

## THE VOLCANO-TECTONIC HISTORY OF THE MANINJAU CALDERA, WESTERN SUMATRA, INDONESIA

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### ABSTRACT

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Recent investigations help elucidate the volcano-tectonic history of Mt. Maninjau, Sumatra. Three stages may be distinguished: the pre-volcanic edifice stage, the pre-caldera stage and the caldera-formation stage.

During the pre-caldera stage, fissures opened in this part of Sumatra as a result of stresses, the largest presumably being vertical. In the next stage basaltic to andesitic magma ascended to the surface, building up a number of strato-volcanoes, one of which formed the N-S oriented Maninjau compound volcanic complex. The caldera-formation stage was preceded by the ejection of some 220-250 km<sup>3</sup> of pumiceous tuff. This was subsequently followed by the collapse of the top part of the volcano, and the radial failure of the western flank. Two eruptions of acid magma have taken place, the first yielding an unwelded and the second a welded tuff, the latter presumably ejected from the southernmost crater. Since then, obvious volcanic activity has ceased at Mt. Maninjau.

### INTRODUCTION

Mt. Maninjau is a volcanic edifice located about 15 km west of Bukittinggi, the second most important city of West Sumatra Province, Indonesia. Its central part is occupied by a caldera about 20 km long and 8 km wide. A lake measuring nearly 100 km<sup>2</sup> is present in the caldera bottom<sup>4</sup>. (Fig. 1).

The geology is little known and in 'The Geology of Indonesia', VAN BEMMELEN (1949; 2nd ed. 1970) makes only brief mention about this mountain and its caldera (p. 685).

The earliest accounts of Mt. Maninjau are those by VERBEEK (1883) and FENNEMA (1887). It was also Fennema who in 1883 made the first bathymetric chart of Lake Maninjau. In con-

nection with rumours of renewed activity of Mt. Maninjau, Kemmerling in 1919 made a volcanological and geological investigation of the volcano (KEMMERLING, 1921-b). After 36 years there have been no perceptible changes in the lake bottom configuration, although improved surveying techniques of course led to more accurate maps.

The newly published material includes the 1 : 250,000 geological quadrangles of Padang by KASTOWO & LEO (1973) and of Solok by SILTONGA & KASTOWO (1975). Also incorporated are the publications by ZEN (1972) on the pyroclastic flows of the Padang Highlands, and by POSAVEC ET AL. (1973), on the tectonic controls of volcanism and complex movements in this part of Sumatra. Other publications that contain information on Mt. Maninjau or that provide background of general character are by VERSTAPPEN (1973), TJIA & POSAVEC (1972), NISHIMURA & IKEDA (1978), and NISHIMURA ET AL. (1978-a, b).

Investigations for the proposed Maninjau hydro-electric power plant from mid-1974 till mid-1976 (by M.M.P. and M.L.S.) and regional surveys within the framework of the International Decade of Ocean Exploration (by S.S.) gave us first-hand information on the volcano-tectonic history of the Maninjau volcanic complex. A synthesis is presented in the following lines.

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<sup>4</sup> The use of the name Maninjau is usually restricted to the lake inside the caldera, instead of the whole mountain complex. The lake, in turn, is called after the village of Maninjau. Bukittinggi is the former Fort de Kock.

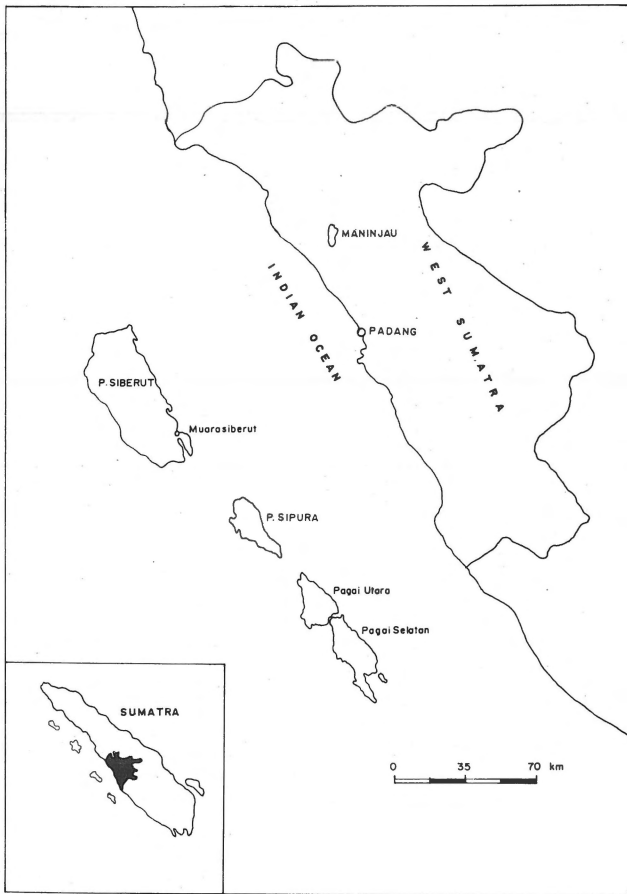


Fig. 1  
Location map of the West Sumatra province.

## GEOMORPHOLOGY

From afar, Mt. Maninjau does not resemble a volcano, owing to its truncated cones. A number of tops surrounds the approximately north-south extending Maninjau caldera, with the highest in the northern portion (see Fig. 2).

The caldera lake, lying 464 m above sea-level, is divided into a northern part and a much smaller southern part. At the separation it is only 3 km wide, while the width is 9-12 km elsewhere. There are some small islets in the lake, that measure only a few hundred m<sup>2</sup>. The lake bottom slopes gently southward, and the deepest points are found in the southern part (Fig. 3).

The caldera walls are mostly steep, especially the southern and the southwestern walls. The gently sloping northern lake shore and adjacent lands are occupied by ricefields, in contrast with the steep walls which are mostly covered by primary forest. A number of small streams debouch into the lake, and this, in turn, is drained by the Antokan River. This stream flows along a steep-walled canyon which breaches the volcanic body.

The Maninjau volcanic edifice is thought to be composed of three individual volcanoes (POSAVEC ET AL., 1973) or is a com-

pound volcano (KEMMERLING, 1921-a), arranged in a north-south direction. The number of craters is not known precisely, on account of derangement during the formation of the caldera. Based on geomorphological evidences and by analogy with similar phenomena, the volcanic activity appears to have shifted gradually from north to south. In the southern part broad divides are still present, in contrast with the northern part where the divides have narrowed to relatively narrow crests, which indicate an advanced stage of erosion.

## GEOLOGY

The oldest rocks in the area of Mt. Maninjau are phyllites, limestones, granodiorites, and diabases. Their ages range from Palaeozoic to Tertiary. From outcrops downstream along the Antokan valley, the following sequence of Maninjau volcanic rocks can be distinguished: dark grey to blackish basalts, tuffaceous breccia, pyroxene andesites, laharic breccia, and pumiceous tuff. The basalts, which are the oldest, are dense and have an aphanitic texture. In addition to plagioclase and pyroxene, the rocks are characterized by the presence of olivine crystals; the plagioclase has an average composition of 62% An. Chlorite is widespread. In places there is irregular jointing. In one of the boreholes, joints and other openings are filled with calcareous material, part of which recrystallized into calcite.

The tuffaceous breccia is for a substantial part composed of air-borne andesitic to basaltic material. The matrix is tuffaceous and the whole mass is densely packed. The components range in size from 0.5 to about 8 cm, but occasionally larger ones are found.

The pyroxene andesites form lava sheets which show an aphanitic to porphyritic texture. The rocks are mostly light grey with black dots of magnetite. Although lighter in colour, the andesites mineralogically resemble the basalts of the lower lying horizons, except for the absence of olivine. The plagioclase is less basic, with an average composition of 42% An. Where jointed, the openings have been cemented, mostly by tuff. In contrast to the basalts, this material is not calcareous.

The laharic breccia is derived from mudflows that originated on the higher slopes of the Maninjau volcano before the caldera formation. The components are mostly rounded, which points to a certain degree of wearing during transport in an aqueous agent. Their size varies greatly: from sand to huge blocks of several metres in diameter. The finer fractions have mostly been washed out.

The pumiceous tuffs were laid down during the formation of the caldera. In general, the tuffs are light brown to yellowish, and are composed of pyroclastics in which pumice of various sizes forms an important part. This deposit will be discussed in greater detail in the next section, because of its importance in the volcano-tectonic history of Mt. Maninjau.

Structurally, this part of Sumatra is dominated by the approximately southeast-northwest trending Semangko Fault

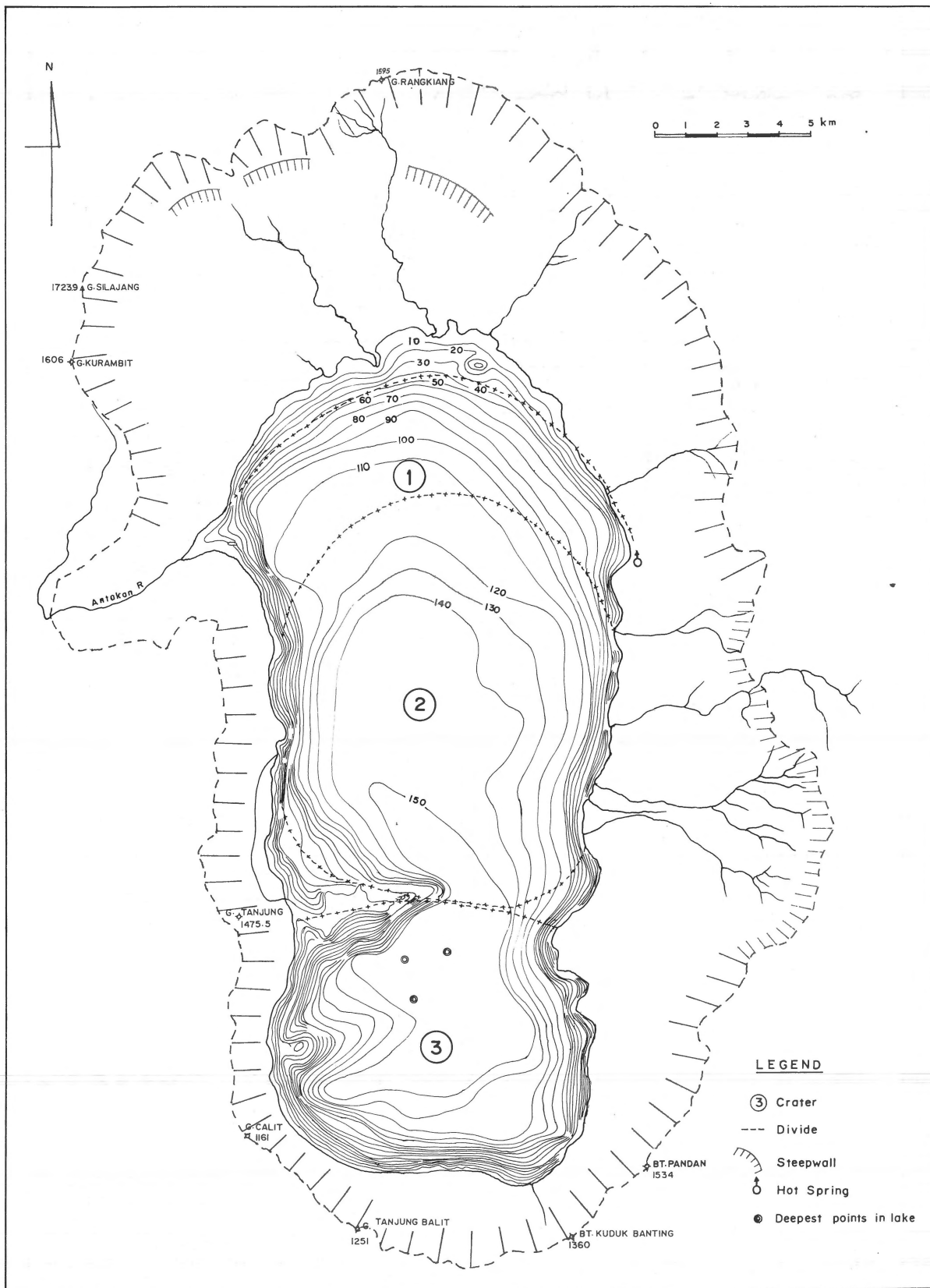


Fig. 2 Lake Maninjau: bottom configuration (after Kemmerling) and other significant geomorphological features inside and surrounding the caldera.

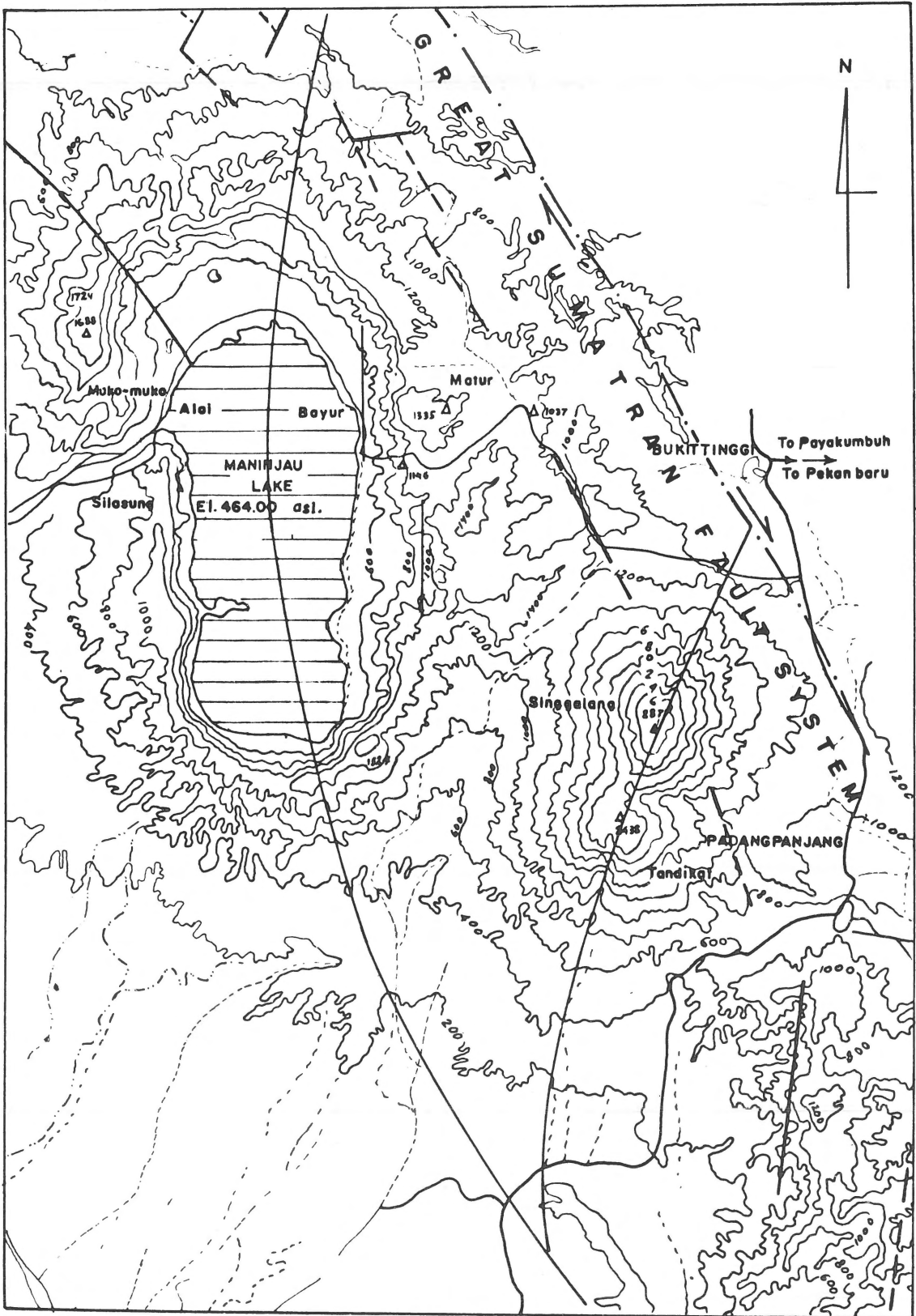


Fig. 3 Mt. Maninjau and surrounding country with faults, identified and inferred, after Kemmerling (1921), Kastowo & Leo (1973) and Posavec et al. (1973).

System (see, e.g., VAN BEMMELEN, 1949) which is presently better known as the Great Sumatran Fault System (see, e.g., KATILI, 1970). This system of faults is traceable along the entire length of Sumatra, over a distance of some 1500 km. For much of its length this system consists of two or three parallel or sub-parallel faults. The central one is the active master fault (POSAVEC ET AL., 1973). Recent movements are known at many places, the latest one associated with the March 9, 1977 earthquake in the Pasaman area, some 75 km north of Maninjau (newspaper report; actual displacement and direction not indicated).

Evidence of faulting in the area of Maninjau and surroundings is mostly based on inference. In a recently published geological map by KASTOWO & LEO (1973) a number of north-west-southeast more or less parallel faults are indicated. Earlier, VERBEEK (1883) and KEMMERLING (1921-a) indicated two north-south faults within the caldera. Based on lineaments, POSAVEC ET AL. (1973) showed additional faults. Curiously, none of the indicated faults is mentioned in any subsequent publication. During our fieldwork, we tried to collect evidence to confirm or disregard them, and in our opinion most identifications are reasonable, but some have to be accepted with a certain reserve. Our interpretation is summarized in figure 3.

## VOLCANO-TECTONICS OF MT. MANINJAU

### *Pre-volcanic edifice stage*

The latest part of the pre-volcanic edifice period was a period when tectonic stresses were mounting along the whole western part of Sumatra, and this was followed by the formation of faults. In addition to wrenching along the Great Sumatran Fault Zone, more to the west the largest stress appears to have been vertical, especially in the area under discussion. As a result, predominantly N-S striking normal faults developed. The opening of fissures facilitated the ascent of magma to the surface. The peculiar north-south lineaments which show up on aerial photographs (POSAVEC ET AL., 1973) may be related to these fissures and faults (Fig. 3). Tectonic activity took place in approximately early Tertiary time (VAN BEMMELEN, 1949, p. 672). Since then the western part of Sumatra has been displaced right-laterally some 250-270 km relative to the part east of the Great Sumatran Fault Zone (TJIA & POSAVEC, 1972).

### *Pre-caldera stage*

The ascending magma has given birth to a number of volcanoes, one of which was the Proto-Maninjau volcano. This volcano must have had an altitude in excess of 3000 m. Gradually, the feeding channel shifted southward, and along with it also the eruption centres. In this way a compound volcano was formed, with the proto-volcano in the north having the biggest and tallest cone, as can be deduced from the geomorphology.

In much the same way this southward-shift of activity must also have affected the neighbouring twin volcano Singgalang (2578 m)-Tandikat (2437 m). Here, too, the younger of the twin volcanoes is the southernmost, Mt. Tandikat, which is still active. Its latest eruption was in 1914 (VAN BEMMELEN, 1941, p. 8; HAMIDI, in press).

### *Tuff deposits of the West Sumatra province*

Discussion about the formation of the Maninjau caldera is inseparable from the extensive tuff deposits of the West Sumatra Province – or, as termed by some authors, the Padang Highlands – which puzzled many investigators. VERBEEK (1883, p. 530-531), without mentioning the source, thought that they had been deposited in lakes. DE HAAN (1935, p. 97) mentioned the occurrence of pumiceous tuffs about 30 km north of Bukittinggi, also without indicating their actual source. VAN BEMMELEN (1949, p. 686) thought the tuffs might be produced by fissure eruptions in the presently called Great Sumatran Fault System, and so did WESTERVELD (1952, p. 565). ZEN (1972) surmised that the tuffs might be air-borne deposits derived from a gigantic outburst of the Maninjau volcano prior to its caldera formation. Incidentally, POSAVEC ET AL. (1973, p. 54) have suggested that the Maninjau caldera is the product of three major eruptions which blasted out the core of a large central volcano and buried the surrounding region with tuff. KASTOWO & LEO (1973) and SILITONGA & KASTOWO (1975) have given sufficient evidence as to their aerial distribution. Kastowo and Leo, however, did not come to a final conclusion. They regarded the tuffaceous deposits to represent either late eruptions from the Maninjau caldera or fissure eruptions related to the Great Sumatran Fault Zone.

Our surveys have shown that even very close to the caldera rim, many of the broader ridges, and the entire southern foot of Mt. Maninjau are covered by pumiceous material. The tuffs, however, are not always easily recognizable, especially where the material has been laid on slopes where it is mixed with pyroclastics or where erosion has been active. Furthermore, topographical irregularities make assessment of the actual amount of ejected material even more difficult.

The farthest mappable deposits of tuffs are those in the areas of Sijantang and Kumanis, some 75 km southeast of the Maninjau caldera. To the west they are indicated up to a distance of around 25 km, where they occur in a strip of alluvial deposits along the Indian Ocean. More to the north, they may be buried under alluvial material (Fig. 4). Core drilling at a number of places in the alluvial strip has revealed that up to depths of 20 m the base of the tuff deposit was not yet reached.

Judging from the distribution of the pumiceous tuffs we conclude that a large part must have been air-borne. The material typically consists of pumice and glass shards, and depending on the distance from Maninjau, it may or may not contain quartz grains and other lithic particles as well as obsidian, pitchstone and other foreign material. As can be seen

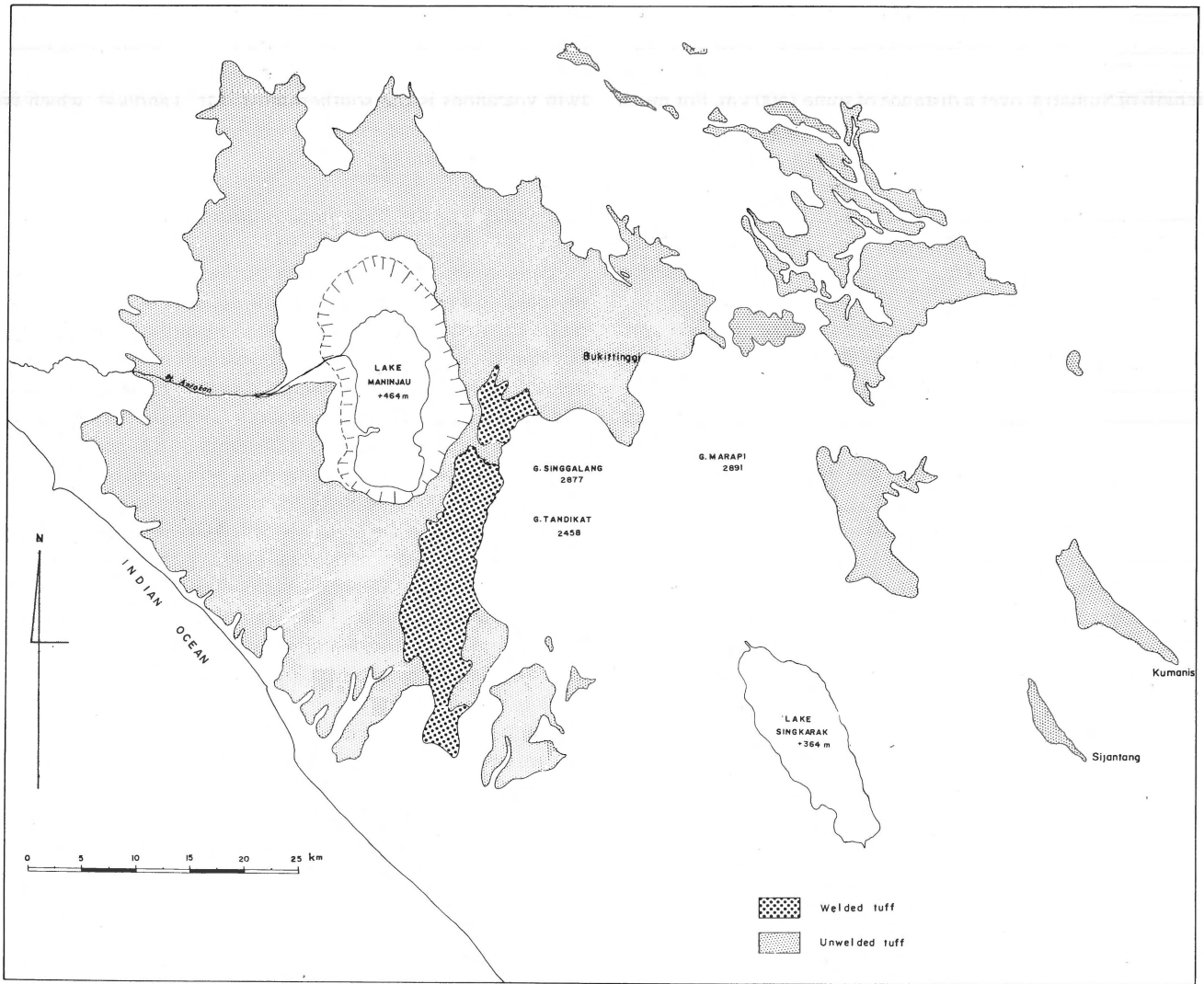


Fig. 4  
Distribution of the Maninjau tuffs, after Kastowo & Leo (1973), Silitonga & Kastowo (1975) and own observations.

in many outcrops, the material is unsorted and no clear stratification is present. Being unwelded, the material must have been emplaced at a temperature lower than the minimum welding temperature of  $600^{\circ}\text{C}$ , as suggested by ZEN (1972). In addition to the unwelded tuffs, we (MMP and MLS) have observed in places welded material that moreover shows a flow structure. This is the case, for example, with a deposit along the road to Malala village, east of the caldera. Elsewhere the tuff character is more distinct. Most probably, this rock is the same as the hornblende-hypersthene pumiceous tuff of KASTOWO & LEO (1973), found between Mt. Maninjau and the twin volcano Singgalang-Tandikat, as a strip or belt over more than 30 km. According to these authors, the field relations suggest that this type of tuff overlies the unwelded tuff. ROSS & SMITH (1961, p. 18) point out that the most important single criterion for recognition of the pyroclastic nature of ashflow tuffs in the field is the presence of pumice fragments. Based on this, we

can conclude that there are at least two types of pumiceous tuff in Maninjau, the welded and the unwelded, and that the first type is the youngest. In the literature in the past, other names have been applied in addition to pumiceous tuff, such as acid tuff, ash tuff, and ignimbrite. To avoid confusion, we refrain from using the other terms.

Based on the presently available information we are only able to approximate the amount of tuff ejected during the eruption. Although the farthest tuff deposits are about 75 km away, the localities are southeast of Mt. Maninjau. To the east and northeast (SILITONGA & KASTOWO, 1975), they are found up to about 50 km away. To the west, southwest and south, the distribution cannot be checked accurately on account of the ocean.

Based on recorded volcanic eruptions such as the 1919 Kelut eruption, where the distribution of the ash was much influenced by the prevailing winds (KEMMERLING, 1921-b, p.

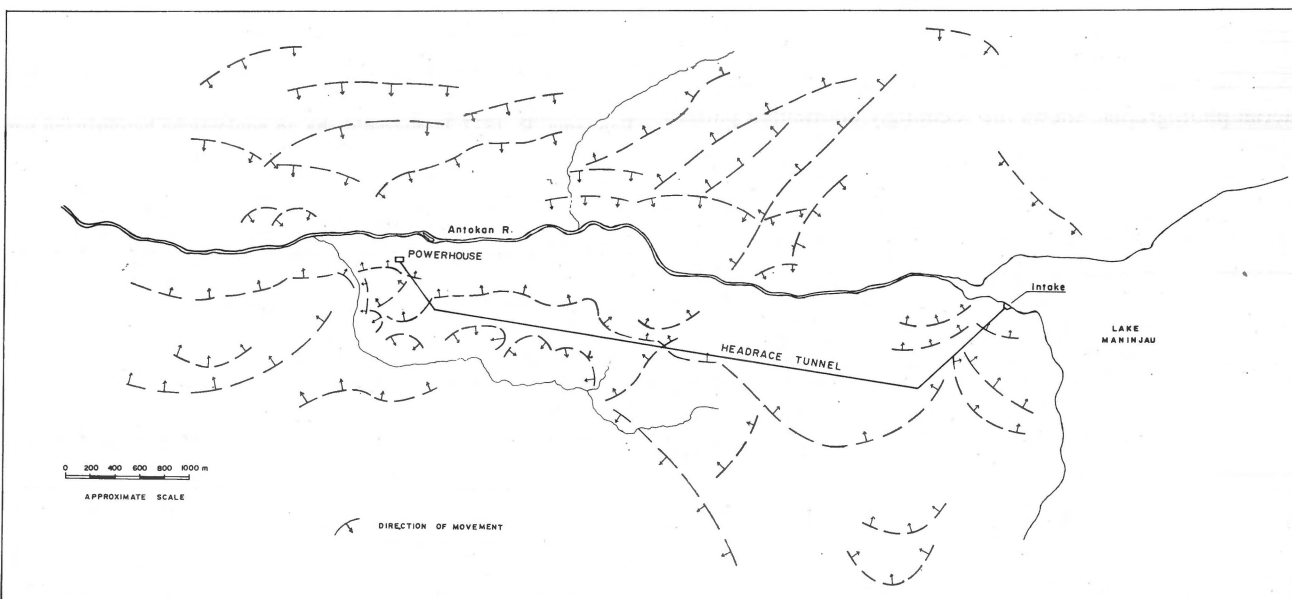


Fig. 5  
Pattern of slumping and sagging along part of the Antokan valley.

37-39; Plate VII), we may presume that the same situation existed during ejection of pumiceous tuff at Maninjau. We can also assume that the area that was covered by a thick blanket of tuff was elliptical with a long axis of 120 km and short axis of 90 km. The extent of this blanket must then have been roughly 8500 km<sup>2</sup> (part of the tuff might have been transported farther away, but owing to its restricted thickness it cannot now be detected).

ZEN (1972) estimated the deposit in Bukittinggi at 15 km from the volcano between 75-150 m thick. Earlier, VERBEEK (1883, p. 530) came to a figure of 83 m. At an outcrop near Lake Singkarak to the southeast, at a distance of about 40 km from Mt. Maninjau, we observed at an outcrop (not indicated on the published geological map), a thickness of less than 25 m. If we assume the average thickness of the elliptical tuff blanket to be 25 m, then the volume of the material was about 212 km<sup>3</sup> (we may add some 5% that had been transported farther away and the actual figure might then be around 220 km<sup>3</sup>).

Let us now turn to the Maninjau depression. With a length of about 20 km, a width of 8 km and a depth of some 1400 m, the volume is 224 km<sup>3</sup>. This tallies fairly well with the above-suggested figure for the amount of ejected tuff. As such, the actual amount of ejected pyroclastics during the pre-caldera eruption must be in the order of 220-250 km<sup>3</sup>, which means that it is about one-tenth or one-eighth the amount of material suggested for the Toba tuffs in North Sumatra (VAN BEMMELEN, 1949, p. 202).

Age-dating experiments are being conducted on volcanic ash and tuffs from Indonesia (NISHIMURA ET AL., 1978-a). The method used is a fission-track technique, and five samples from the West Sumatran tuff deposits have been tested. Pre-

liminary results indicate that the tuffs range in age between 70,000 and 80,000 years. We assume that the unwelded tuff was ejected first, and that the younger welded tuff had its origin from the southernmost crater. This is the deepest and also the one with the most youthful features.

#### *Caldera formation and the origin of Antokan Valley*

After the acid magma had been ejected, the volcanic edifice was deprived of its support and started to founder. The Proto-Maninjau must have been located closest to the magma chamber. Hence, it is also this volcano that has undergone the most profound changes as a result of the collapse. The process of readjustment to a new equilibrium must have proceeded over a long period of time; first a prelude of concentric fracturing and rupturing that was subsequently followed by the falling of blocks into the emptied chasm, a sagging and slumping of lumps, and ultimately by massive sliding and falling of rocks. The last types of mass movement are still taking place, especially during the rainy season. The hillocks, mounds, benches, and small islands within the caldera are all relicts of mass wasting.

The collapse has also resulted in a decrease of the overall mass density, as can be seen clearly by the result of a gravity survey that was carried out recently by NISHIMURA ET AL. (1978-a). The distribution of symmetrical negative anomalies across Lake Maninjau is called by them a typical feature of so-called 'low anomaly-type caldera'.

Along with changes at depth other features added to concentric fracturing, namely radial failure of the western part of the volcanic edifice. This was followed by sagging and slumping at the surface that formed the Antokan breach. Our inves-

tigations for the proposed Maninjau hydro-electric power plant indicate that along the Antokan River at least part of the movement must have been rotational. Figure 5, drawn from aerial photographs, shows the seemingly unoriented pattern of the downslided blocks.

The primary sliding plane at the base could not be detected by the drilling which was too shallow (15 m at the weir site, and 200 m along the headrace tunnel). Resistivity and seismic surveys, which could only penetrate to about 200 m, gave no further information. From the topography, however, we infer that the blocks have slumped or sagged some 500 m at the intake and less westwards.

### CONCLUSIONS

Mt. Maninjau is a little known volcano. Newly published material and the results of investigations for the proposed Maninjau hydro-electric power plant indicate that the extensive tuff deposits of West Sumatra Province came from Mt. Maninjau and erupted prior to the formation of the caldera. Based on field observations the emplacement of the unwelded tuff was followed by collapse of the top part of the volcano, that gave rise to the formation of a caldera. The areal distribution of the welded tuff strongly suggests that it was derived from the southernmost crater.

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