond the limit of the study area, stretching over a distance of 30 km. long with an average width of 7.5 km..

The exact boundary between the lower volcanic footslopes (FV2) and the fluvio-structural basin (FS1) is quite arbitrary. What is certain though is that, this basin is partly fed with sediments by rivers emanating from the southwestern, western and northwestern slopes of the volcano. Thickness of sediments is not ascertained.

3.4 Fluvial Landforms

Three units of fluvial origin have been mapped within the area: **the river bed and floodplain (F1)**, **abandoned channels (F2)** and **the river terraces (F3)**. The river bed and floodplain (F1) unit of the Quinale River, north of Mayon, includes the river bed, pointbars and the channel bars within it. Its river bed is bigger than that of Yawa River. The river itself is 100 m. wide on the average. It is fed by tributaries coming from Mts. Mayon and Masaraga and thus has a bigger catchment area than the Yawa River. It then unloads in Tabaco Bay.

On the other hand, the Yawa River is smaller and only catches load from the southern drainages of the volcano. It migrates now and then as observed from the differences in its courses in the 1951 and 1982 aerial photographs. In the former, its course was meandering near Gogon, Legazpi City. However, in the latter, it has already abandoned the two meanders (F2) and followed a straighter course. It has also partly shifted its course near its mouth in Bonot, Legazpi City.

The river terraces (F3) unit is composed of the lower and upper terraces which are mostly found along the Quinale river. But, considering the scale and the purpose of mapping these were not differentiated from each other.

3.5 Fluvio-Marine Landforms

The small **active deltas (FM1)** at the mouths of Quinale and Yawa Rivers in Malinao and Legazpi City, respectively, constitute the landforms of fluvio-marine origin in the area. They are discrete protuberances of stunted outline consisting of unconsolidated materials of generally sandy texture. According to Gulliver's classification of deltas (in van Zuidam, 1986) based on actual coastal outline, the stunted outline has more marine than fluvial influence.

3.6 Marine Landforms

Landforms of marine origin include the **beach (M1)**, **spit (M2)**, **young tidal flats/swamps (M3)**, **old tidal flats/swamps (M4)** and the **islets (M5)**.

The beaches (M1) found along the Albay Gulf coast are nearly flat and very gently slope towards the sea. They posses a smooth surface consisting of sandy materials from Mayon. Widths vary from 10 to 15 m. from the mean low tide line to the point where there is permanent vegetation. From the texture of the beach deposits, it is inferred that active marine aggradational processes maybe more predominant over degradational processes.

Several spits (M2) have been developed along the coast of the study area. These are indicative of a prograding coast. The most significant of these spits is the one which is tied to the coast of Malinao and stretches, with a width of 130 m. over a length of 5.7 km., towards the coast of Tabaco. The Malinao spit terminates in a hook and trails landward in the direction of Tabaco. Evans (in van Zuidam, 1986) attributed this type of phenomenon to wave refraction around the terminal end. King and McCullogh (in van Zuidam, 1986) explained such occurrences as the result of the interplay of wave trains arriving from different directions. With the development of spits, small narrow inlets have also been developed behind them.

Tidal flats/swamps consist of the young tidal flats (M3) and the old tidal flats (M4). The former is vegetated with mangrove and nipa. Some portions are also utilized for fish and prawn culture ponds. The latter unit has mostly been converted to settlement areas. Where it is still uninhabited, marsh and nipa vegetation grow.

Small islets (M5) are found off the coast of Malinao and Tabaco.

3.7 Denudational Landforms

Five denudational landform types surround the study area. These are all low hills and slopes developed in different lithologic assemblages.

The **low hills and slopes underlain by andesites (D1)** lie on the eastern, northeastern, northwestern and southern margins of the volcano. The andesites are of Pre-Mayon origin. Subordinate olivine basalts and dacite are found in association with the andesites. This unit is characterized by moderately steep slopes having predominantly straight slope forms. Degree of dissection of the slopes is moderate. Highest elevation is 480 m. above sea level found in Bulakawan Hills, Malilipot.

Hills and slopes underlain by metamorphic rocks (D2) occur in the southwestern part of the volcano in Bubulusan, Guinobatan. Highest peak of this unit is only 235 m. above sea level. Underlying lithology consists of metamorphosed siliceous volcanic rocks probably of trachytic or latite parent material (Newhall, 1977). This unit possesses short, moderately steep slopes which have straight forms.

The southern margins of the volcano abuts with **low hills and slopes underlain by dacite-rhyodacite-andesite rock assemblage (D3)**. These hills are characterized by convex slopes which are undissected to slightly dissected. Their short slopes are sloping to gently sloping. Highest relief is only 100 m.

Low hills and slopes underlain by limestone and clastic rocks (D4) occur on the southwestern margins of the study area. This is a part of the extensive sedimentary basin found on the western side of Albay province.

Gently undulating hills and slopes underlain by undifferentiated sedimentary rocks (D5) are also found in the southwestern section of the study area. These are nearly undissected slopes having absolute relief of no more than 100 m.

4. Volcanic hazards

Hazards brought about by the eruptive processes of Mayon include flowage and non-flowage hazards. Flowage hazards include those processes which hug close to the ground like lava flows, pyroclastic flows and lahars. Airfall, on the other hand, is a non-flowage hazard. Within a single eruption, one, two, three or all of these hazards could occur. But, more often, these four hazards are present.

In general, eruptions of Mayon show a sequence of events. Airfall comes first followed by pyroclastic flows, lahars and lava flows. Lahars could continue months after the eruption though. These events are not separate, successive stages. Rather, they belong to a continuous phase which lasts during the period of a single eruption. Reasons for this overall sequence in events could be explained by the models of Yamasaki (1959) and Francis (1976) which are both mentioned in Newhall (1977).

Yamasaki suggests that "the high water content immediately prior to an eruption is responsible for the initial piercing of the plug and extreme comminution of the magma into ash. As the water pressure decrease, the average size of fragments decreases and the total energy of each outburst decreases, too. This generates pyroclastic flows. Lava issues when the water has already been considerably depleted. Minor ash fall and pyroclastic flows could still occur even as the eruption is well into the lava stage already. This is because enough water pressure remains throughout the eruptive period."

On the other hand, Francis gave degassing stages as the reason for the overall sequence in events. "Airfall results from the early degassing deep in the volcanic conduit which ejects materials straight up into the atmosphere. Following near-surface degassing results in a less directed cloud which either collapses or flows over the crater rim as pyroclastic flows. Late stage degassing results in quiet effusion of lavas."

Most volcanic processes are hazardous to man. To understand these hazards entail a good knowledge of the volcanic products which are mute witnesses to the processes that were responsible for their emplacement.

As this study is primarily based on geomorphological mapping, the identification of volcanic products was limited to those which have been deposited by flowage processes. Airfall products were not included since they do not leave morphologically distinct deposits.

4.1 Lava Flows

Lava flows are streams of molten rocks that are laterally and surficially poured out from a vent or a fissure. Theoretically, three types of lava flows are known: the pahoehoe, aa and the block lava flows. Pahoehoe flows are characterized by ropy, smooth and billowing crusts. They are generally associated with fluid basaltic lavas. Aa lavas are generally thicker than pahoehoe. They are characterized by a surface of rough, clinkery and spinose fragments. The interior of aa lavas are usually massive (Fig.5.1). Block lavas are similar to aa lavas, only that the surface is composed of large polyhedral blocks. They are well developed in intermediate to siliceous lavas.

Mayon lavas are predominantly aa lavas. Blocky gradational components are also present.

4.1.1 Rheological Considerations:

A Newtonian fluid such as water has low viscosity and needs 0 stress to make it flow. A non-Newtonian fluid on the contrary, is characterized by certain degree of viscosity. Lava flow is regarded as a non-Newtonian fluid or as a Bingham plastic (Young & Wadge, 1990; Francis, 1993). At low stresses, it appears to be solid and does not flow at all. However, when sufficient stress is applied to overcome its yield strength, it starts to flow and at higher stresses, it behaves like Newtonian fluids. One of the principal sources of stresses for lava to flow is gravity on a slope having sufficient amount of steepness.

Although Mayon lavas do not have measurements for viscosity and yield strength, it is deduced that they have moderately high viscosity and yield strength based on their petro-chemical composition and temperature. Since andesitic lavas are known to have higher viscosities than basaltic lavas, Mayon lavas must then have considerable viscosities owing to their mineral chemistry.

Temperature also influences viscosity. A temperature measurement of the 1984 lava flow using optical pyrometer was recorded at 850 °C. This was measured from a partially molten core of a disintegrated rock found at the terminus of this flow. No other published direct field measurements of temperatures were obtained. Nonetheless, a microprobe study of this same lava flow by Magalit and Ruelo (1985) yielded estimates of temperature range from 1215 °C to 1500 °C based on plagioclase geothermometers. Considering that the lava flow of 1984 is a two-pyroxene andesite, this temperature range for plagioclase crystallization is well above the temperatures taken from basalts and basaltic andesites of Mts. Etna and Sakura-jima which have temperatures of 1050 °C to 1130 °C and 880 °C to 1050 °C, respectively (Blong, 1984). The presence of well defined lateral ridges or levees and the relatively thick deposits (25 m. thick on the average) also attest for high viscosities and yield strength.

Velocities of lava flows are determined by temperature, yield strength, viscosity and slope gradient. Considering only temperature, yield strength and viscosity, flow velocities of Mayon lavas ought to be low. However, this is compensated by the very steep and steep gradients on the upper and middle volcanic slopes. Hence, flow velocities are much higher on the upper volcanic slopes, decrease considerably in the middle volcanic slope and then move at very slow rates once lavas reach the upper volcanic footslope. Faustino (1929) noted that it only took the 1928 lava flow approximately 9 hours to reach elevation 1000 m. (over a distance of 2400 m.) and a total of 36 days to reach elevation 500 m. (over and additional distance of 1750 m.). The 1968 lava flow took 24 days to travel a distance of 4500 m.. The 1993 lava flow started rolling down the Bonga Ravine on March 18 and reached 3100 m. after 4 days. It reached its final resting place (5474 m. from crater) after approximately 50 days. From this limited number of velocity observations, a rough average of velocities on the upper volcanic slope and the middle volcanic slope to the upper volcanic footslope is obtained:

149 m/hr on the upper volcanic slopes

2 m/hr on the middle volcanic slopes downwards.

An overall average is computed from the velocities on both slopes parts to be 5.7 m/hr. A general average of 7.9 m/hr was also calculated from the averages found in Table 5.1. These were computed from the distances lava flow fronts reached over the duration of the eruption. One snag in this estimation is that the durations used cover the whole duration of the eruption and not the lava stage alone. But, with the available data, this is the closest that could be obtained. Comparing the results with the documented/reported flow velocities of the 1928, 1968, 1984 and 1993 lava flows, the results are closely similar.

4.1.2 Petrology and Mineral Chemistry of Lava Flows

Mayon lavas are predominantly two-pyroxene andesites. Subordinate olivine-augite basalts and hornblende andesites also occur (Table 5.3). They contain silica from 51-59 %, calcic plagioclase and common modal olivine (Newhall, 1979). Basaltic flows contain more modal olivine than andesitic flows. Lavas are commonly highly porphyritic with 48-55% phenocrysts (Magalit & Ruelo, 1985). Phenocrysts consist of plagioclase, augite, hypersthene, olivine and titaniferous magnetite. These phenocrysts are set in a groundmass of the same minerals and glass. Petrographically, the texture is generally hyalopilitic, but some are hyaloophitic and pilotaxitic.

Newhall (1977 & 1979) was able to model the medium term cyclic variation in Mayon lavas through modal and whole rock chemical analyses of lava flows of 1978 and older. He identified two of these most recent cycles:

• Cycle 1 - 1800 to 1876

• Cycle 2 - 1881 to present

Each cycle consists of six to ten andesitic flows and one to three basaltic flows. Three marked points were distinguished in each of these cycles (Table 4).

LAVA FLOW	DISTANCE REACHED (m.)	DURATION (days)	ESTIMATED VELOCITY (m/hr)
1984	4154	27	6.4
1978	4137	63	2.7
1947	3757	52	3.0
1900	3417	6	23.7
1897	3588	50	3.0
1895	2174	130	0.7
1893	3217	28	5.6
1892	4385	27	7.6
1891	4034	62	2.7
1890	4451	21	8.8
1886	4780	246	0.8

Table 3. Estimated lava flow velocities from the distances reached by these flows over the duration of eruption.

POINT IN CYCLE	CHARACTER OF ERUPTIONS	PETRO-CHEMICAL INDICATIONS
1. Beginning of basaltic lavas	Frequent effusive eruptions with or without an early Plinian eruption	Decrease in alkalies and increase in olivine
2. Beginning of andesitic lavas	Frequent weak to moderately explosive Strombolian eruptions	Begins after 1 to 3 basaltic eruptions
3. Levelling of SiO_2, K_2O & K_2O/Na_2O values	Less frequent explosive Vulcanian eruptions	Whole rock SiO_2, K_2O & K_2O/Na_2O values begin to level off

Table 4. Three points in a medium term cycle characterized by changes in the petro-chemical properties of lava flows.

Newhall's model has a significance in predicting the type and character of upcoming eruptions. Early recognition of the position in the point/cycle, through regular updates on the study of lava flows, could give extra preparation for a possible highly explosive eruption at the onset of a basaltic point.

Using this model, he was able to conclude that the preceding two to three eruptions after 1978 will still be andesitic. True to this conclusion, the lava flows of 1984 and 1993 (Annex 1) indeed remained as two-pyroxene andesites. If his model work well, the next eruption or the one after next, will mark the start of a basaltic point heralding the onset of a new cycle.

4.1.3 Morphochronology of Mayon Lavas:

Morphostratigraphy, rather than lithostratigraphy, is more useful in delineating the sequence of events as volcanic products do not differ substantially around the volcano (Verstappen, 1988). Thus, this geomorphological criteria, which relies heavily on the law of superposition, has been chiefly used to establish the sequence of lava flows in Mayon Volcano. Historical accounts, Newhall's datings, the degree of dissection of lava flows and vegetation cover density also aided this process.

A total of eighty-five lava flows (Fig.4) have been delineated. Of these 7 have been positively dated, 10 have been dated tentatively by Newhall and 20 others are dated tentatively in this study (Table 8). Lava flows which are neither positively nor tentatively dated are grouped according to three classes. The first group, coded as V60001, consists of several old lava flows which have probably been deposited within the recorded eruption history (1616-present) because their degree of dissection is comparable to those which have been dated. V60002 lava flow units are those which are probably older than the 1616 eruption

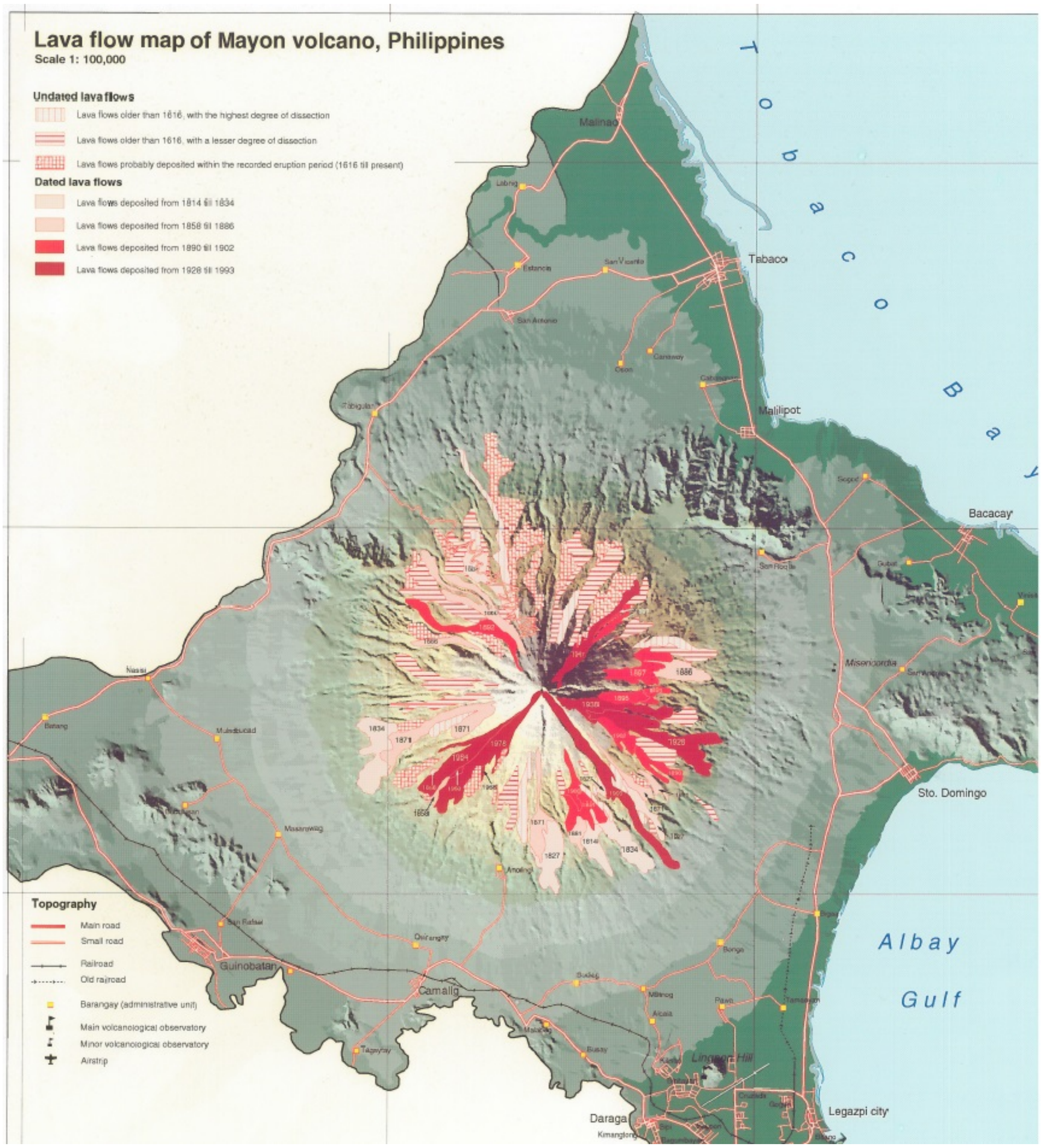

Fig.4. Map of the distribution of lava flows in Mayon Volcano.

and V60003 are still much older as manifested by the several younger deposits which are found on top of them and by their high degree of dissection.

4.2 Pyroclastic Flows

Pyroclastic flow terminology can be very frustrating since there has been so much confusion in the usage of this word (Francis, 1993; Bong, 1984). Others refer to it as nuée ardente, while some others as glowing clouds and so on. In general, pyroclastic flows are defined as density currents comprising of heated mixtures of volcanic gases and ash travelling down the flanks of a volcano or along the surface of the ground. Pyroclastic flows range between two end member types (Francis, 1993):

- those that involve vesiculated dense low density pumice, and,
- those that involve unvesiculated, dense lava clasts.

Within each of these principal types, further genetic subdivisions have been made by Francis. These are:

- SURGES - are flows that involve turbulent lateral movements of expanded low concentration gas-solid dispersions. They have lower density than either pumice or block and ash flows. Deposits are usually fine-grained, crystal-rich, and which may sometimes be finely laminated. Occassionally, they show cross bedded structures.
  - BASE SURGE - is a ring-shaped cloud of gas and suspended solid debris that moves radially outward at high velocity as a density flow from the base of a vertical explosion column. Deposits consist of highly fragmental and non-juvenile lithic materials.
  - GROUND SURGE - deposits are usually found immediately underlying basic ignimbrite and pumice flow deposits. Generally exhibit thin and finely laminated coarse sand size fragments which are better sorted than the other pyroclastic flow deposits.
  - ASH CLOUD SURGE - deposits are very similar to ground surge deposits only that, their occurrence is not limited at the base of ignimbrites.
- PUMICE FLOWS - are associated with the collapse of convecting eruption columns. They involve vesiculated low density pumice. Deposits are poorly sorted mixtures of vesiculated clasts and dusty ash with a variable amount of lithics and crystals.
  - PUMICE FLOWS - leave deposits of ignimbrites and pumice and ash deposits.
  - SCORIA FLOWS - leave scoria and ash deposits.
  - SEMI-VESICULAR ANDESITE FLOWS - leave semi-vesicular andesite and ash deposits.
- C. BLOCK AND ASH DEPOSITS - also called as nuées ardentes, glowing clouds, glowing avalanches or pyroclastic flows sensu stricto (Blong, 1984). These are flows of unvesiculated dense clasts. They involve flows over the ground surface of fragmental material or hot, gravity-controlled, concentrated gas-solid dispersions. The deposits left behind are called block and ash deposits which consist of poorly vesiculated to unvesiculated juvenile magma in an ash matrix.
- PELEEAN TYPE - nuées ardentes associated with lava dome collapse.
- SOUFRIERE TYPE - produced by the collapse from an eruption column. This occurs when the convective thrust phase of a rising tephra column fails to take over from the initial gas thrust phase (Blong, 1984).
- MERAPI TYPE - nuées ardentes which are essentially hot avalanches formed by gravitational collapse from

lava domes and lava flows.

Table 5. Legend of Lava Flow Map. In some cases (ie. 1968 lava flow), area and volume estimates differ from previous reports because estimates were based on present surface exposures.

CODE	LAVA FLOW AGE	LITHOLOGY	TOE MORPHOLOGY	MAXIMUM REACHED (m)		AREA COVERED (km^2)	ESTIMATED VOLUME (km^3)	REMARKS
				DIST. FR. CRATER	ALTITUDE			
V61993	1993	Augite-Hypersthene Andesite	Linear	5931	246	1.49	0.037	Positive dating
V61984	1984	Hypersthene-Augite Andesite	Linear	4154	480	1.03	0.026	Positive dating
V61978	1978	Augite Hypersthene Andesite	Bifurcated	4137	458	1.46	0.036	Positive dating
V61968	1968	Augite-Hypersthene Andesite	Linear	3183	630	0.07	0.002	Positive dating
V61947	1947	Augite-Hypersthene Andesite	Linear	3757	573	0.78	0.020	Positive dating
V61938	1938	Augite-Hypersthene Andesite	Linear	3503	580	0.89	0.022	Positive dating
V61928	1928	Augite-Hypersthene Andesite	Bifurcated	5114	328	1.72	0.043	Positive dating
V61902	1902	-	Irregular	2920	740	0.41	0.010	Tentative date (this paper)
V61900	1900	Augite-Hypersthene Andesite	Irregular	3417	620	0.30	0.008	Tentative date (this paper)
V61897	1897	Augite-Hypersthene Andesite	Fan-type	3588	628	1.17	0.029	Tentative date (this paper)
V61895	1895	-	Linear	2714	772	0.37	0.009	Tentative date (this paper)
V61893	1893	Olivine-Augite-Hypersthene Andesite	Bifurcated	3217	600	0.20	0.005	Tentative date (this paper)
V61892	1892	-	-	4385	500	0.86	0.021	Tentative date (this paper)
V61891	1891	-	Fan-type	4034	505	0.62	0.016	Tentative date (this paper)
V61890	1890	-	Bifurcated	4451	423	0.42	0.011	Tentative date (this paper)
V61886	1886	Olivine-Augite-Hypersthene Andesite	Linear	4780	437	2.17	0.054	Tentative date
V61881	1881	-	Fan-type	4468	411	0.44	0.011	(Newhall,1977)
V61871	1871	Augite-Hypersthene Andesite	Fan-type	4805	420	2.43	0.061	

V61858	1858	-	Bifurcated	4000	480	0.15	0.004	Tentative date
V61834	1834	Augite-Hypersthene Andesite	Fan-type	5725	291	2.89	0.072	(Newhall,1977)
V61827	1827	Olivine-Augite-Hypersthene	Linear	5360	312	1.42	0.035	Tentative date (this paper)
		Andesite						Tentative date (this paper)
V61814	1814	-	Fan-type	5474	320	0.52	0.013	Tentative date (this paper)
V60001	un					2.97	0.074	Tentative date
V60002	un					7.70	0.192	(Newhall,1977)
V60003	un					6.04	0.151	Tentative date (this paper)

In general, Mayon pyroclastic flows are developed from the collapse of an eruption column. Newhall (1977) called this as the St. Vincent type nuée ardente. Francis (1993) terms this type as the Soufriere type nuée ardente. The pyroclastic flows leave block and ash deposits consisting of poorly vesiculated to unvesiculated large blocks and breadcrust bombs in a matrix of ash and lapilli

In other instances, Mayon pyroclastic flows were not formed from eruption column collapse. Several small pyroclastic flows during the 1993 eruption issued from the crater and simply flowed over the notch along Bonga Ravine. Cruz et.al. (1985) also observed several pyroclastic flows which spilled over the crater rim as discrete masses along well-developed paths.

4.2.1 Rheological Considerations:

Moore and Melson (in Blong, 1984) estimated the velocities of the 1968 pyroclastic flows to range from 9-63 m/sec. On the average, velocity for these pyroclastic flows is 31 m/sec, which they considered as moderate. Corpuz (1988) reported that velocities of the 1984 pyroclastic flows were in excess of 50 m/sec. The small pyroclastic flows of 1993 had velocities ranging from 10-20 m/sec. These velocities are maintained until they reach approximately 600 m. elevation where they start to diverge and deposit as fans.

High velocity pyroclastic flows have the momentum to climb topographic barriers and cause substantial erosion. Cruz et.al. (1985) estimated that 13 x 106 m3 of old volcanic debris had been eroded from the Bonga Ravine by the voluminous pyroclastic flows of 1984.

Obtaining temperatures of actual pyroclastic flows in progress is impossible. So, Moore and Melson (in Blong, 1984) measured the temperature of a pyroclastic flow five days after emplacement instead. Their measurement rendered a reading of 98 °C. They were also able to measure higher temperatures (approx. 240 °C) from a large block on the surface of this pyroclastic flow.

4.2.2 Characteristics of Deposits and Flow Dimensions:

Block and ash deposits of Mayon are very poorly sorted, non-welded, poorly stratified to unstratified deposits ranging in thickness from 0.2 to 25 m. Like lahars, a wide range of grain sizes is present but the abundance of breadcrust bombs aid in distinguishing it from lahar deposits. Random visual estimates give average grain size distribution of 10 % blocks/bombs, 20 % pebble to cobble-size fragments and 70 % sand and ash which constitute as matrix. Laboratory grain size analysis which only represent the grain size distribution of the matrix yielded grain size distributions given in Fig.5.7. In comparing the grain size distributions of the matrices of lahars and pyroclastic flows, it has been observed that the pyroclastic flow matrix is relatively more sorted than that of the lahar.

Lateral dimensions of pyroclastic flows are varied. Area coverage of individual flows range from 0.64 to 4.02 km2 .

Morphostratigraphic studies of pyroclastic flows is much more complicated than for lava flows since they tend to deposit on top of previous deposits. As a result only a few number of deposits have been dated. Undated pyroclastic flows have been coded according to increasing age as V70001, V70002 or V70003.

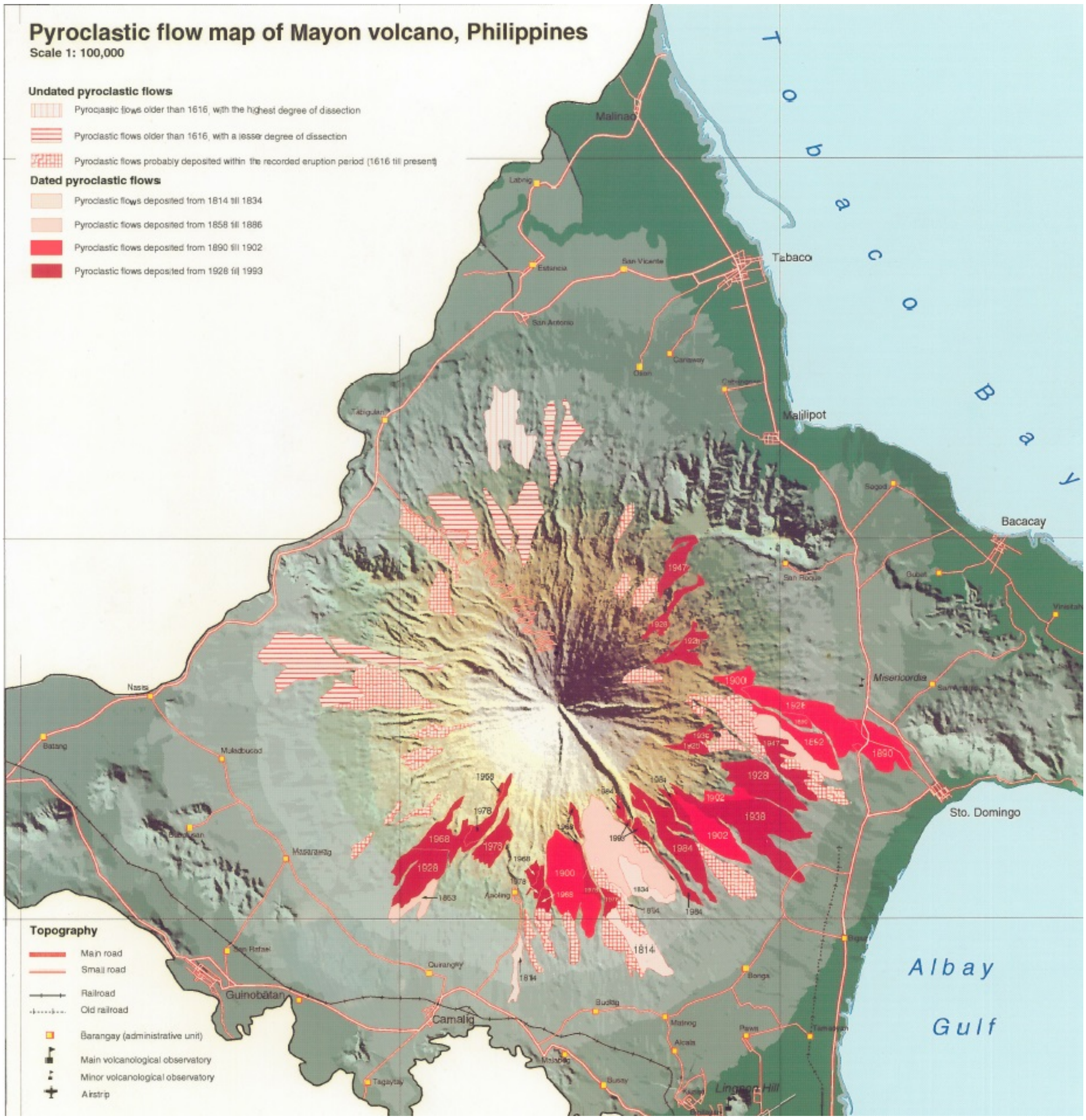

Fig.5. Map of the distribution of pyroclastic flows in Mayon Volcano.

4.3 Lahars

Lahar is a debris flow associated with volcanoes. It arises through the sudden drenching of accumulations of fine-grained volcanic dust and ashes commonly found on the slopes of a volcano (Hutchinson, 1988). Macdonald (1972) referred to it as mudflow which he defined as a "slurry of fine material mixed with water to form a mud that flows down the mountainside under the force of gravity." During an international convention of volcanic sedimentologists in 1988, lahar has been defined as"...a rapidly flowing mixture of rock debris and water from a volcano. A lahar is an event. It can only refer to one or more discrete processes (such as debris flows and hyperconcentrated streamflows) but does not refer to a deposit." (Rodolfo & Arguden, 1991).

CODE	PYROCLASTIC FLOW AGE	MAXIMUM REACHED (m)		AREA COVERED (km^2)
		DIST. FR. CRATER	ALTITUDE	
V70001	undetermined	8119	81	10.48
V70002	undetermined	7962	212	7.04
V70003	undetermined	8562	118	1.76
V71814	1814	7760	149	1.37
V71834	1834	5897	256	0.64
V71853	1853	6925	230	1.52
V71871	1871	5714	286	2.81
V71886	1886	7697	103	0.99
V71890	1890	9297	45	1.38
V71892	1892	7491	120	0.82
V71897	1897	7960	119	1.84
V71900	1900	5977	264	2.52
V71902	1902	6234	190	1.40
V71928	1928	6700	143	4.02
V71938	1938	7697	97	3.03
V71947	1947	7274	133	1.44
V71968	1968	5143	343	1.48
V71978	1978	5600	312	1.59
V71984	1984	6377	204	2.21
V71993	1993	4148	428	2.03

Table 6. Legend for the map of pyroclastic flows.

Lahars are processes in continuum. The continuous spectrum of sediment concentration includes the sediment-laden river (extreme and high streamflows) through ephemeral streams (hyperconcentrated streamflows) through debris flows (lahars). For this reason, the actual lahar and the hyperconcentrated streamflow deposits were not differentiated in the mapping.

Lahars have been differentiated into primary and the secondary lahars (Alexander, 1993). Primary lahars are directly associated with eruptions. Secondary lahars are generated after an eruption by different causes. The primary lahars of Mayon are generated during eruptions by rainstorms related to convecting eruption columns (Moore & Melson in Tilling, 1989). Torrential rainfall after an eruption trigger secondary lahars in the area.

4.3.1 Rheological Considerations:

Lahar is a debris flow and a debris flow is regarded as a Non-Newtonian fluid characterized by yield strength, bulk density and viscosity that are much higher than that of clear water (Rodolfo, 1989). It owes its mobility to the water it contains which is typically not greater than 20 % (Rodolfo, 1989; Umbal, 1986).

Yield strength and plasticity enables lahar to move as a coherent mass, carrying with it large clasts. Yield strengths of <400 dyne/cm2 have been measured from Mayon lahars. This is rather low that turbulent flow results and the muddy water and coarser sediments behave as independent phases (Rodolfo, 1989). Umbal (1986) observed otherwise. He described lahar flows to behave with a slurry-like consistency, moving in a laminar fashion.

Grab samples of active lahars (Umbal, 1986) yielded 20-85% volume solids. From these samples, densities were calculated and results showed a range from 1.8 to 2.4 g/cm3.

Flow velocities from the 1984 lahars were measured directly and indirectly. Direct measurements of moving flows range from 2 to 5.6 m/sec at slopes of 9.4 to 5.6 ° (Umbal, 1986). Indirect measurements were made by Arguden and Rodolfo (1990) following Chow's formula "which was based on the tendency of fluid flows to reach higher elevation on the outside of channel bends due to radial acceleration." Results of their calculations show that mean velocities range from 2 to 4 m/sec. 2 m/sec was computed as mean velocity for unchannelized flows. Channelized flows showed a higher mean velocity of 4 m/sec. Furthermore, they observed that "at comparable distances from the crater and on similar slopes, hot debris flows appear to have flowed faster than cold debris flows. From the historical accounts, Newhall (1977) made estimates of lahar velocities. His estimates, which range from 8.3 to 13.8 m/sec are obviously much higher than those of Umbal and Arguden & Rodolfo. Nonetheless, all four authors agreed that flow velocities decelerate as lahars descend the volcano. Arguden and Rodolfo (1990) further observed that hot lahars decelerate faster than cold lahars.

4.3.2 Lahar Initiation:

The presence of large quantities of volcanic debris is the primary requirement to initiate lahars. An appreciable amount of ash cover enhances lahar mobilization since ash reduces infiltration and more run-off is promoted. The second requirement is water, which, in the case of Mayon, comes from rainfall. A comparative plot of monthly lahar frequency with average rainfall was done in 1984-1986 (Umbal, 1986). It showed that more lahars occurred during the early part of September-October, 1984 than the succeeding days. This is because, most materials in the source areas have already been transported down and a higher rainfall intensity and duration was necessary to re-mobilize the debris left behind.

Umbal (1986) observed that rain in excess of 1 mm/min and lasting for more than 20 minutes can immediately trigger lahars. He concluded that rainfall intensity-duration is an important trigger for lahar initiation. Following Caine's method and using the 1984 to 1986 data, an empirical rainfall intensity-duration threshold limit of I=27.3D-0.38 has been determined for Mayon lahars by Rodolfo and Arguden (1991). In this equation, I is expressed in mm/hr and D is expressed in hours. This method of threshold determination does not consider wet antecedent conditions of the slopes, however.

4.3.3 Characteristics and Dimensions of Deposits:

Most lahar deposits have been observed to consist of a chaotic jumble of fragments of different sizes and lithologies derived from the upper slopes of the volcano. Deposits are usually unstratified but some exhibit faint stratification (Fig.5.9). These have probably been formed by less turbulent processes. Occasionally, crude reverse grading is also observed. Arguden and Rodolfo (1990) suggested that this structure is probably due to lack of cohesion and a considerable dispersive pressure in the flow.

A wide range of grain sizes has been observed from lahar deposits. In general these are fines depleted. Random visual estimates of grain size distribution show an average of 25% boulders, 25% pebbles and cobbles, 40% sand and 10% silt and clay. Laboratory analysis of matrix materials show that silt and clay fractions do not exceed 5%. Cumulative distribution is less tightly grouped than that of pyroclastic flows.

Lahar deposits are difficult to distinguish from pyroclastic flow deposits since there is generally a longitudinal and lateral overlap between these two deposits. One of the main distinguishing criteria used is the difference in their surface morphologies. Pyroclastic flows tend to deposit lobate mounds while lahar deposits are normally deposited as smooth broad sheets found at the distal parts of pyroclastic flow deposits. Sedimentologically, lahars are heterolithologic while pyroclastic flow deposits are monolithologic. There are also differences in the degree of rounding of clasts. Clasts of pyroclastic flow deposits are less rounded than than those of lahars. In addition, pyroclastic flow deposits contain abundant breadcrust bombs.

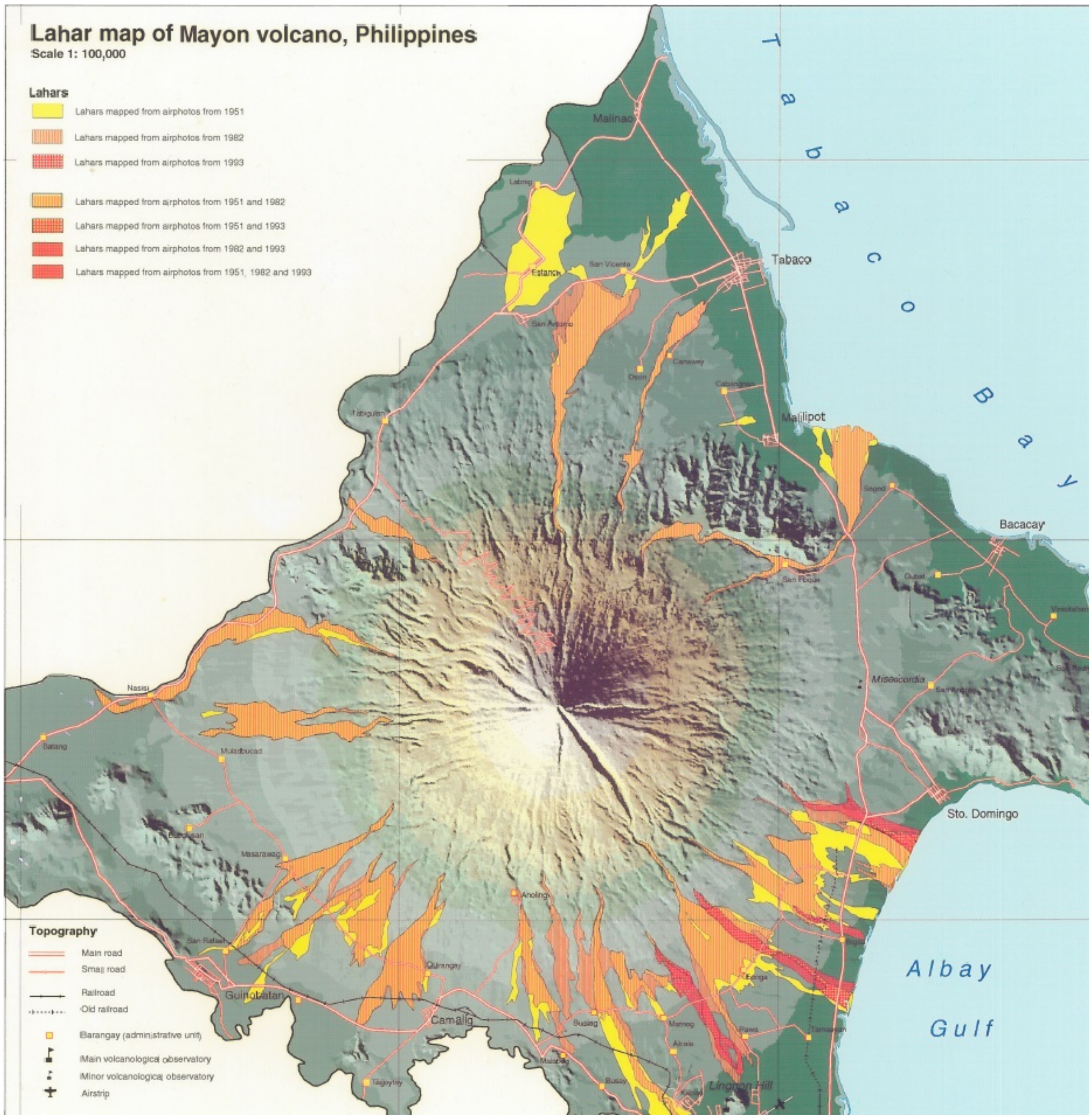

Fig.6. Map of the distribution of Lahar flows in Mayon Volcano

5. Conclusions

This report attempted to make a contribution towards individual hazard susceptibility maps through an inventory of the major Mayon volcanic products which are mute witnesses to the processes and hazards that led to their emplacement. Geomorphological mapping, using multi-scale and multi-temporal aerial photographs and field check, proved to be very useful in inventorizing the deposits left by flowage processes. However, its usefulness is very little in mapping products by airfall and ashfall processes. Therefore, the study has been limited to the three major flowage products: lava flows, pyroclastic flows and lahar deposits.

Treatment of geomorphological criteria, like morphometry and morphography, as external factors that control the deposition of the three different volcanic products, was necessary in the absence of a lot of data on internal (rheological) factors. An advantage of using these geomorphological criteria is that, at the scale of mapping (1:50,000), some of these can be expressed spatially, making overlaying with the distribution of the different volcanic products possible. However, for more detailed studies, numerical simulations would probably be more applicable.

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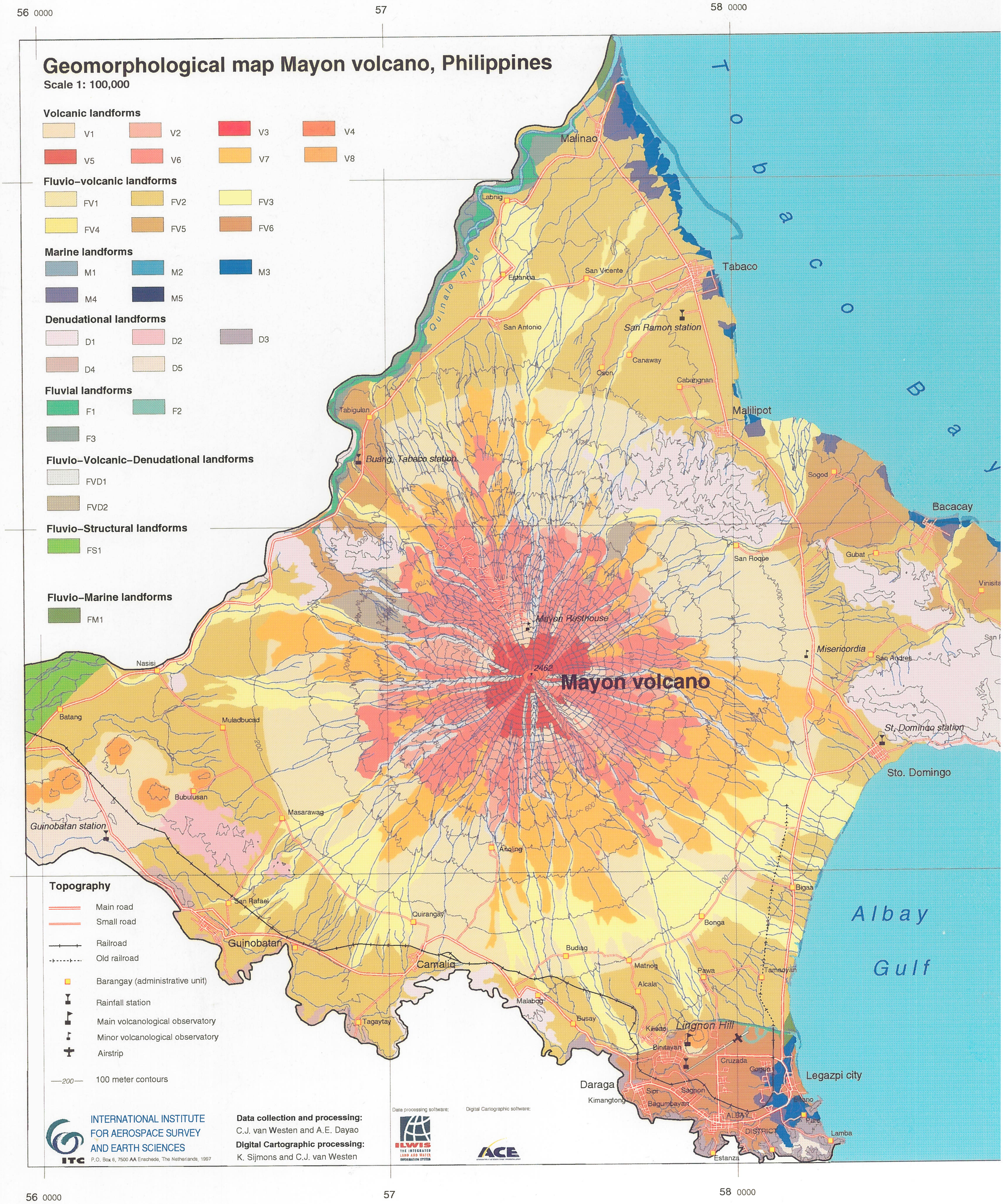

Geomorphological map Mayon volcano, Philippines
Scale 1: 100,000
Volcanic landforms
V1
V2
V3
V4
V5
V6
V7
V8
Fluvio-volcanic landforms
FV1
FV2
FV3
FV4
FV5
FV6
Marine landforms
M1
M2
M3
M4
M5
Denudational landforms
D1
D2
D3
D4
D5
Fluvial landforms
F1
F2
F3
Fluvio-Volcanic-Denudational landforms
FVD1
FVD2
Fluvio-Structural landforms
FS1
Fluvio-Marine landforms
FM1
Topography
Main road
Small road
Railroad
Old railroad
Barangay (administrative unit)
Rainfall station
Main volcanological observatory
Minor volcanological observatory
Airstrip
100 meter contours
INTERNATIONAL INSTITUTE FOR AEROSPACE SURVEY AND EARTH SCIENCES
ITC
P.O. Box 6, 7500 AA Enschede, The Netherlands, 1997
Data collection and processing:
C.J. van Westen and A.E. Dayao
Digital Cartographic processing:
K. Sijmons and C.J. van Westen
Data processing software:
Digital Cartographic software:
ILWIS
ACE
Mayon volcano
2462
Mayon Resthouse
Tobacco Bay
Albay Gulf
Quinale River
Malinao
Labnig
Tabaco
San Vicente
Estancia
San Antonio
San Ramon station
Canaway
Oson
Cabangnan
Malilipot
Tabigulan
Buang, Tabaco station
Sogod
Bacacay
Gubat
San Roque
Misericordia
San Andres
St. Domingo station
Sto. Domingo
Nasisi
Batang
Muladbucad
Bubulusan
Masarawag
Guinobatan station
Anoling
San Rafael
Quirangay
Guinobatan
Camalig
Budiao
Bonga
Bigaa
Matnog
Alcala
Pawa
Tamaoyan
Malabog
Busay
Tagaytay
Kimantong
Lingnon Hill
Binitayan
Cruzada
Legazpi city
Daraga
Sipi
Bagumbayan
ALBAY DISTRICT
Lamba
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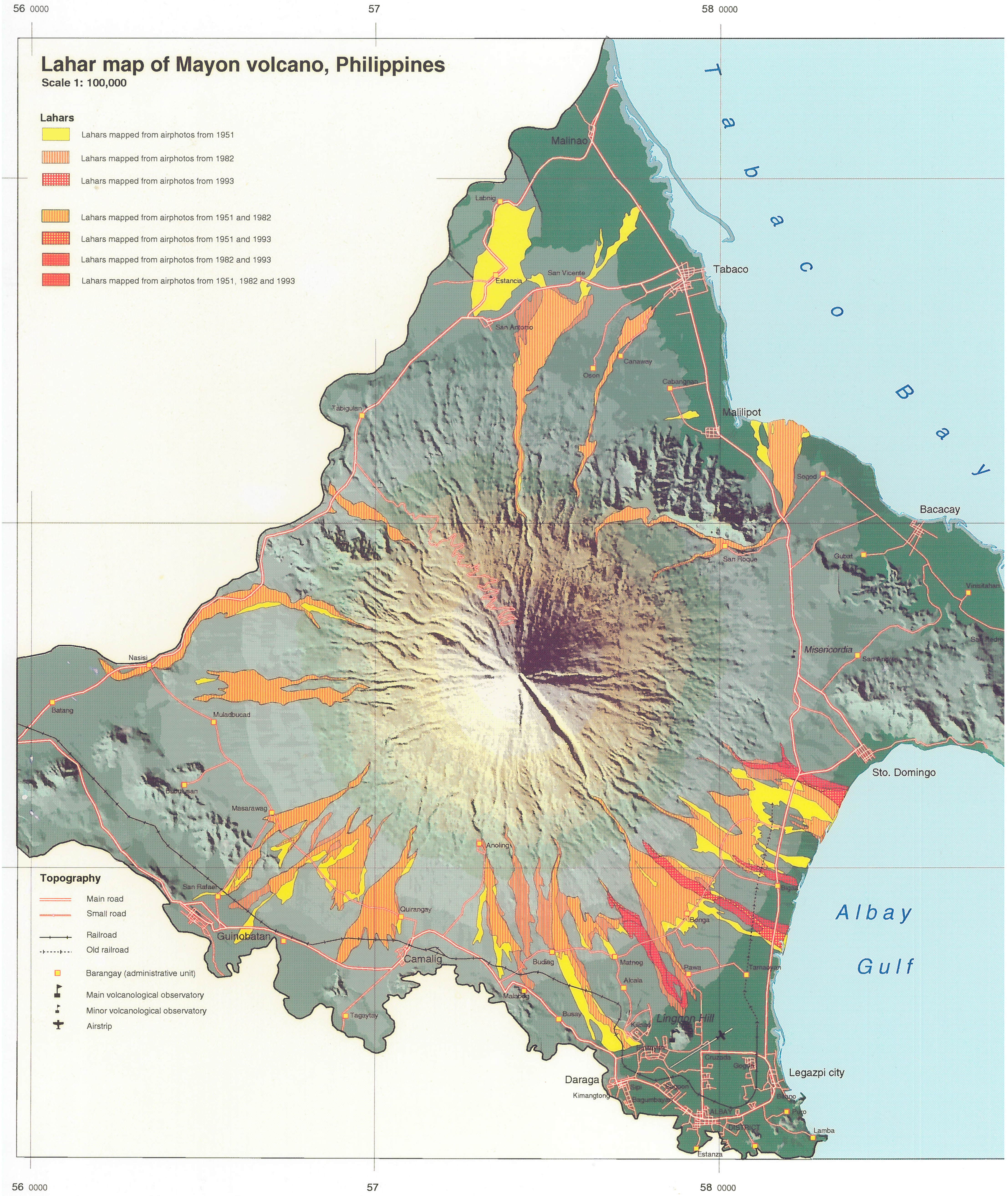

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58 0000
Lahar map of Mayon volcano, Philippines
Scale 1: 100,000
Lahars
Lahars mapped from airphotos from 1951
Lahars mapped from airphotos from 1982
Lahars mapped from airphotos from 1993
Lahars mapped from airphotos from 1951 and 1982
Lahars mapped from airphotos from 1951 and 1993
Lahars mapped from airphotos from 1982 and 1993
Lahars mapped from airphotos from 1951, 1982 and 1993
Topography
Main road
Small road
Railroad
Old railroad
Barangay (administrative unit)
Main volcanological observatory
Minor volcanological observatory
Airstrip
Tabaco Bay
Albay Gulf
Malinao
Labnig
Estancia
San Vicente
San Antonio
Tabaco
Canaway
Oson
Cabangnan
Malilipot
Tabigulan
Sogod
Bacacay
San Roque
Gubat
Misericordia
San Andres
Sto. Domingo
Nasisi
Batang
Muladbucad
Masarawag
San Rafael
Guinobatan
Anoling
Quirangay
Camalig
Budiag
Matnog
Alcala
Pawa
Bonga
Tamaoyan
Malabog
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Tagaytay
Lingnon Hill
Daraga
Kimangtong
Legazpi city
Lamba
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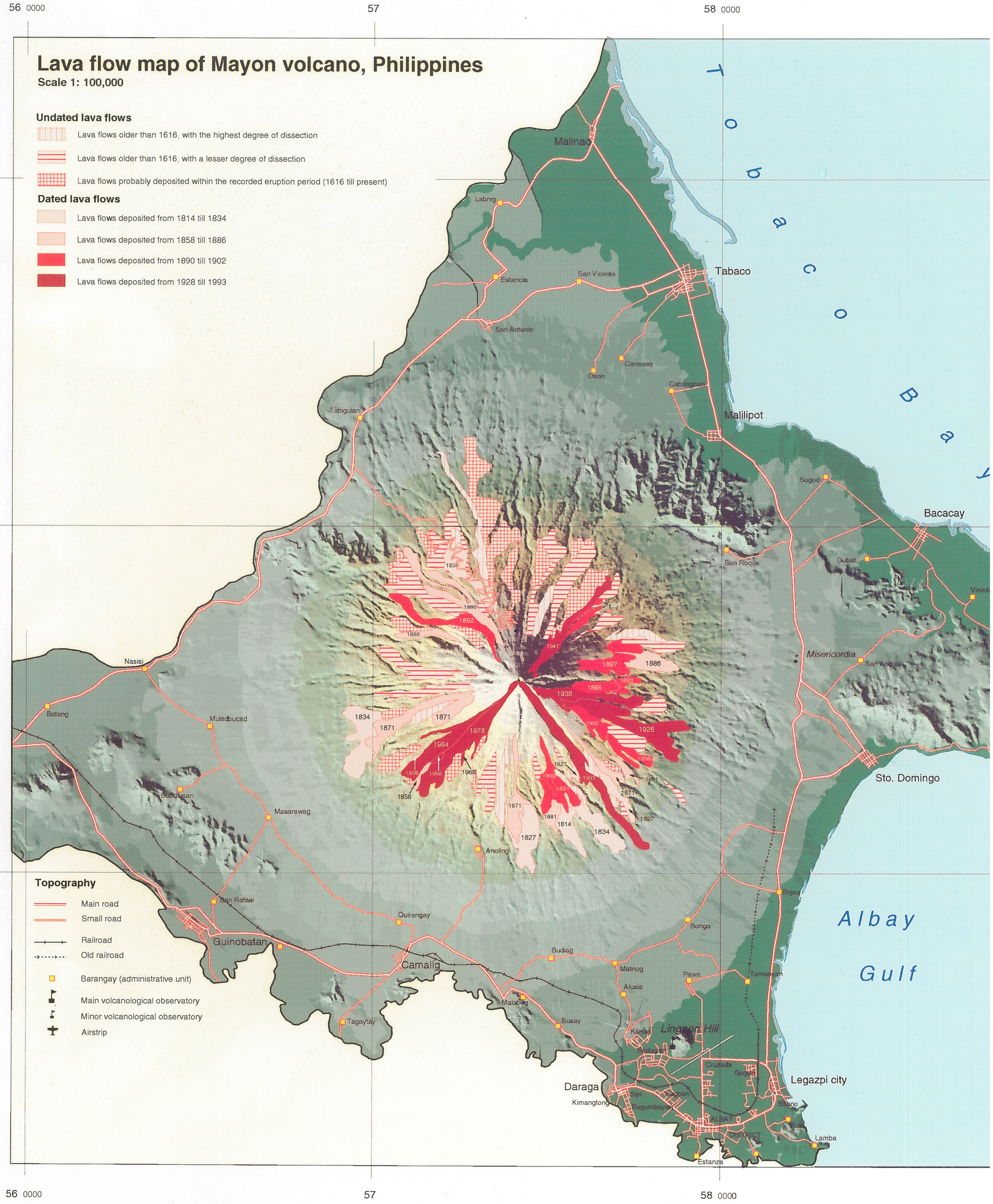
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Lava flow map of Mayon volcano, Philippines
Scale 1: 100,000
Undated lava flows
Lava flows older than 1616, with the highest degree of dissection
Lava flows older than 1616, with a lesser degree of dissection
Lava flows probably deposited within the recorded eruption period (1616 till present)
Dated lava flows
Lava flows deposited from 1814 till 1834
Lava flows deposited from 1858 till 1886
Lava flows deposited from 1890 till 1902
Lava flows deposited from 1928 till 1993
Topography
Main road
Small road
Railroad
Old railroad
Barangay (administrative unit)
Main volcanological observatory
Minor volcanological observatory
Airstrip
Tobacco Bay
Albay Gulf
Malinao
Labnig
Estancia
San Vicente
Tabaco
San Antonio
Oson
Canaway
Cabangnan
Malilipot
Tabigulan
Sogod
Bacacay
San Roque
Gubat
Misericordia
San Andres
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San Rafael
Guinobatan
Quirangay
Camalig
Budiag
Bonga
Matnog
Alcala
Pawa
Tamaoyan
Bigaa
Malabog
Busay
Tagaytay
Lignon Hill
Daraga
Kimangtong
Legazpi city
Lamba
Estanza
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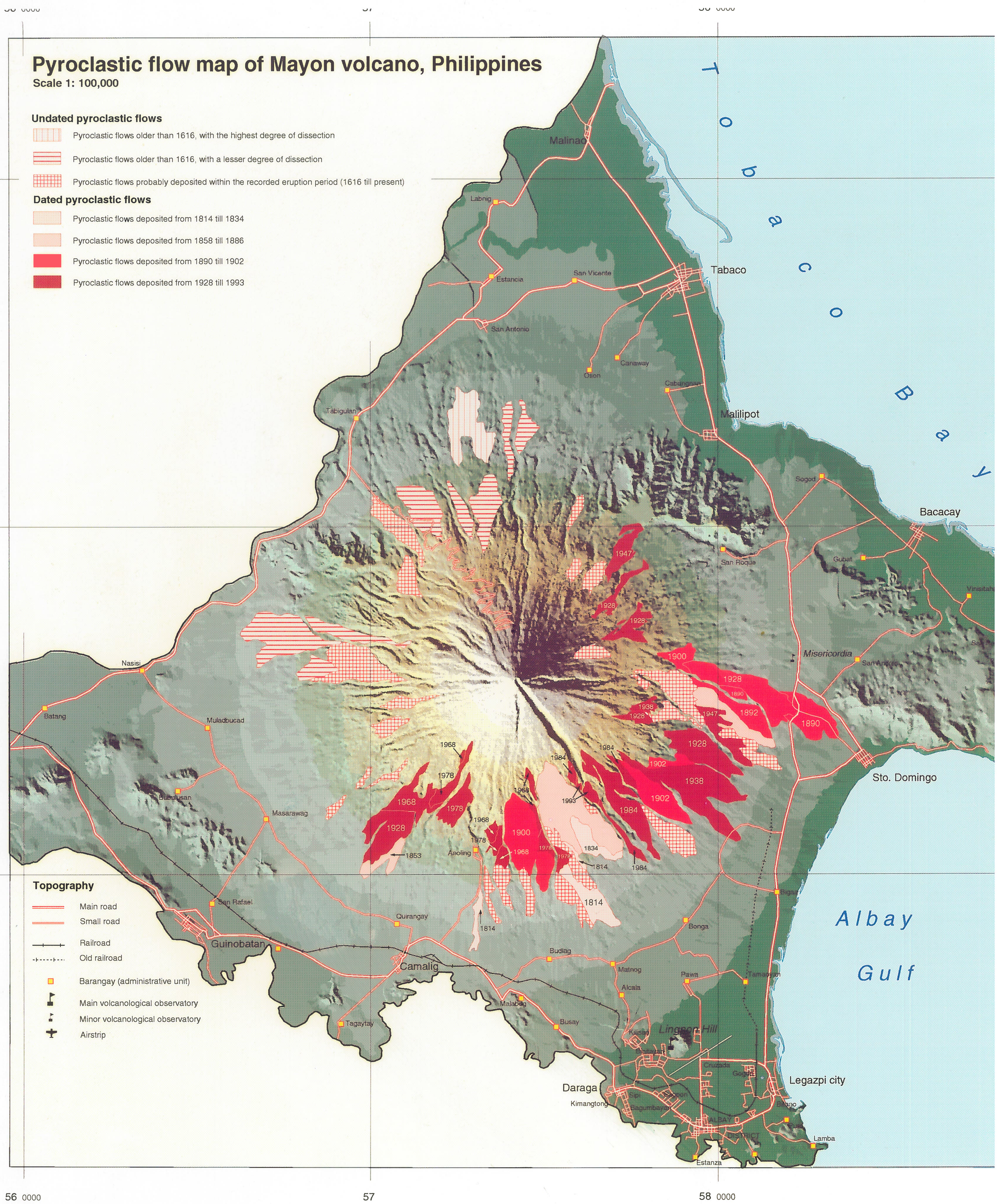

Pyroclastic flow map of Mayon volcano, Philippines
Scale 1: 100,000
Undated pyroclastic flows
Pyroclastic flows older than 1616, with the highest degree of dissection
Pyroclastic flows older than 1616, with a lesser degree of dissection
Pyroclastic flows probably deposited within the recorded eruption period (1616 till present)
Dated pyroclastic flows
Pyroclastic flows deposited from 1814 till 1834
Pyroclastic flows deposited from 1858 till 1886
Pyroclastic flows deposited from 1890 till 1902
Pyroclastic flows deposited from 1928 till 1993
Topography
Main road
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Tabaco
San Antonio
Canaway
Oson
Cabangan
Tabigulan
Malilipot
Sogod
Bacacay
San Roque
Gubat
Misericordia
Sto. Domingo
Nasisi
Batang
Muladbucad
Masarawag
San Rafael
Guinobatan
Quirangay
Camalig
Apoling
Budiao
Matnog
Alcala
Bonga
Pawa
Busay
Malabog
Tagaytay
Lingnon Hill
Daraga
Kimangtong
Legazpi city
Estanza
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