KARST REGIONS IN INDONESIA

by
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Between the Eurasian and Australian continents stretches a vast archipelago on both sides of the Equator. Composed of more than 20,000 islands, the East-Indian Archipelago* is one of the most diversified, continually moving and changing, parts of our Globe. This is due to its being a point of junction of three huge tectonic units. From the north, the southeast shield of the Asiatic Massif (*Southeast India* and the inundated *Sunda Shelf* as well as the northeast flatland of *Sumatra* and the southwest one-third of *Kalimantan*) wedges into the heart of the archipelago; on the south and west the remnants of the *Gondwana Massif* – the Indian Shield, the bottom of the Indian Ocean, the Australian continent, and the associated *Sahul Shelf* – form an arched, rigid wall; on the east the abyssal craton of the Pacific Ocean borders the region. (Fig. 1)

The three stable tectonic units are hemmed in by three huge sedimentary troughs:

a) between the Eurasiatic and the Gondwana Massifs there is the *Alpine-Himalayan-Sunda* orogenic belt which, beyond *Arakan Joma*, *Burma*, is split up and submerged, its emergent portions being the *Andaman islands*, *Sumatra*, *Java*, and the *Little Sunda islands*;

b) the circum-Pacific orogenic belt, whose Asiatic arch, crossing the *Philippines*, entwines *Kalimantan* and the northern half of *Sulawesi;*

*The naming of the archipelago flanked by Southeast Asia and Australia has been a vexed question for a long time. If the insular world, geographically belonging together (including. beyond the political borders of present-day Indonesia, the island groups of Andaman and Nicobar, the Christmas island, northern Kalimantan, the Philippines, and the entire complex of Irian (New Guinea) and the surrounding islands, covering a total area of 2 832 000 km^2), is considered, perhaps terms such as the "Australe-Asiatic Archipelago" proposed by Sar Qasin or Zeuner's "Indo-Australian Archipelago" would be the most apropriate.

A good term would also be "Insulinde" as proposed by Douwes Dekker (Multatuli) as early as 1860, but this has not become familiar in common usage. Much more common is, however, the name "Malayan Archipelago", though it is unclear whether it should include Irian — an island whose aboriginal population is of non-Malayan origin. "Sunda Archipelago" also is a term of more restricted geographic implication. In his monograph devoted to the archipelago under consideration, Bemmelen (7) has also used a number of names for the insular world as a whole — "Indonesia and adjacent archipelagoes", or simply "Indian Archipelago" or "East-Indian Archipelago". In the present paper the latter term has been used to denote the archipelago *as a whole*, while the islands belonging to the *Indonesian* nation have been termed the "Indonesian Archipelago".

c) the Australian arch of the circum-Pacific orogenic belt extends from *New Zealand* through *Caledonia* and *Irian* (New Guinea) up to the *Halmahera* island.

Largest of the three orogenic belts is the *Alpine-Himalayan-Sunda* system, whose nearly 20,000-km long sedimentary zone gave rise to the intracontinental sea of the *Tethys* of varying extension. The pressure of the continent-blocks has compressed and folded the enclosed, many-thousand-meter thick sediment body, stresses to which the sediment masses have yielded by emerging from the sea. In the East-Indian Archipelago — junction of different tectonic stresses — the variation of the endogenic forces in the geologic past has brought about a variety of landforms, resulting in a random distribution of land and sea both in space and time. Geologic investigations have permitted to outline the geohistoric evolution of the archipelago. Earlier authors still suggested that the series of islands were remnants of a dying continent. Modern workers believe, however, that no contiguous continent may have existed — at least since *Middle Paleozoic* time — in what is now the East-Indian Archipelago and that the present-day distribution of the islands is the result of quite young, *Tertiary* and even *Quaternary*, tectonic movement.

Distinct manifestations of the active endogenic forces of the region are the recent volcanic phenomena occurring throughout the orogenic belts, the intensive seismic activity, and the unusually large gravimetric anomalies.

Nearly 1,000 recent volcanoes occur in the region, of which 177 can be considered still active today (Bemmelen). The active volcanoes are of explosive nature, producing little lava and plenty of gas resulting in heavy, destructive eruptions yielding immense quantities of pyroclastic materials. This type of volcanism is characteristic of an orogeny in evolution.

The archipelago is one of the most seismic areas of this planet. Seismographs have recorded more than 500 earthquakes a year. Most of the earthquakes are of tectonic origin, their epicentres being submarine. Some of them have hypocentres lying as deep as 500 km or more. Seismic shocks connected with volcanism are very great in number, but of reduced magnitude, their hypocentres being close to the surface. Hence, earthquakes of this type are of local importance.

Very interesting and puzzling phenomenon is the zone of negative gravimetric anomaly extending in a width of 100 to 200 km along the outer embryonic island arch of the *Sunda* mountain system throughout the archipelago. The −204 millidyne difference in gravitation between *Sulawesi* and *Halmahera* is the highest isostatic gravity anomaly ever recorded on earth (Fig. 1).

I. Karst regions in the Indonesian Archipelago, as against the general physiographic background

After the above short review of the general geologic features of the unstable zone between the two continents, the further discussion will be restricted to Indonesia (onetime *Dutch East Indies)* and attention will be concentrated on the *general* scientific information concerning the karsted areas of Indonesia. A somewhat more detailed *regional* description of a few typical karst regions is given in the second part of the present paper.

1. Stratigraphy

The dating of the crystalline and other metamorphic rocks, held for the oldest in the Indonesian Archipelago and described as *Precambrian*, is rather uncertain. Some of these rocks may have been formed in *Paleozoic* or even *Mesozoic* time; the more so, in

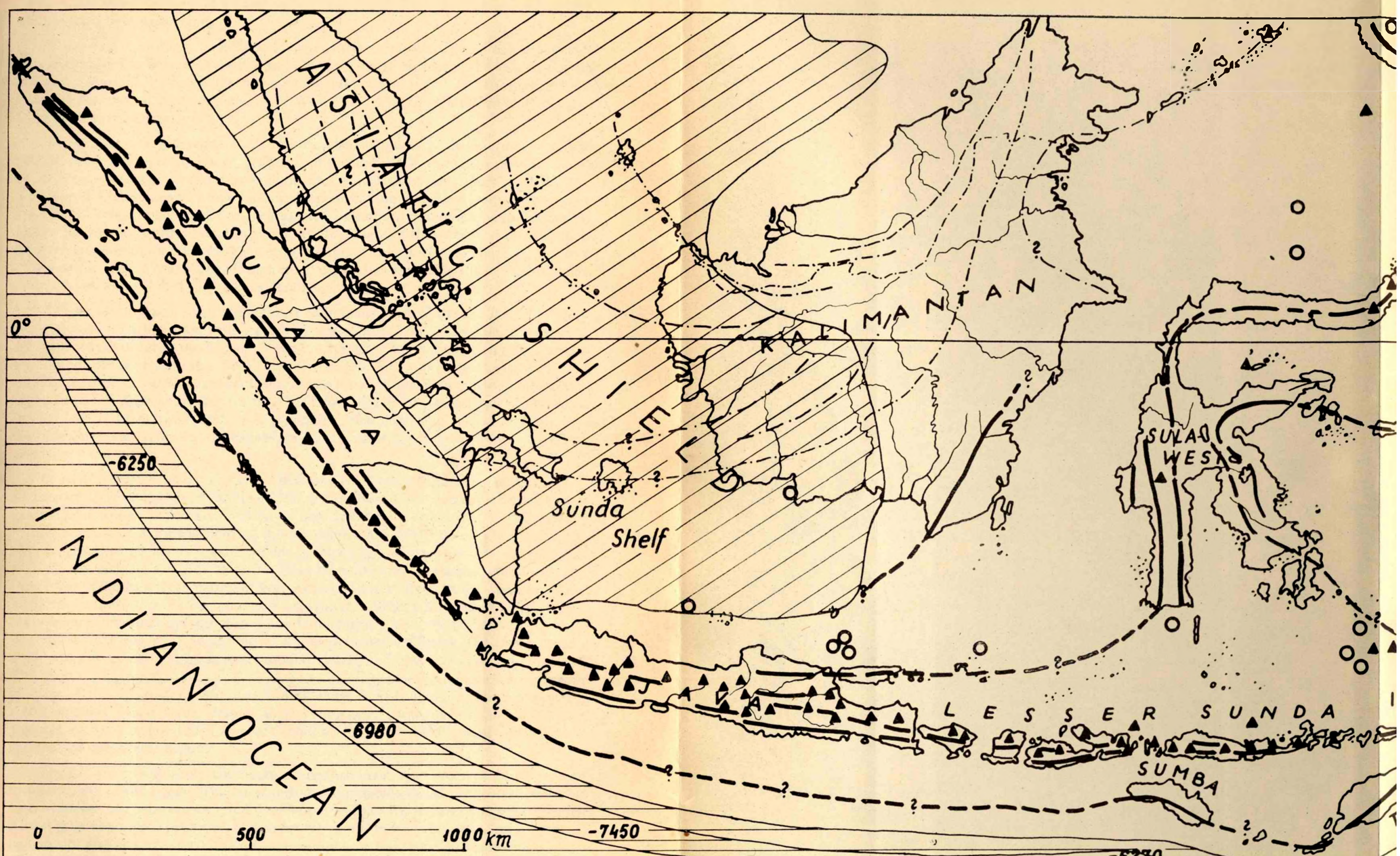


Fig. 1. Geological map-scheme of the Indonesian Archipelago.

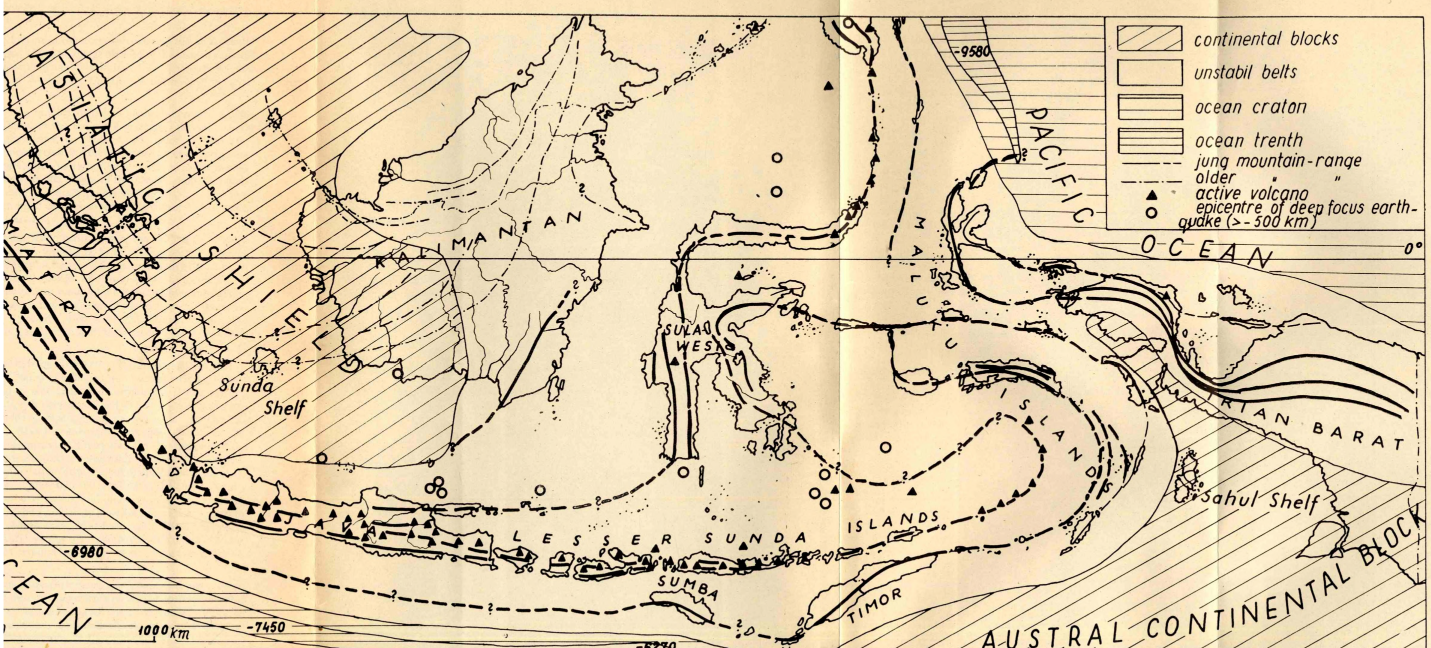


Fig. 1. Geological map-scheme of the Indonesian Archipelago.

western *Kalimantan* and Southwest *Sulawesi*, crystalline rocks containing *Eocene* nummulites have been discovered.

Lower Paleozoic rocks have been known in the areas surrounding the archipelago — in Australia and Southeast Asia — for a long time, but because of the insufficiency of geological research, Paleozoic fossils were long unknown in Indonesia. The earliest fossil found in the central limestone massif of West Irian, *Hallysites wallichi Reed*, is dated from the *Upper Silurian.*

Upper Paleozoic sediments occur in a number of places in the Indonesian Archipelago. Along the west coast of Sumatra, in the *Barisan* Range, considerable masses of slates, sandstones, quartzites, conglomerates, graywackes, etc., dated as *Paleozoic*, are exposed. Limestones are also often encountered, but the crystalline limestones containing *Permo-Carboniferous* fossils are represented by rather large outcrops in the *Gunung Saribu* Mountains, central Sumatra, only. In the ranges of the *Timor-Ceram Arch* there are *Permian* limestones. In the high central mountain ranges of West Irian — still very little known — the *Upper Paleozoic* high-lifted calcareous sediments with corals, crinoids, brachiopods, and trilobits play a considerable part.

The *Mesozoic deposits* can be encountered in many parts of the archipelago, though they form extensive limestone surfaces in very few places. *Triassic* limestones represented by small blocks occur in the *Barisan* Mountain Range of Sumatra as well as on the eastern islands of the archipelago *(Roti-Timor-Ceram-East-Sulawesi* Arch, *Sawu*, and *Misoöl* island). *Jurassic* calcareous sediments have been found in the *Barisan* Mountains and in several parts of *Kalimantan*, but form rather large surfaces in the east part of the archipelago *(Roti-East-Sulawesi Arch*, and especially *West Irian* and *Misoöl* island). The distribution of the *Cretaceous* deposits is similar to that of the *Jurassic.* They do not form any large karst region.

Most of Indonesia's karst areas have developed of *Tertiary* calcareous marine deposits. In Tertiary time more than 10,000 to 15,000 m of sediment was accumulated in the vast geosynclinal trough which lay in what is now Indonesian Archipelago. The Tertiary mainly consists of marine sediments, though continental and brackish-water facies can also be encountered in many parts of the archipelago (on the large islands). The Tertiary locally includes volcanic materials (lava flows, eruptive breccias, submarine tuffs, etc.) which indicate intensification of volcanism in Tertiary time. In the west part of the archipelago the *Lower Tertiary* deposits are chiefly terrestrial, while in the east part foraminiferal limestones predominate. The latter forms the lithologic basis of the Sulawesi Karst Area which has yielded the most splendid karst landforms. The *Upper Tertiary* sediments are represented by sandstones, clay shales, and limestones for the most part. The largest and best-known karst areas of the archipelago have been formed on limestone plateaus of this age (mainly *Miocene)* (South Java, West Irian, etc.). These are mainly reef-limestones which form, despite their young age, comparatively hard, compact sequences, providing good stratigraphic conditions for the development of typical karstic surface and subsurface features.

The calcareous sediments, coral reefs of the *Quaternary* system can be found exposed in many parts of the region. The latest tectonic movements in the particularly unstable eastern islands have sometimes lifted the *Pleistocene* coastal coral-reef and lamellibranch masses several hundred meters high. This loosely consolidated calcareous rock could, of course, not give rise to any typical karst topography, but the peculiar landforms of these areas are of interest for the explorer. Such very late limestone surfaces can be found chiefly on the central and southeast *Maluku* islands *(Ambon, Haruku, Kai, Tanimbar, Aru)* and in *West Irian.*

2. Geological history and tectonics

The large extension and extremely varied geological past of the archipelago make it impossible to carry out a complex analysis of the evolution of landforms in scattered karst areas lying far away from one another. Otherwise, opinions concerning the past tectonic movements of the archipelago have been rather hypothetical, often even contradictory.

In general, geologists agree that late orogenic movements began in *Cretaceous* time and were connected (associated) with intensive granite and peridotite intrusions. The basic patterns of the present-day archipelago's arch were developed by the main, *Miocene*, orogenic phase. These movements have brought about vast land areas (Sunda Land), on Sumatra and the eastern islands nappe-fold structures have come into being.

From the point of view of karst development, the tectonic deformations of the *Plio-Pleistocene* period have been significant, as the present-day karst areas took shape that time. Late in Tertiary time and in the Pleistocene the orogeny — associated with heavy volcanism — rhythmically continued and was manifested mainly by the uplifting of fault blocks, though on the east, subsidences took place. The *Miocene* reef-limestones making up more than 50 per cent of the present-day karst areas have been affected by little folding, if any. Their emergent fault-blocks are horizontally stratified, or just a little tilted. (The genetics of the individual karst areas will be discussed in the part II. of the present paper devoted to regional features.)

It should be noted here that the evolution of karst landforms in Central Europe and North America was adversely affected by Pleistocene climatic changes, as those karst areas lie within the glacial or periglacial zones, respectively. In the Indonesian Archipelago we can dispense with an analysis of paleoclimatic conditions, as one-time climates may have but little differed from present-day climate, so that the evolution of karst features could continuously proceed under the same tropical climatic conditions.

3. Climatic conditions

The climate of an area is basically defined by its geographic situation. The Indonesian Archipelago lies on both sides of the Equator, the northernmost point being 6° north of the Equator, the southernmost one at 11° s. l. The karsted surfaces are confined predominantly to the southern hemisphere. This geographical situation implies a p r i o r i that the archipelago has a *tropical* climate -- warm, humid, moist. Within the notion of tropical climate, the actual climatic pattern of the archipelago is determined by two factors which are due, again, to geographic situation.

The first factor is the *island nature* of the land areas which means that, because of the proximity of sea throughout the archipelago, the climatic agents are rather balanced. This holds particularly true of the *temperature* which has an annuaal average of 26°C throughout the archipelago. No difference greater than 1 to 2°C in mean temperature between the warmest and coldest months of the year occurs, the average *daily changes* in temperature are also rather limited, in the dry season the daily temperature amplitude is 7 to 10°C, in the rainy season 5 to 7 °C. Of course, in the more inland parts of the islands some continental effects are felt, effects manifested in some growth of the daily temperature ranges. The value of the local mean temperature is naturally influenced by the hypsometric elevation of the area: on the average, the temperature decreases by 0.55 to 0.6 degrees centigrade for each 100 m height.

The second factor — the influence of the two near-by continents — play a much more important part in the control of the tropical (equatorial) climate of the archipelago. The prevailing winds are the *monsoons* which make themselves felt to varying extent because of the different periods of warming of the two continents. When in the summer of the northern hemisphere (June to September) the upward air movements are predominant, then the archipelago, too, witnesses air currents bound for the northern continent, winds resulting in considerable rainfall in the northern regions. In this same period it is winter in Australia — the south continent; the high-pressure, dry winds blow toward the archipelago, provoking droughts which are particularly prominent in the closest island range — the *Little Sunda islands*, the *southeast Maluku* islands, and *eastern Java*, too. Nota bene, the monsoon effect is felt here most markedly — in some places and years not a single drop of rain does fall from June till September. That is what people call here "musim panas" (arid season) or simply "musim timur" because of the southeasterly winds (eastern monsoon). (Fig. 2).

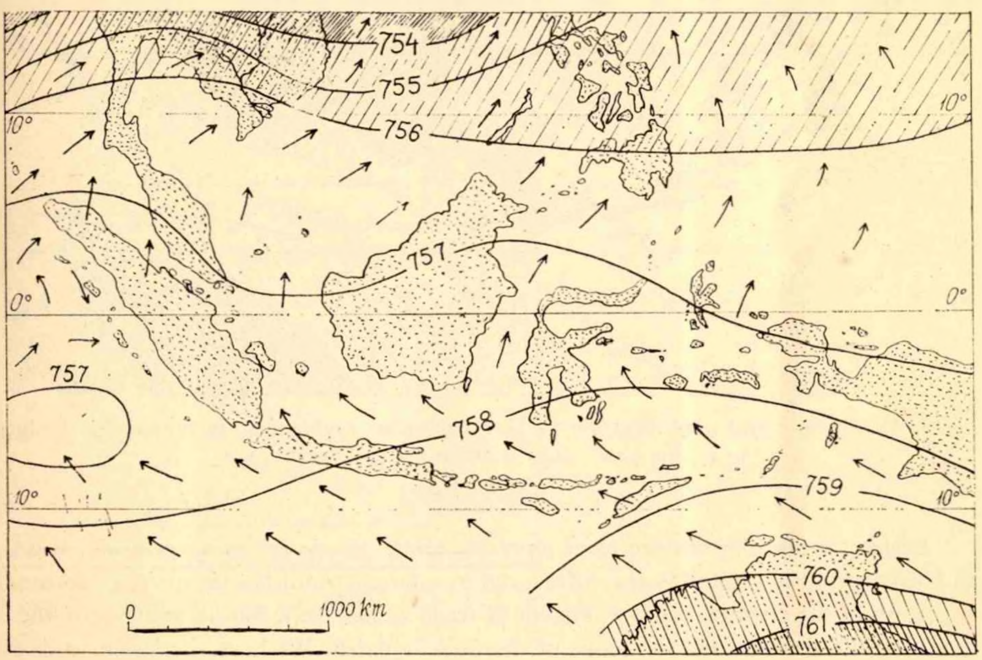


Fig. 2. Air pressure and wind direction in the East-Indian Archipelago in July (according to C. BRAAK, after R. W. VAN BEMMELEN)

After a transitional, changeable period, the situation changes in the winter of the northern hemisphere (i. e. from December till March as a rule). In the interior of the Asiatic continent a high-pressure centre is formed, from where the air masses flow south- and southwestwards. Whereas in Southeast India these air-currents result in a comparatively drier season, the air masses which become more moist after travelling their long way through the seas, cause precipitations in many places throughout the archipelago. The more so, in the south zone — South Sulawesi, Southeast Maluku islands, etc. — the rainy season is in this part of the year, a season which is called here "musim hudjan" (season of rains) or "musim barat" (western monsoon) because of the predominance of northwesterly winds. From the islands the air masses flow toward the centre of the Australian contient, where the upward air-current (low air pressure) predominates in this period of the year. (Fig. 3).

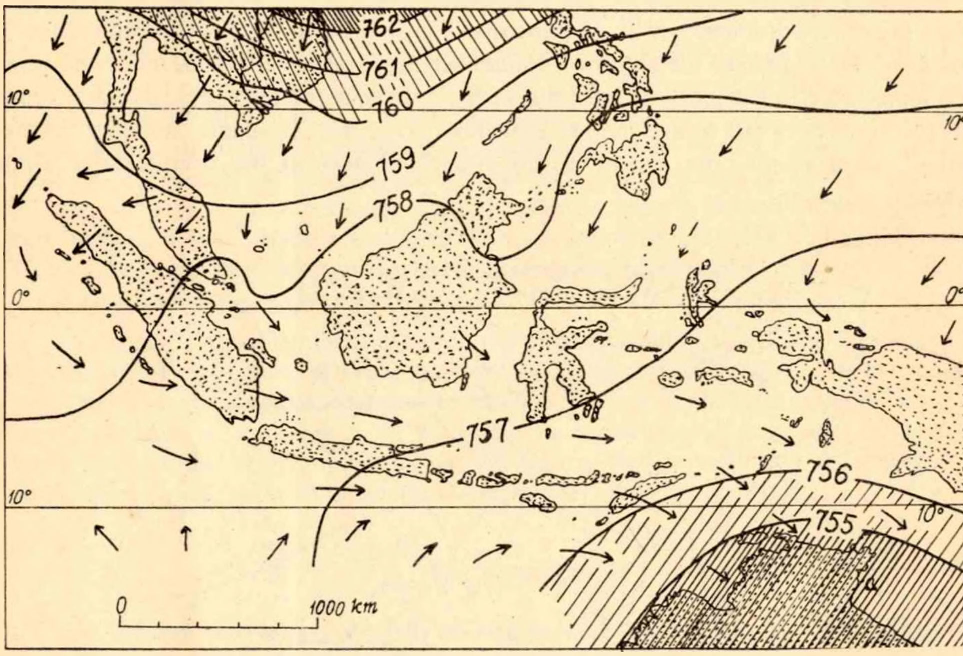


Fig. 3. Air pressure and wind direction in the East-Indian Archipelago in January (according to C. BRAAK, after R.W. VAN BEMMELEN)

Beside the afore-mentioned chief monsoon effect, the system of air pressure, winds, and distribution of rainfall is also influenced by a number of other factors (e.g. seasonal migration of the climatic equator, system of trade winds, etc.), but an analysis of these agents would pass beyond the scope of the present paper. We have, however, to dwell upon the chief characteristics of rainfall, as the distribution of rainfall largely affects the denudation of the karst areas.

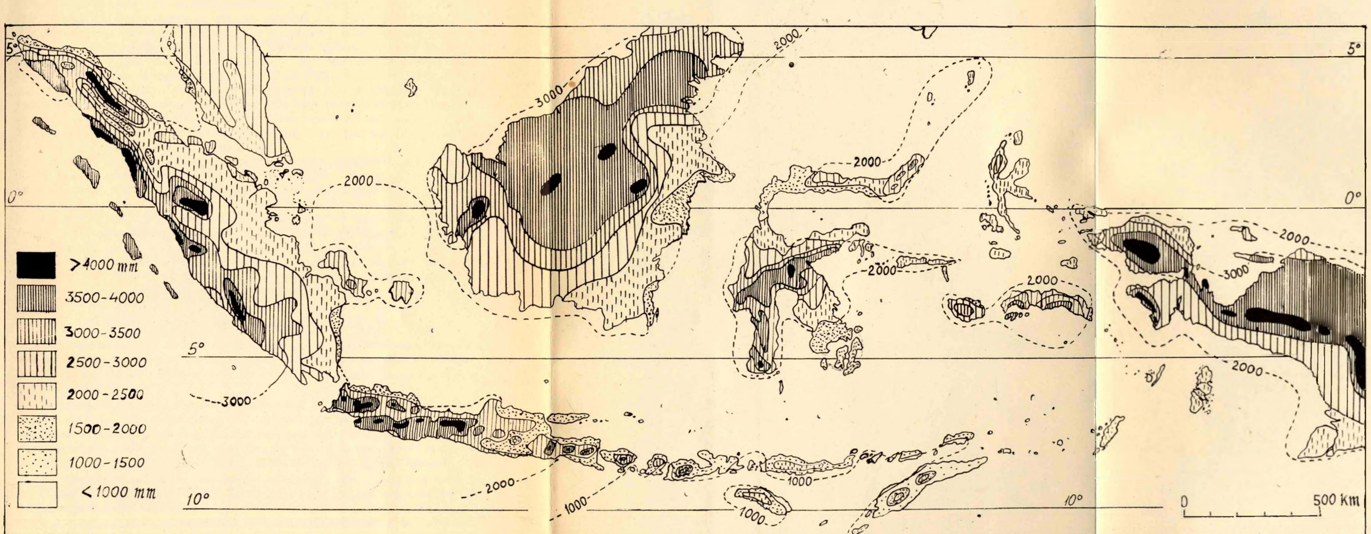


Fig. 4. Rainfall in the Indonesian Archipelago (from KLAUS WYRTKI)

In T a b l e 1 the author has assembled the precipitation data which had given characteristic values for the major karst areas of Indonesia (8). The data readily show, the areas of *western Java*, *northeast Kalimantan*, *southwest Sulawesi*, *central Maluku*, and *west Irian* enjoy the highest amount of rainfall, while *southeast Java* and the *Little Sunda islands* have comparatively little precipitation. (Fig. 4). The average value obtained for the 18 stations of different karst regions presented here is 2,462 mm per year. T a b l e 1 also indicates that in the individual areas the round-the-year distribution of rainfall is characterized by a very sharp seasonality due to monsoon effect. On *east Java*, the *Little Sunda islands*, *southwest Sulawesi* and the *southeast Maluku* islands the amount of June-to-September precipitation hardly attains a few millimeters a month, much of which immediately evaporates as a result of the high temperature. 80 to 90 per cent of the annual amount of precipitation are concentrated to the December-to-March period when the heavy showers recurring every day wear away the surface of the karst areas. As shown by statistics, the number of the rainy days of the rainy season averages 15 to 20 a month, whereas in the dry season this figure is not higher than 1 to 2, as shown by long-term statistic information (Table 2).
From the point of view of the intensity of karstification, the amount of rain falling during 24 hours is very important. As shown by long-term observations, the rainfall maxima of 18 stations (the highest amount of precipitation measured during 24 hours) yield an average figure of 124 mm which is considerably higher than the results obtained in the temperate belt. The cloudburst of an August day of 1933 which amounted to 702 mm at the *Ambon* meteorologic station is held for a record even within the Indonesian Archipelago. In studying the records of the gauging stations 6 additional rainy days were found on which from 600 to 700 mm of rain had fallen, values of 500 to 600 mm could be found for another 10 days. I think, it needs no commentary how enormous devastation may result from the precipitation of this colossal amount of water on a karsted surface.

4. **Vegetation and animal kingdom**

The flora and fauna of the karst regions of the Indonesian Archipelago will be dealt with only to the extent required, on the one hand, by a portray of the physical and biological patterns of the karst landscapes, on the other hand, by the interpretation of geomorphologic phenomena.

The tropical, equatorial climatic conditions (high temperature, abundant rainfall, vapour saturation, lack of cold season, etc.) are, as a rule, favourable for the development of exuberant evergreen, tropical vegetation. Although the soil conditions on the limestone surfaces are far from being so advantageous as e. g. on the slopes of volcanoes, a very rich, multi-level, dense forest plant cover has been developed nevertheless.

The elevation a. s. l. of the karst regions of Indonesia varies, in general, between 200 and 600 m; single blocks soaring to 1,000 m height are rare; and high karst plateaus are known in the central mountain range of *West Irian* only. If the latter be disregarded, it will no longer be necessary, nor possible, to examine the vegetation of the karst areas according to orographic zones, as the rest of the archipelago is mainly composed of areas of low to medium elevation.

Accordingly, the external pattern of the karst flora is additionally influenced by
1. the quantitative changes in the amount of rainfall and
2. interference of man.

Monthly and annual mean rainfall in

Karst region	Station	Number of years of obser-vation	Height above sea level in meters	Jan.	Feb.	March
Central Sumatra	Pajakumbuh	63	512	263	207	235
Central Sumatra	Buo	27	260	217	159	171
Kalapanunggal, W. Java	Kalapanunggal	34	100	379	391	422
Nusa Kambangan, Central Java	Tjilatjap	63	6	306	267	302
G. Sewu, Central Java	Wonosari	33	210	306	310	254
N. Barung (SE-Java)	Puger	56	3	232	194	201
Java NE-area	Bodjonegoro	62	15	292	270	289
Blambangan (SE-Java)	Bantenan	27	1	242	182	185
Nusa Penida (N-Coast)	Sampalan	11	4	215	126	120
Sumba	Waikabubak	30	360	298	292	317
Timor	Kupang	63	2	386	347	234
NE-Kalimantan	Muarawahau	13	40	158	163	231
SW-Sulawesi	Maros	30	5	761	536	411
Ambon-Hitu	Ambon	63	1	128	116	134
Tanimbar	Saumlaki	30	?	335	223	239
Manokwari-Karst (West-Irian)	Manokwari	40	30	305	239	335
Ajamaru-Karst (West-Irian)	Aitinjo	6	150	384	271	292
Fak-Fak-Mountains	Fak-Fak	40	52	265	230	231

[ ] the highest monthly mean rainfall.

Mean rainfall in mm									
Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
247	170	119	96	151	168	233	241	[263]	2393
195	145	99	59	114	199	235	[241]	198	2032
404	344	200	124	162	175	354	395	355	3705
293	298	336	239	185	186	439	[476]	393	3720
185	106	77	22	12	25	76	188	248	1809
93	65	44	26	14	21	52	139	230	1311
174	114	71	34	26	42	83	186	291	1872
120	82	95	39	25	30	49	115	203	1367
76	39	65	40	15	5	39	82	141	963
156	98	51	33	33	37	50	201	[320]	1895
65	30	10	5	2	2	17	83	232	1413
312	308	231	155	144	152	145	260	[321]	2580
237	148	84	50	17	22	80	238	591	3175
283	529	[634]	598	416	240	157	110	130	3475
285	308	171	81	14	6	20	51	218	1951
283	197	184	137	141	126	119	164	261	2391
467	762	[609]	358	436	435	207	243	385	4819
304	359	[367]	312	272	316	324	231	226	3437
							Mean rainfall		2462

Mean number of rainy days, mean daily maximum and absolute maximum of

Karst region	Station	Mean					
		Jan.	Feb.	March	Ápr.	May	June
Central Sumatra	Pajakumbuh	16,8	12,3	15,5	16,1	12,0	9,3
Central Sumatra	Buo	12,6	10,1	11,5	11,2	9,1	5,6
Kalapanunggal, W. Java	Kalapanunggal	18,1	17,3	[18.5]	15,5	13.0	9,3
Nusa Kambangan Central-Java	Tjilatjap	19,2	16,8	17,5	17,6	15,3	13,3
G. Sewu Central-Java	Wonosari (Tjendogo)	[16,7]	16,3	15,3	9,8	6,8	5,1
N. Barung (SE-Java)	Puger	11,3	10,2	10,0	5,3	3.8	3,1
Java NE area	Bodjonegoro	[18,7]	16,7	16,7	11,3	8,5	5,3
Blambangan (SE-Java)	Bantenan	[14,5]	11,8	11,9	9,2	6,5	5.4
Nusa Penida (N-coast)	Sampalan	[13,4]	8,9	8,3	6,9	4,2	5,5
Sumba	Waikabubak	[16,8]	[16,8]	17,0	9,8	6,1	3,0
Timor	Kupang	[18,1]	15,5	13,2	5,0	2,5	1,2
NE-Kalimantan	Muarawahau	9,5	8,5	10,9	12,7	[12.8]	11,1
SW-Sulawesi	Maros	[22,4]	17,5	17,0	11,8	9,9	7,1
Ambon-Hitu	Ambon	13,6	12,1	14,5	18,5	22,9	[23,8]
Tanimbar	Saumlaki	[16,3]	14,2	13,9	12.6	12,9	10,6
Manokwari-Karst (West-Irian)	Manokwari	[16,1]	12,8	14,8	13,6	11,3	11,5
Ajamaru-Karst (West-Irian)	Aitinjo	20.8	14,2	16,4	19,8	[24.6]	20,2
Fak-Fak-Mountains (West-Irian)	Fak-Fak	14,6	13,1	14,4	14.5	15,2	[15.3]

The frame [ ] means the highest monthly mean number of rainy days.

rainfall in different karst regions in Indonesia Table 2

number of rainy days							Mean daily maximum in a month mm	Absolute maximum	
July	Aug.	Sept.	Oct.	Nov.	Dec.	Year		first mm	second mm
8,2	11,1	12,3	16,3	17,1	17,4	164,4	91	180	160
4,6	7,5	10.5	12.0	13,3	12,5	120.5	88	126	120
6,2	6,6	7,9	13,1	15,5	16,4	157,4	119	190	170
11.5	9.6	10,0	16.7	20,1	20,2	187,8	164	272	260
2,2	1,3	1,8	5,5	10,8	15,2	106,8	98	167	140
1,9	1,2	1,5	3,8	8,4	11,6	72,1	103	189	151
2,9	2.2	2.9	6,2	12,6	17,3	121,3	95	157	144
3,6	2,8	1,8	3,5	7,0	12,1	90,1	92	160	155
3,5	1,3	0.8	2,5	6,5	7,5	69,3	106	195	173
3,0	2,3	2,7	5.2	11,7	16,3	110,7	104	210	170
0,8	0,3	0,3	1,3	6,9	14,7	79,8	124	197	190
7,4	7,5	7,8	7,5	12.5	12,7	120,9	115	161	137
3,7	1,3	1,4	5,4	12,0	20,0	129,5	175	326	269
22.6	19,9	15,4	13,0	10,6	12,8	199,7	188	702	303
7,6	2,9	1,5	1,7	4,4	12,3	110,9	134	350	210
9,7	10,0	9,1	9,3	10.4	14,4:	143.0	131	265	237
15,4	22,0	17,7	12.2	17,0	17,6	217,9	126	132	130
4,8	14,3	14,2	13,9	10,6	12,3	167,2	155	280	264
					Mean values	131,6	123	237	188

The annual amount of the *precipitation* exceeds 1,200 to 1,500 mm in most of the karsted lansdcapes, which is enough for the formation of a tropical tree-vegetation or for its preservation, respectively. In some parts of the Little Sunda islands, especially on the northeast sides, however, the amount of precipitation is now and there inferior to 1,000 mm; the less so, a droughty period lasting for several month may occur. For this reason a karren-type landscape has been developed in these areas *(N. Penida, Sumba, Timor)*. The surface is covered by a grassy vegetation *(alang-alang)* which dries out in the droughty season.

Man's intervention has, except for Java, but little disturbed the primary forest vegetation of the karst areas, as over much of the archipelago the density of population is not so high as to require reclamation of the limestone surfaces rather disadvantageous for tilling. On the overpopulated Java, however, people has settled even on the comparatively large limestone areas; the primary forests were burnt; and people have made efforts to preserve humidity and reclaim the soil cover by developing terraces on the steep mountain slopes. The one-time forests have been replaced by teak plantations in some of the more rocky slopes, unsuitable for irrigation. Where repeated human intervention does not help afforestation, the one-time forest is now represented only by a dense thicket or alang-alang; and higher-organized plants grow at best in the deep rifts, whereinto soil portions are brought by slope-wash.

The specific composition of the forests covering the karsted plateaus is rather varied, a feature characteristic of the tropical forests. Usually three tree strata have been developed: the 5- to 10-m high shrubby-lianeous vegetation underlies the foliage of 20- to 30-m high tropical trees, above which 40- to 50-m tall, smooth, gray trunked giant trees soar like enormous mushrooms, forming scattered canopies of foliage, 10 to 20 m across, above the middle leafage carpet underneath. The dense, coherent foliage markedly reduces the penetration of sunshine. In spite of this fact, a rich underwood can be found everywhere. This type of vegetation is characteristic of the undisturbed cone-featured karst areas, and karst plateaus of low elevation. In areas, however, where the topography consists of steep limestone walls, of rugged rocky land dissected by clefts of 1-m spacing, there is an impenetrably thick vegetation cover — trees and thicket interlaced by countless lianes. The roots of the trees penetrate as deep as 20 to 30 m down the fissures and the masses of lianes crawling in all directions spin a green carpet even on the vertical precipices of rock.

Since a considerable part of the karst areas is inaccessible to man, the karst offers good protection for the *animal kingdom*. On Sumatra *tiger*, *leopard* and of course, many races of *monkey*, and *wild-hog*, etc. still live in great number in the karst areas. The populated karst areas of *Java*, however, are substantially poorer in big games than the former island, though *monkeys* are still abundant. Going eastward, we can encounter more and more *deers*, *elk*, *wild-boars*, *giant lizards*, which on the Aru islands are associated with the representatives of the Australian faunal region — *kangaroos* and *cassowaries*. Safety of man is endangered by the omnipresent *snakes* of a great number of species. In the karst forests, especially on the east, there are countless birds, too. In the karsted caverns there are hosts of *bats*, while their larger relatives — the *flying foxes* — dwell within the foliage of tall trees.

5. Hydrography

A general hydrographic peculiarity of limestone areas is the development of subsurface hydrographic systems. Because of the high solubility of the rock and its consequent jointed and cavernous structure, the rains falling onto its surface are — in case of proper emplacement of the rock mass — drained partly underground. The water swallowed by the karst masses dissolves, depending on the carbon dioxide content, a certain amount of rock and carries it in dissolved form. This phenomenon typical of karst areas in general occurs in the tropical karst areas as well, but in the latter they show some quantitative divergences with reference to the former, which is due to the peculiar climatic conditions.

Hydrodynamically, we should emphasize the copious supply of meteoric waters yielded by heavy seasonal rains, a factor to be considered first of all. Although the rate of evaporation is markedly higher than in the temperate zone, the ratio of runoff — partly torrential waters running down valleys, partly underground rivers — is, however, higher than in the temperate zone. As a result of torrential rain-showers of random distribution in time, the springs connected with the free sink-holes are characterized by very unsteady yields. The minor karst springs run dry in the rainless season, as e.g. in some parts of the Little Sunda islands they have hardly any recharge for 3 to 4 month each year. The karst water level changes according to the variation of the dry and rainy seasons. The emplacement of the karst springs and the water supply of the wells sunk in the region are also irregular and uncertain, as the paths and passageways of the underground water flows may often vary. Comparatively large amounts of waste are carried by water through the open sink-holes into the underground galleries during showers. Accumulation of waste fill and plug now and there the underground passages, so that water has to seek for new paths.

The *physico-chemical characteristics* of the Indoneasian karst areas also differ from the corresponding parameters of the temperate zone, difference due, again, to climatic conditions in the first place. The data of hundreds of water analyses carried out in various karst areas can be summarized as follows:

Combined data of the karst springs studied:

	Limiting values	*Average values*
Levels of emergence to surface	1 to 380 m a.s.l.	about 30 m a.s.l.
Yields	8 to 300 000 l/min.	about 22 000 l/min
Water temperatures	23.3 to 27.6°C	25.9°C
pH	6.8 to 7.3	7.1
Ca-ion content	24.3 to 132.9 mg/l	65.2 mg/l
Mg-ion content	3.2 to 30.4 mg/l	8.4 mg/l
$CaCO_3$ content	114.2 to 415.8 mg/l	196.1 mg/l
Carbonate hardness	6.4 to 23.3 German degrees	11.0 German degrees

According to the chemical analyses, the average carbonate content of 37 karst springs combined was found to be higher than the figures of other tropical karst areas. (H. Lehmann quotes 145 mg/l of $CaCO_3$ of 8.2 German hardness degrees from *Cuba*; A. Gerstenhauer measured 158 mg/l (8.9 German degrees) of dissolved $CaCO_3$ on the cone-featured *Tabasco* karst of Mexico; whereas J. Corbel found the *Kissimmee* spring to be as hard as 11.0 German degrees (196 mg/l); the members of the German hydrogeological expedition of 1961 (H. Flathe and D. Pfeiffer) measured 9.5 to 15.5 German degrees of hardness for karst spring-waters of *G. Sewu* and 10 to 19 German degrees on the *Madura* island at the middle of the rainless season.)

The tropical karst waters—inclusive of the spring waters of the Indonesian karst regions — are considerably softer than their temperate-zone equivalents. So for instance, the average value obtained for hundreds of chemical analyses of the five largest karst springs of Hungary was 17.9 German degrees of hardness (319.5 mg/l $CaCO_3$; average water temperature 11°C).

The analyses were, however, not restricted to karst springs alone, but all running or standing waters available anywhere (both on the surface and underground) on the karsted areas were analysed. Let me quote some combined average values from a separate study devoted to the synthesis of the hydrochemical analyses:

	Number of samples analysed	Temperature of water °C	pH	Chemical analyses			
				Ca^{++} mg/l	Mg^{++} mg/l	Carbonate hardness $CaCO_3$	
						mg/l	German degrees
I. Surface waters							
a) Small standing water bodies on karsted surfaces (puddles after rains, 100 m^3)	12	25.2	6.9	—	—	149.8	8.4
b) Karst ponds, dolina pools (G. Sewu)	4	28.8	6.7	—	—	78.6	4.4
c) Water masses running down the dry valleys of karsted areas during torrential rains	2	23.5	7.0	33.6	5.8	106.2	6.0
d) Streams swallowed by the sink-holes of the karst after travelling down the slope of an impervious karst edge (exogenic underground rivers)	4	26.8	6,8	20.7	7.7	84.4	4.7
II. Subsurface waters							
a) Seeping karst waters (captured in general on the roof of caves and rock salients)	29	24.3	7.1	66.1	7.8	172.6	9.7
b) Underground rivers, and pools (concentrated water streams)	6	25.5	7.1	79.0	7.2	222.7	12.5

6. Karstic denudation

In the *humid tropical areas*, because of the high temperature and the abundant rainfall, the weathering of the rocks exposed as well as the removal and redeposition of the weathered material are comparatively intensive processes. The strong leaching of the ground by rainwater, a process leading to lateritization, is well-known. The weathering of the rocks is promoted by the "erosion" of the roots of the dense vegetation, the mass-decay of organic substances, the formation of various organic acids, human activity, etc.

The rate of wearing away of the surface materials can be measured by indirect methods only — systematic measurement of the rate of sediment transport — both dissolved and solid — by the rivers draining the area. Information of this kind has been collected all over the world, and some data are available on Indonesia as well. Among other authors, it was Rutten who studied the rate of erosion in the archipelago. Of his paper, I shall quote the 10 most striking values confronted with 10 counterparts from the drainage basins of, mainly temperate-belt, rivers, as found by back-calculation (7)

Indonesia:		*Comparative data:*	
Pengaran river	>3.7 mm/year	Durance (South France)	0.8 mm/year
Var river	2.64 mm/year	Tagliamento (Italy)	0.5 mm/year
Seraju river	1.6 mm/year	Rhine (upper reaches, Germany)	0.46 mm/year
Djranggang river	1.48 mm/year	Kander (Switzerland)	0.37 mm/year
Tjilamaja river	1.4 mm/year	Piave (North Italy)	0.37 mm/year
Deli river	0.9 mm/year	Ganges (India)	0.29 mm/year
Lusi river	0.88 mm/year	Reuss (Switzerland)	0.25 mm/year
Banjuputih river	0.4 mm/year	Irrawaddy (Burma)	0.24 mm/year
Tjimanuk river	0.4 mm/year	Po (North Italy)	0.22 mm/year
Tadjum river	0.3 mm/year	Amu-Darja (Soviet Union, Turkmenistan)	0.12 mm/year

The rivers obtained some of their waste in areas under karstification. The ratio of karst-derived sediment is, however, unknown. Denudation in Indonesia is, on the average, 3 to 4 times that in the temperate belt. According to Feliciano and Cruz (Bemmelen), the mean rate of denudation in the drainage basin of the *Angel* river (732 km^2), Philippines, NE of Manila, attains nearly 3 mm a year.

As found by Van Dijk and Vogelzang (Bemmelen), the rate of denudation in the drainage area of the *Tjilutung* river (southwest slope of *Tjareme* volcano) is as follows:

	data of 1911–1912	data of 1934–1935
removal of solid material	0.9 mm/year	1.9 mm/year
removal in dissolved form	0.08 mm/year	0.07 mm/year
total denudation (in round figures)	1.0 mm/year	2.0 mm/year

No reliable information on the rate of denudation of the karsted area-units is available. Relying on observations in springs, I sampled data to assess the rate of wearing away by corrosion (wearing away through chemical dissolution). This has led to the following results:

Drainage basin of the *Sanghi* river (*G. Saribu*, central Sumatra)	0.063 mm/year
Kalapanunggal karst region (western Java)	0.099 mm/year
Drainage area of underground river *Baron* (*G. Sewu*, central Java)	0.086 mm/year
Southwest Sulawesi	0.083 mm/year
Average	0.083 mm/year

For comparison, I should like to note that hundreds of data sampled from the five largest karst areas of Hungary have yielded a value of 0.020 mm per annum for the rate of denudation in Hungary.

On the rate of mechanical erosion (wearing away of rock matter in solid form by running water) in the karst regions of Indonesia only a few data are available. From these, it can be calculated that the karstic mechanical denudation varies between 0.1 and 0.4 mm a year. Consequently, it is substantially greater than the rate of corrosion, but its sum total is nonetheless inferior to the figures pertaining to nonlimestone areas (1 to 3 mm a year). This is quite reasonable, as clays, volcanic breccias, and tuffs are much less hard than limestones; thus they are more liable to weathering. This is, after all, the reason why the tropical karst areas have so striking features imposing karst pinnacles soaring above the surrounding non-karsted areas.

7. Morphology

The eventful geological past of the Indonesian Archipelago and especially the regional differences in the history of the *Pliocene* and *Pleistocene* epochs are manifested by the abundance and variety of landforms in the Indonesian karst areas. The diversity of karst features has been promoted by the fact that the karsted rocks have very different petrographic characteristics: from the unconsolidated *Quaternary* coral reef surfaces back to *Paleozoic* crystalline limestones carbonate, sediments of all ages and structure can be encountered in the karst areas of Indonesia.

The basic feature distinguishing the Indonesian karst areas from the klassical karst formations of Europe can be termed *tropical*. The karst landforms in any part of Earth reflect the given climatic conditions; consequently, in the equatorial Indonesian Archipelago the karst phenomena are represented by tropical landforms. What is the essence of this distinctive feature? First of all, it is manifested by the *large forms* of the karsted surfaces. The temperate-belt karst plateaus are characterized by broad, dishlike depressions — dolines, uvalas, and poljes; the positive forms such as pinnacles and cones being subordinate — isolated limestone klippens (hums in the poljes of the Dinarian Karst). The tropical karst plateaus — inclusive of those of the Indonesian Archipelago — are characterized, on the contrary, by the predominance of the *emergent* or *positive forms*, the multitude of karst hills and cones, while depressions, if any, are insignificant.

The development of the two different climatic types of karst morphology is the result of differences in precipitations. These differences are not only quantitative, but also qualitative, as discussed above. Coupled with appropriate geological preconditions, the heavy torrential tropical rains provide large scope, first of all, for sheetwash on emergent karst blocks lying high above the base level, a process during which the erosion by deep torrential streams entwining the limestone block results in the formation of limestone „islands". On the other hand, the slow rains typical of the temperate belt are favourable for the formation of shallow depressions produced by the dissolving effect of the infiltrating rain water. The process cannot be, however, restricted to the differences in the amount and intensity of rainfall, though this is fundamental, but the temperature aspect of the process and the resultant differences in soil cover and vegetation have also to be taken into consideration.

The karst regions of the Indonesian Archipelago form a number of sub-types within the group of *tropical landforms*. The most significant and splendid types, confined to the tropical belt alone, are the so-called *conical karst* or cone-featured karst (Kegelkarst in German) and the *pinnacled karst* (Turmkarst in German). The first one is characterized by hosts of limestone cones of arched base contour, rising to 50 to 100 m relative height, with slope angles of 30 to 45° and usually rounded summits (e.g. *Gunung Sewu*, Java). (Fig. 5.) The cones occur in part completely detached, while others are linked into chains ("gerichteter Karst"). The second type includes higher hills—steep, rocky pinnacles of 100 to 300 m height, with an angular base pattern and zig-zagged summit, which on

Fig. 5. The sinusoidal (conical) karst region of Gunung Sewu (Middle Java, along the shores of the Indian Ocean)

the edges are isolated, to become a coherent, impenetrable, rugged rocky landscape, interlaced by rifts and fissures, toward the centre of the plateau. (The best example for this in Indonesia is the *Maros* Karst Region, SW Sulawesi or *Harau* and *Gunung Saribu*, Sumatra.) (Fig. 6.) The formation of the karstic cones and pinnacles represents an instantaneous state of one and the same process—tropical denudation. So it is natural that there are numerous forms of transition and differences in the degree of development between the two leading types.

Whereas the tropical karst features are, in a common sense, the manifestations of climatic morphogenesis, the individual pinnacle and cone forms are in turn due to differences in geological setting. Pinnacled mountain forms have usually developed in areas, where thick masses of compact, hard, well-karsting limestone had been lifted comparatively high by late tectonic movements. The karst-induced mountain features are though not agecontrolled, yet it is obvious that the steep pinnacles resisting

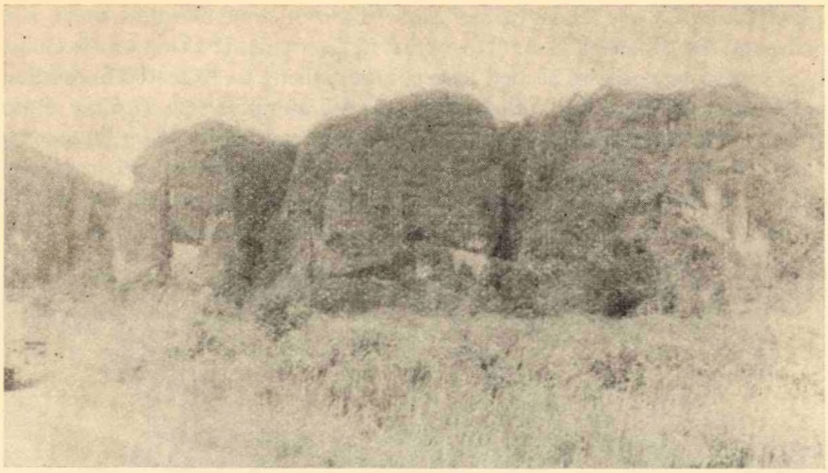


Fig. 6. The pinnacled ("Turm"-) karst region of Harau, Central Sumatra. (Entrance to the Harau-canyon from the north.)

erosion have been sculptured out of rocks which had underwent proper diagenesis. For these reasons, in Indonesia true karst pinnacles have been developed of *Paleogene* or *pre-Paleogene* limestones (the pinnacled karst of southwest Sulawesi is built up of *Eocene* limestones, the karst pinnacles of the *Sinamar* river, Sumatra, of *Carboniferous* limestones). On the contrary, cone-shaped features occur in most of the cases where the rocks are of comparatively looser structure (of later origin), not high-lifted and of rather low relief (e.g. *Ajamaru* Karst, Irian-Barat; *Gunung Sewu*, Java, etc. are, all, composed of *Miocene* limestones). Some of the cone-featured karst landscapes has been developed on the basis of comparatively thin limestone strata; the base of the isolated cones is sometimes made up of impervious rocks (e.g. *Gunung Sewu* in the region of *Punung*). Conical features may be formed on the surface of thick massifs of compact, old limestone, if the limestone blocks lie relatively little higher than the base level. If in the later history of the area the uplifting of the karst massif is speeded up, a wide variety of mixed conical and pinnacled features may evolve (west part of *Gunung Sewu*). Hence, all things considered, under appropriate geological conditions, the shapes of the tropical karst hills and mounts are controlled by laws governing the processes of vertical and lateral fluviatile erosion. In this connection, lateral erosion may be largely associated with corrosion-made under-carving (*Maros* Karst Region, Southwest Sulawesi).

In the humid tropical regions such as the Indonesian Archipelago, the cone- and pinnacle-shaped landforms mentioned in the former paragraph cannot always be encountered. This may be due to many a cause such as the emplacement of the limestone mass (very little higher than base level, e.g. *Kai-Ketjil* island, Fig. 7.), initial stage of karstification (karst block uplifted to a sufficient height, but karstic denudation active only for a comparatively short time, hence still initial forms of cones available), the young age of rock and its unconsolidated structure (*Late Pleistocene* coral and lamellibranch accumulations uplifted to considerable heights, e.g. near *Hitu*, *Ambon* island, etc.) (Fig. 8.)

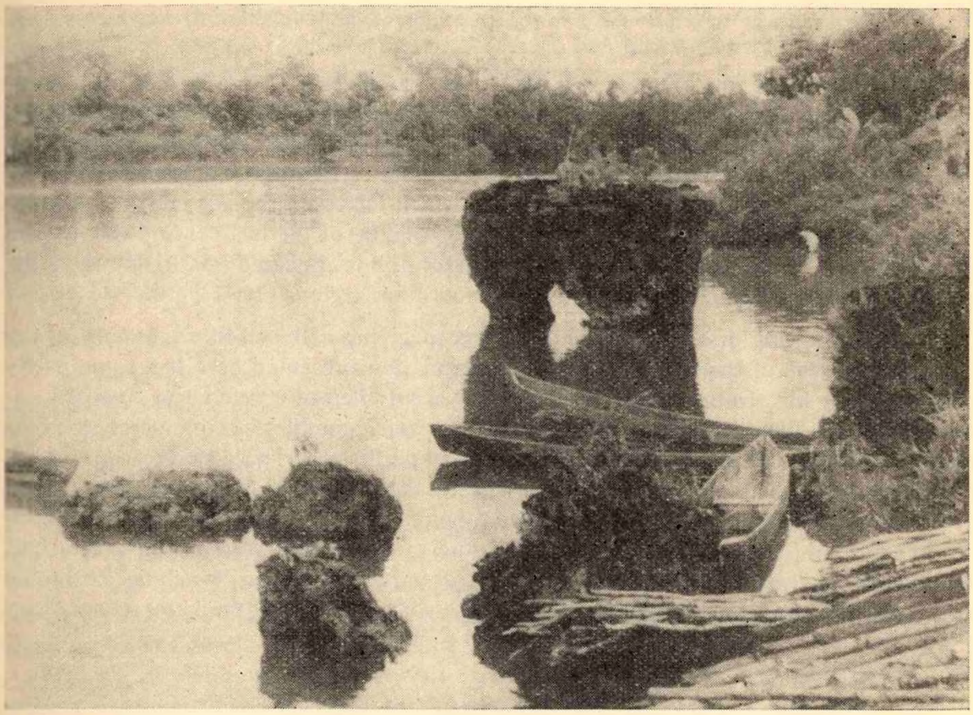


Fig. 7. Pliocene coral reliefs formed by abrasion — off Kai Ketjil island (SE Maluku Island Group)

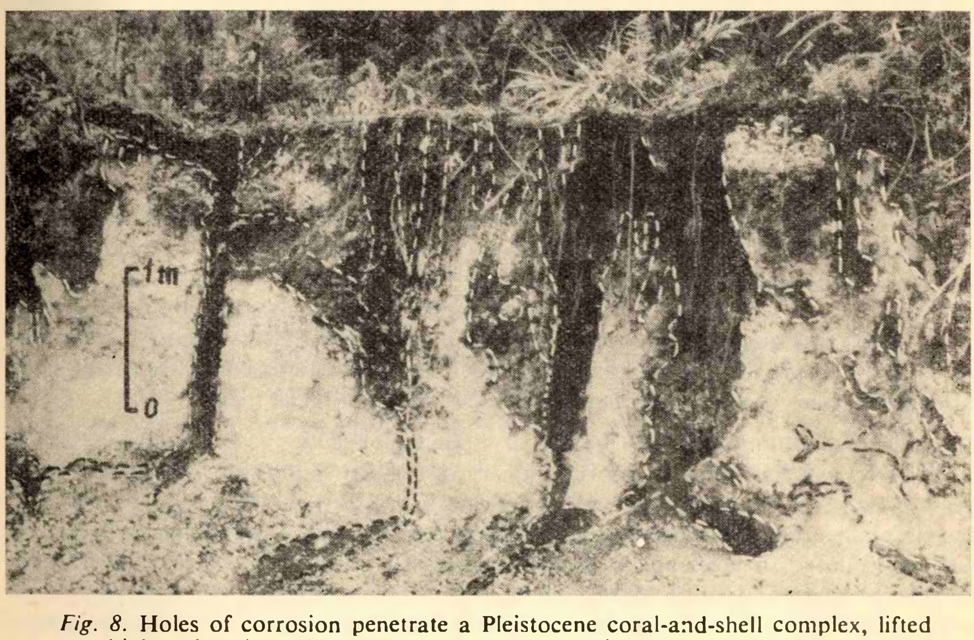


Fig. 8. Holes of corrosion penetrate a Pleistocene coral-and-shell complex, lifted to higher elevations (300 m above sea level) on Hitu Peninsula (Ambon island)

II. Schematical description of a few karst region of the Indonesian Archipelago

The karst areas are in most of the cases an obstacle, a handicap to economic progress. Hence, it is no accident that under Dutch administration the karst regions of the archipelago were dealt with hardly any. Particularly faint are the geomorphological records concerning the karst areas of the archipelago. The only exception to this rule seems to be the *G. Sewu* Karst Area of Java, which has been the subject of a number of reports, scientific papers, and essays since the middle of the last century (20, 21, 28, 35, 36, 42, 54). In recent years more detailed descriptions appeared (60, 61) on the karst areas of *Southwest Sulawesi*, and brief reports on other regions (26, 27, 49).

In the following discussion I shall attempt at giving a sketch-like summary of the major karst areas of the archipelago. The information presented here has come partly from my own observations, partly the rather scant literature references available to me have been made use of. The review is far from being complete, being merely the first attempt at summarizing the investigations hitherto performed. There are scores of areas in the archipelago, which have been left blank on the geological maps, though not even the coloured parts do mean in every case that the respective area has been geomorphologically explored. Particularly unfavourable is the situation in *West Irian*, in the centre of some of the *Maluku* islands, and in some central parts of *Sulawesi*. Much has still to be done, however, on *Kalimantan* and *Sumatra* too, where especially the karst morphology is unexplored.

1. Sumatra

Large western island of the Indonesian Archipelago, the 435 000 km^2 Sumatra can be geologically outlined as follows. On the west shores facing the Indian Ocean, stretches a narrow, zig-zagged beach, of which emerge the NW-SE-striking *Barisan* Chains forming the island's axis. The mountains are characterized by a complex structure and history, mainly uncleared to date. The main role in their composition is played by *Permo-Carboniferous* deposits, granitic intrusions, and eruptive rocks of different ages, which have-been repeatedly folded, nappe-folded, and block-faulted by exogenic stresses. In addition, *Mesozoic* and *Tertiary* sediments were deposited.

In the central part of the *Barisan* Chains, a deep graben system — the *Semangko* depression — has formed along the strike. The zone of this fault in *Tertiary* and *Quaternary* times wittnessed heavy volcanism; in fact, 21 volcanoes can be regarded active even today. Here too, as throughout the archipelago, the highest elevations are these *Quaternary*, mainly andesitic, volcanoes (*Kerintji*, 3800 m, is the highest volcano of the archipelago). To the east, the *Barisan* Chains are joined by a hill country consisting of gradually flattening *Tertiary* deposits and then, by a broad diluvio-alluvial plain.

In the second tome of "The Geology of Indonesia" (Economic Geology) a collection of papers by van Bemmelen, a short summary of the distribution of limestones on the island of Sumatra has been given (p. 195). Accordingly, *Permo-Carboniferous* limestones occur in many areas within the *Barisan* Chains, from *Atjeh* to *central Sumatra*. Now and there rather large surfaces are limestone-covered. In some places, *Triassic* limestones are exposed (east and south shores of Lake *Toba* including the vicinities of *Prapat*, *Balige*, and *Kudu*, western Sumatra and *Djambi-Palembang* region); *Jurassic* limestones occur in small, scattered patches between *Atjeh* and *Palembang*; local occurrences of

Cretaceous limestones are also known; in many places the calcareous sediments of the *Paleogene* and *Neogene* epochs are being karsted. The limestone areas of Sumatra are usually characterized by scattering, block-like occurrence, and the rarity of contiguous karst plateaus, where typical landforms of tropical karst topography could evolve.

No detailed geomorphologic treatise of Sumatra's karst areas has so far been published. So I have had to rely on my own observations on the karst surfaces of central Sumatra, which I could visit in part. The area studied extends from the line of the Equator up to 1° of southern latitude, its surface being formed by the *Barisan* Chains and its intramontane basins. About 3.5 per cent of the 10 000 km^2 mountain area has been karsted (350 km^2). (Fig. 9.)

a) *Karst areas of Padang Highland, western Barisan*

As mentioned above, the *Barisan* Chains are split up into two chief ranges by the strikeward *Semangko Graben*. The west range 30 to 50 km broad, and the higher, lifts its steep-sloped peaks 1500 to 2000 m high above the coastal plain of central Sumatra. In its composition granitic intrusions, *Paleozoic* deposits, and omnipresent late volcanic cover are essential.

On the west slope of the high *Barisan* Chains a few limestone outcrops are known (e.g. east of *Padang*, near *Indarung*, where a big cement plant is being operated).

On the *Semangko-Graben*—facing east slope of the western *Barisan* Chains, the exposures of *Permo-Carboniferous* limestones are more frequent and extensive. The largest karst region has developed on the west side of Lake *Singkarak*.

The karstic features begin to occur 3 km southwest of *Tandjungsawah* on the lake shore and can be traced for about 20 km along the lake, in a 3- to 5-km-wide zone trending southeastward, to the village of *Kasih* (about 50-60 km^2). The karst-featured landscape slopes markedly toward the lake, being rendered impenetrable by hundreds of karst pillars and pinnacles covered by a dense plant cap. Man could intrude only into the eastern one-third of the region, where coffee plantations have been developed. The most striking point (1,625 m) of the ridge-forming west part of the karst region is *G. Gadang**. The karst ridge is broken through by a number of epigenetic valleys, resulting in a number of blocks. The individual karst blocks are drained merely by episodic surface streams (floodwaters rushing downslope during and after rainstorms), and the bulk of the hydrographic network has developed underground. On topographic maps, names referring to caves can be found.

South of the townlet of *Padangpadjang*, yet another 10- to 15-km^2-large karst block — northwest continuation of the *Singkarak Karst Region* — cane be found.

b) *Karsted areas of Pajakumbuh Basin*

Stretching around the town of *Pajakumbuh* over an 300 to 400 km^2 area of 500 to 600 m elevation, the basin has been produced by a natural dam due to eruptions of *Malintang* volcano still active at the end of the *Pleistocene* epoch. It was filled by wastes of diverted rivers, deposits, of which the karst masses, largely attacked by solution, emerge like islands.

In the north part of the basin, the levelled, flat, boggy surface is surrounded by vast, level karst plateaus made up of horizontally bedded *Eocene* (?) limestone. Incision

*The individual geographic names have been indicated in the present paper by adopting abbreviations used on Indonesian maps, such as G. = gunung — mountain; Bt. = bukit — hill, mount.

by basin-bound rivers from various directions has dissected the karst plateaus and given rise to delta-like reentrants bordered by vertical or even recessing, barren limestone walls of 100-200 m height. This landscape is very similar to the karst borderland near *Bantimurong*, southwest Sulawesi. The development of gradually broadening, vertical-walled basins and valleys is attributed by H. L e h m a n n to large-scale corrosion-made underwash at the topsoil level, a process particularly active in this area. Between *Tandjungpati* and *Taram* the spurs of the individual plateau portions emerge like islands from the alluvium of the basin. (Fig. 10.)

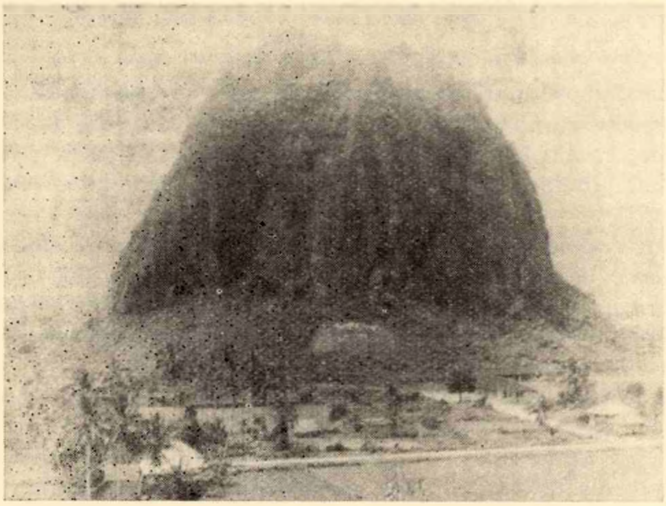


Fig. 10. A pinnacled karst hill in the Pajakumbuh basin, near village Taram (Central Sumatra)

A separate zone in the southeast half of the *Pajakumbuh Basin* is formed by *Permo-Carboniferous* limestones exposed in the largely folded, NW-SE-striking ranges of the *Barisan* Chains. They form no contiguous, large karst area, representing only isolated blocks. In the region of *Pakanarbaa* and *Alanglawas* – northeast foreland of *Malintang* volcano – scenic karst cone groups have been formed.

Touching the southwest foot of *Malintang* volcano, another karsted range extends parallel to the former, roughly along the line of the villages *Sungaidaerah-Baso* (northeast border of *Bukittingi Basin)-Situmbuk-Taluk*, i.e. in NW-SE direction.

c) *Karst areas of the Sinamar-Kvantan-Takung riverine*

The largest karsted range, including the most scenic features, *of central Sumatra* lies in the *Barisan* Chains, southeast of *Malintang* volcano. Since this dissected, rugged mountain region is still unnamed in literature, I refer to it in terms of the three largest marginal rivers representing the local base level. The range is a structural continuation of the limestone mountains bordering the *Pajakumbuh Basin* on the southwest, whose median parts are covered by the eruptiva of *Malintang* volcano.

The karst zone of the *Sinamar-Kvantan-Takung* riverine begins at the southeast foot of *Malintang* volcano with a pinnacled karst plateau between the village of *Halaban* and the *Sinamar* river, then it extends farther southeastward in the *G. Saribu* Mountains

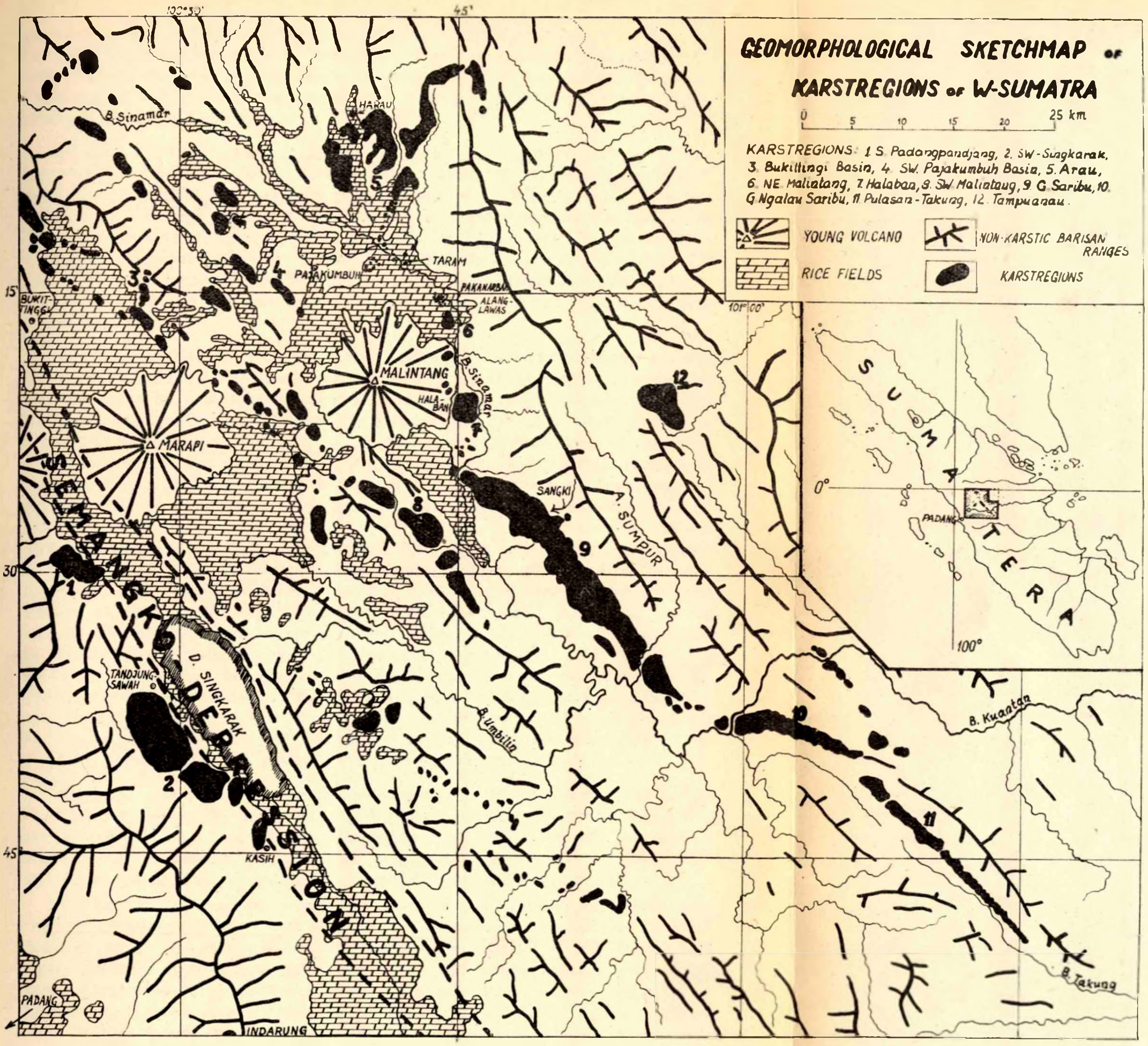

GEOMORPHOLOGICAL SKETCHMAP OF
KARSTREGIONS OF W-SUMATRA
0 5 10 15 20 25 km
KARSTREGIONS: 1. S. Padangpandjang, 2. SW-Singkarak, 3. Bukittinggi Basin, 4. SW. Pajakumbuh Basin, 5. Arau, 6. NE Malintang, 7. Halaban, 8. SW Malintang, 9. G. Saribu, 10. G. Ngalau Saribu, 11. Pulasan-Takung, 12. Tampunanau.
YOUNG VOLCANO
NON-KARSTIC BARISAN RANGES
RICE FIELDS
KARSTREGIONS
B. Sinamar
HARAU
PAJAKUMBUH
TARAM
PAKANBARU
ALANG-LAWAS
BUKIT-TINGGI
MALINTANG
HALA-BAN
B. Sinamar
MARAPI
SANGKI
A. SUMPUR
SEMANGKO DEPRESSION
TANDJUNG SAWAH
D. SINGKARAK
B. Umbilin
KASIH
PADANG
INDARUNG
B. Kuantan
B. Takung
SUMATERA
PADANG
0°
100°
101°00'
100°30'
45'
15'
30'
45'

Fig. 9.

on the east bank of the *Sinamar*. The most beautiful variety of karstic landforms has formed in the 26-km long and 4- to 5-km broad zone. A continuation of the mountains is *G. Ngalau Saribu* halved by the *Kvantan* river, which in turn is continued by the *Pulasan-Takung* range. The whole karst range is 80 to 85 km long, the size of the exposed karstic surface being about 200 km^2.

Geology. The rock making up the karst range is a very hard, compact, crystalline limestone dated from the *Carboniferous* period by fossils such as *Endothyra* and *Bigenerina.* The limestone zone has been preserved against a nappe background, whose softer rocks were less resistant to denudation. The north stretch of the karst zone *(G. Saribu)* is separated from the west by a fault *(Sinamar Graben)* from the so-called *Umbilin Nappe*, whereas the karst massif is thrust over the edge of the *Sumpur Granite Massif.* Here the gradually blockfaulted parts of the south stretch is bordered on the west by the exposed granite massif, the east border being represented by *Permo-Carboniferous* deposits.

Hydrology. The local base level of both surface and subsurface drainage systems of the long-stretching karsted range is represented, as a rule, by the rivers running on the west side of the mountains, parallel to the strike of the range. The narrow karsted belt forms but locally an independent hydrographic unit, being in general merely a transit area for the waters running down the impervious-rock-built slopes of the higher eastern mountains. These waters, flowing perpendicularly to the strike of the mountains, reach the natural limestone barrier in form of concentrated rivers which either carve out narrow canyons, epigenetic valleys, or, for lack of sufficient energy and erosive, scouring material, they sink into subsurface caverns, tending to reach underground the depression on the west side of the mountains. This peculiar hydrography is responsible for the dissection of the onetime continuous mountain range into isolated blocks – dismembered karst plateaus; in addition, this has produced the abundant transient cave systems, so typical of the karsted mountain range. (This latter is responsible for the name of the midde stretch of the mountains – *G. Ngalau Saribu* which can be translated as "Mountains of Thousand Caves".) On the north a part of the karsted range is cut off by the *Sinamar* river, farther southward the *Sario* and *Sumpur* rivers break through the mountains, then the *Kvantan* river – resulting from the confluence of the *Sinamar* with several other rivers – pushed its channel eastwards, across the mountains, again. The largest subsurface hydrographic system in *G. Saribu* has been developed by the *Sangki* river draining the granite slopes and sinking into the karst labyrinth.

Morphology. Pillars and pinnacles are characteristic of the entire mountain range. The karst belt emerges like a set of huge teeth above its gentle, rolling background. The hypsometric elevation of the hills varies between 500 and 900 m, but the relative height of the pinnacles as referred to their background attains only 150 to 300 m. No uniform summit level can be spoken of, except for minor, well-confined areas.

The karst region under consideration takes up 2000 to 3000 mm per year of high-intensity rainfall which helps wear away less resistant, loose rocks around the hard limestone range. At the same time, mechanical and chemical erosion by meteoric waters carves out deep furrows, canyons well within the limestone belt, dissecting it into irregular, dismembered blocks. Deepening of canyons leads in the comparatively broader karst areas *(G. Saribu)* to the formation of drainless, internal depressions, from where meteoric waters are drained by the fast-growing subsurface caverns.

As a result of the above evolution, the karst regions are devoid of the classic temperate-zone depression features such as dolines, uvalas, etc.; instead, they are dominated by deep intramontane systems of ravines, gullies, and collapse sinks. Major, comparatively broad depressions have formed along the east edges of the karst range, on an impervious surface. Materials wheathering more easily (granite, etc.) have been carried away by surface and subsurface rivers, a process that has resulted in the formation of marginal depressions from 100 to 200 m deep and more than two km^2 large.

Never-missing representatives of karstic landscape features are the caves, most of which are active drainage channels. The growth of the open underground spaces is largely promoted by the hard, crystalline abrasive material carried by the underground rivers from the eastern, mainly granitic, areas. In the higher-sited, inactive caverns large-scale stalactite formation is under way whereas the active caves are predominated by the sharp, erosion- and corrosion-made features of the bedrock. The caves are populated by countless bats, in the major cavern systems there is a rich troglobiont fauna (fish, crayfish, etc.) still unpublished.

2. Java

Explored best and most densely populated of all the islands of the Indonesian Archipelago are *Java* and the island of *Madura* belonging to the former both geographically and administratively. In the lithology of the 132 000-km^2 area the limestone sediments play an important part – about 4 per cent of the present-day surface (5500 km^2) are karst.

Stratigraphically, *Java* is almost exclusively represented by *Tertiary* and *Quaternary* deposits with interbedded volcanic materials. From the *Upper Eocene* to the *Pliocene*, some 6000 m of marine deposits were accumulated, of which considerable thick layers are represented by the *Miocene*. At the turn of the *Miocene* and *Pliocene*, in *Late Pliocene* time, and finally early in the *Quaternary*, these beds were folded and then uplifted by block-faulting movement along the W-E-trending *Javanese Anticline*. Controlled by faults, a rather heavy volcanism set in as early as Tertiary time, to attain its maximum late in the *Pleistocene*. Consequently, enormous amounts of eruptiva accumulated at the end of tertiary and in Quaternary times along the Javanese Anticline, a process that promoted amalgamation of a number of islands which lay in what is now Java at the end of Neogene time. The main morphologic characteristics of present-day Java are the smoking volcanic cones, locally exceeding 3000 m height. (Fig. 11.)

When studying a N-S section across Java, we can distinguish three different zones. The northern one is constituted by a largely fractured, southward-folded and more emergent hill- and mountain range of *Mio-Pliocene* age, which is joined along the coast by a diluvio-alluvial plain of varying width. In the central part of the island, along a W-E axis, dozens of volcanic cones emerge, 27 of which can be considered active even today. In the interspaces of the volcanoes the fault blocks of the geoanticline form mounts locally more than 1000 m high, made up of fault-folded sedimentary deposits. On the *Indian-Ocean*-facing side of the anticline we find the third zone – the *southern Tertiary belt*. The bulk of this zone is made up of intensively folded Lower and Middle Miocene tuffs and breccias, mantled by Upper Miocene sediments. The largest karst areas of Java have formed on the exposed limestone member of the sedimentary sequence.

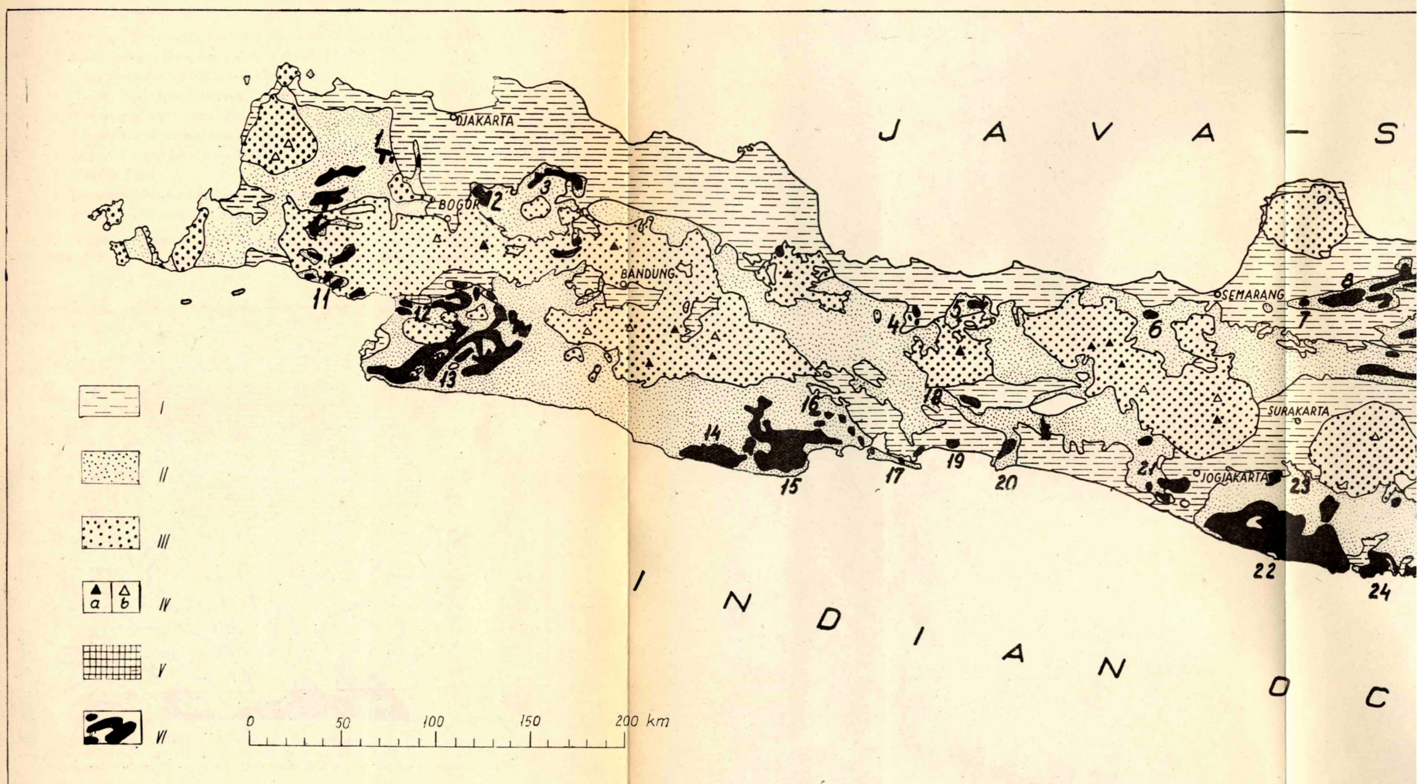


Fig. 11. Karst Regions of Java. I. Quaternary Sediments, II. Tertiary Sediments III. Quaternary and Tertiary volcanics IV.a active and IV.b non activ volcanic cone V. Pre-Tertiary VI. Karst areas

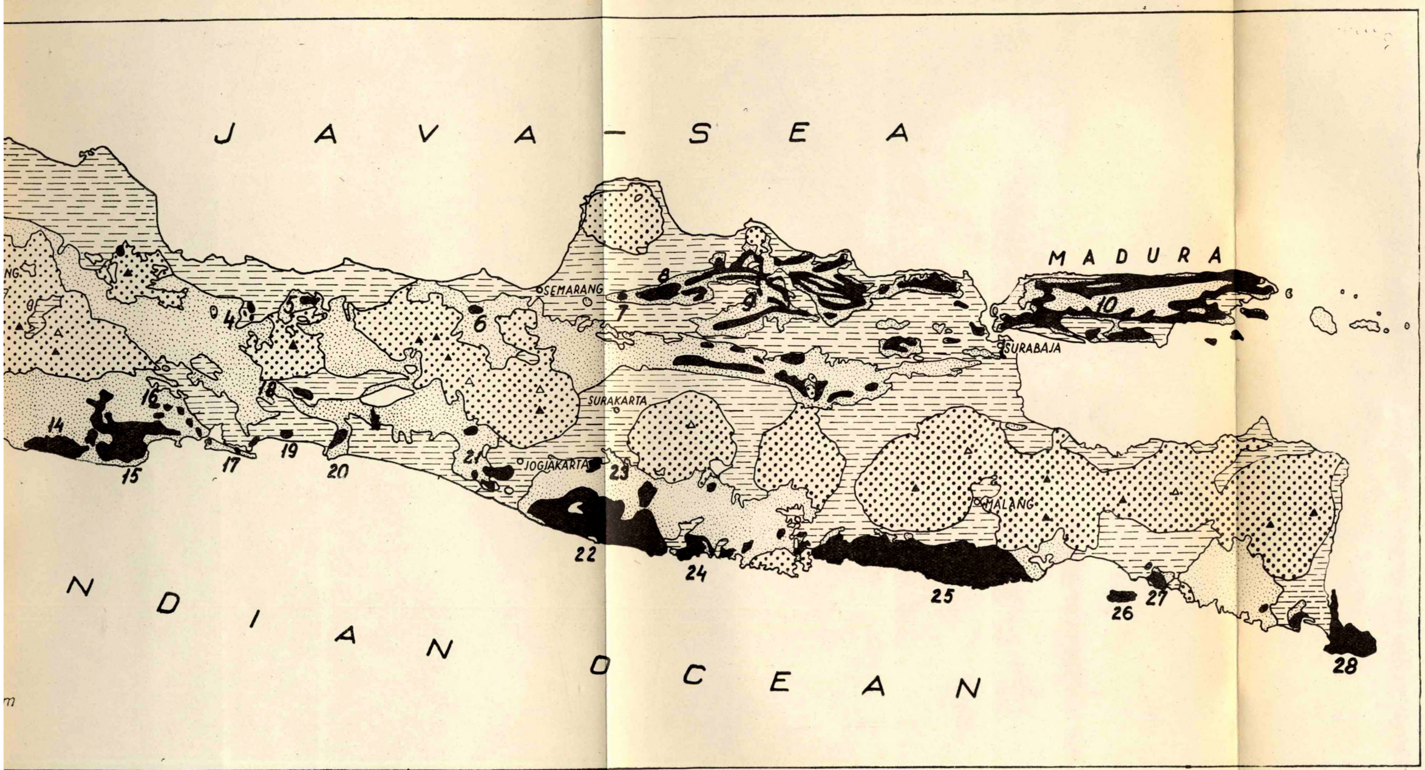


Fig. 11. Karst Regions of Java. I. Quaternary Sediments, II. Tertiary Sediments III. Quaternary and Tertiary volcanics IV.a active and IV.b non activ volcanic cone V. Pre-Tertiary VI. Karst areas

In the *northern Tertiary zone* of Java, we may quote, from the west to the east, the following major karst areas:

1. *Tjisadane Karst* (several isolated limestone blocks northwest of *Bogor*).
2. *Kalapanunggal Karst* (northeast of *Bogor*, Fig. 12.).
3. Karst block *east of Tjikampek* (western Java).
4. *Prupuki* Karst (central Java).
5. *Pemalangi* Karst (central Java).
6. *Tjipluki* Karst (central Java).
7. *Menawan* Karst (northeast Java).
8. *Sukolilo Karst.*
9. Karst areas between *Bodjongore and Lasun* (northeast Java).
10. *Madura island's* karsted areas.

In the central, *volcanic*, belt of Java there are but a few minor karst areas, more or less strewn with volcanic material (e.g. the *Togogapu Karst* west of *Bandung*).

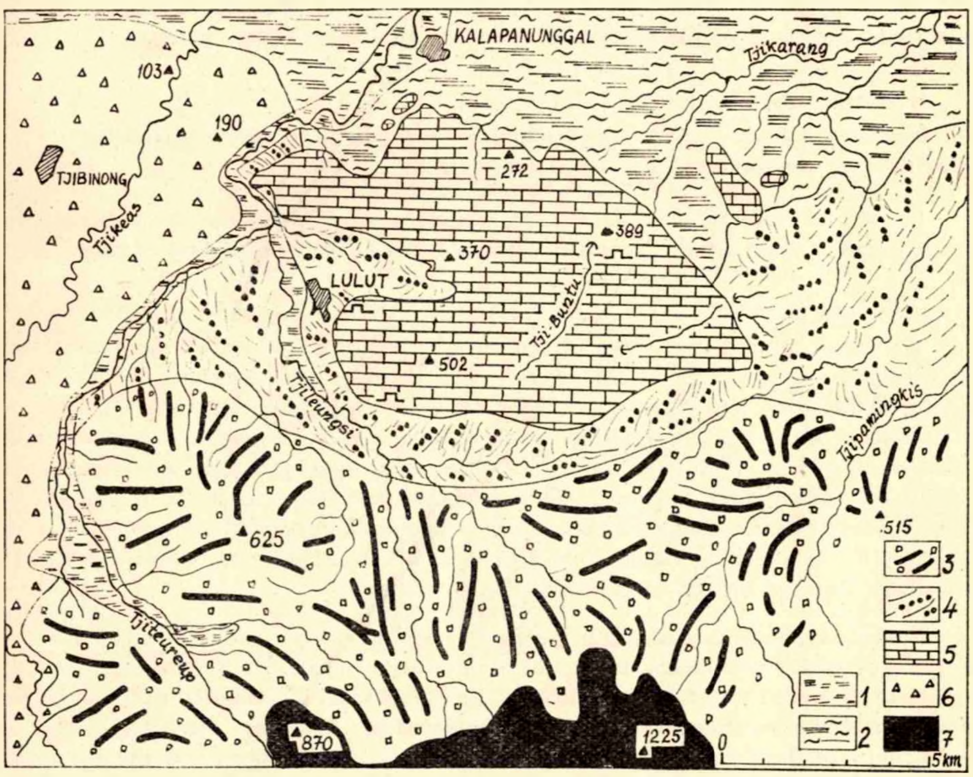


Fig. 12. Karst region in West Java, south of Kalapanunggal. 1. Fluvio-alluvial 2. Marine and fluvio-alluvial 3. Late Tertiary breccias (mountains) 4. Late Tertiary marble (hills) 5. Limestone plateau (Miocene) 6. Old breccias (hills) 7. Eruptive rocks (andesite)

In the *southern Tertiary zone* of the island, from the west to the east, the following major karst regions can be distinguished:

11. Karsted areas *north of Palabuhanratu Bay* (west Java).
12. Karst region of the *Tjimandiri riverine* (west Java).
13. Karst area of the vicinity of *Tjitjurug* (west Java).
14. *Tjiwulan Karst* (southeast of *Bandung* on the Indian Ocean shore).
15. *Tjidulang Karst* (continuation eastward of the former).
16. Karst east *of Parige* (north of *Tjidjulang*).
17. *Nusa Kambangan* (peninsula southwest of *Tjilatjap*).
18. *Adjibarang* Karst (west of *Purwokerto*).
19. *Kroja Karst* (south of the town of Kroja on the ocean coast).
20. *Gunung Sewu of Karangbolong*. Cone-featured karst area on the north slope of the *Karangbolong* Mountains emerging like and island from the coastal plain (Fig. 13.).
21. *Sentolo Karst* southwest of Jogjakarta.
22. *Gunung Sewu*, southeast of Jogjakarta.
23. *Djiwo Hills* north of G. Sewu.
24. Karst Area east of *Patjitan Bay* (properly, continuation of G. Sewu).
25. *East Gunung Kidul* (between the Indian Ocean and river *Brantas*). Largest limestone area of Java without representatives of characteristic tropical karst features.
26. *Nusa Barung island* (east Java, southwest of *Puger*).
27. *Watangan Karst Region* (east of *Puger*).
28. *Blambangan Karst Region* (unpopulated, little explored peninsula of southeast Java with distinct cone-featured karst topography).

Let us pick out only two of the listed karst regions. *G. Sewu and Nusa Barung* for a discussion in some detail. These are representatives of the typical karst of Java.

a) Gunung Sewu

The best-explored karst region, known for the longest time, of the Indonesian Archipelago lies southeast of *Jogjakarta*. The Tertiary belt stretching for the total length of the south part of Java bears the name *Gunung Kidul* (Southern Mountains). It consists of three units: the northern unit includes the *Baturagung* and *Popok* Mountains, south of which two large basins *(Wonosari* and *Baturetno)* form the second unit, finally, the *Gunung Sewu Karst Mountains* extending from there up to the Indian Ocean coast represent the third unit (G. Sewu means Thousans-Peaked Mountains). The W-E length of the karst region attains some 85 km, its N-S width varying between 10 and 15 km. Karst-featured surface covers some 1300 km^2 area.

Geology. G. Sewu is made up of *Neogene* (Middle Miocene) limestones, in the depressions of which *Quaternary* terrestrial sediments, products of weathering, volcanic tuffs, etc. have been accumulated. The mean limestone mass is composed of the so-called *Wonosari Beds* more than 200 m thick, as measured by Flathe and Pfeiffer (28, 29), no exact figure of their thickness being known. In the *Wonosari* Basin and the *Baturetno* Basin these sediments locally grade into porous limestone, soft limestone and calcareous marl facies. The *Wonosari* Limestone is underlain by the still Middle Miocene *Ojo Beds* of extremely varied composition (marl, tuff, limestone breccia, sandstone, conglomerate,

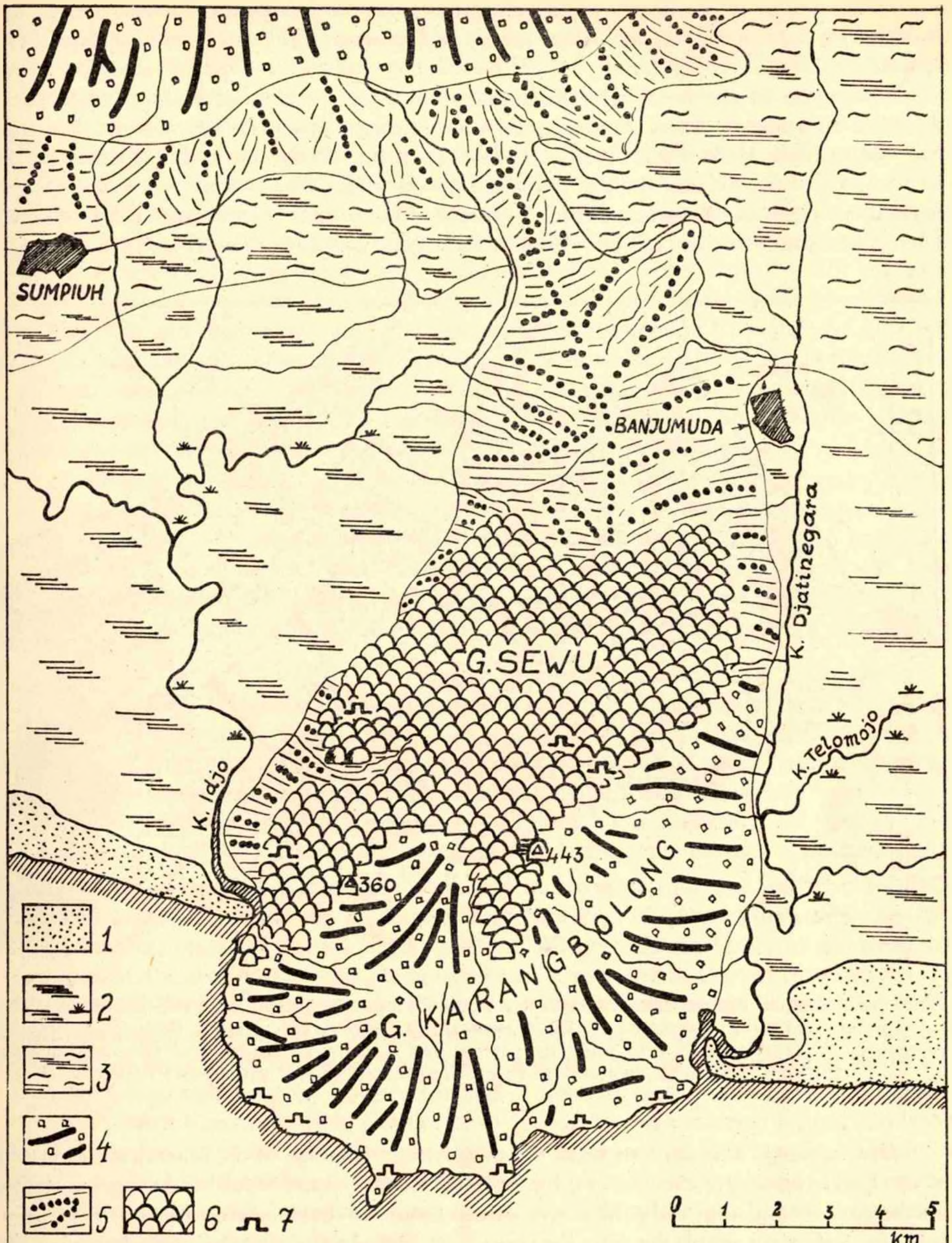


Fig. 13. Conical karst in the Karangbolong Mountains (Central Java, south coast)
1. Marine dunes 2. fluvioalluvial 3. Marine and fluvio-alluvial
4. Late Tertiary volcanic breccia 5. Late Tertiary marble hills 6. Conical karst 7. Cave

etc.). The *Ojo Beds* are partly impervious rocks. In the basins the *Wonosari Beds* are overlain by the impervious, so-called *Kepek Beds* consisting of marly, clayey, and tuffaceous facies.

The strata of the hard, whitish, massive coral-reef limestones making up *G. Sewu* dip with an angle of a few degrees south- to southeastwards. In the western part they rise 400 m high. Here the footwall *Ojo Beds* crop out on the mountain border. In the central part of the plateau there is a distinct up-warping (250—300 m), while the eastern parts show slight, saddle-shaped folds — traces of horizontal compression (350—400 m). The arched south borders of the *Wonosari Basin* are fault-controlled (Fig. 14.).

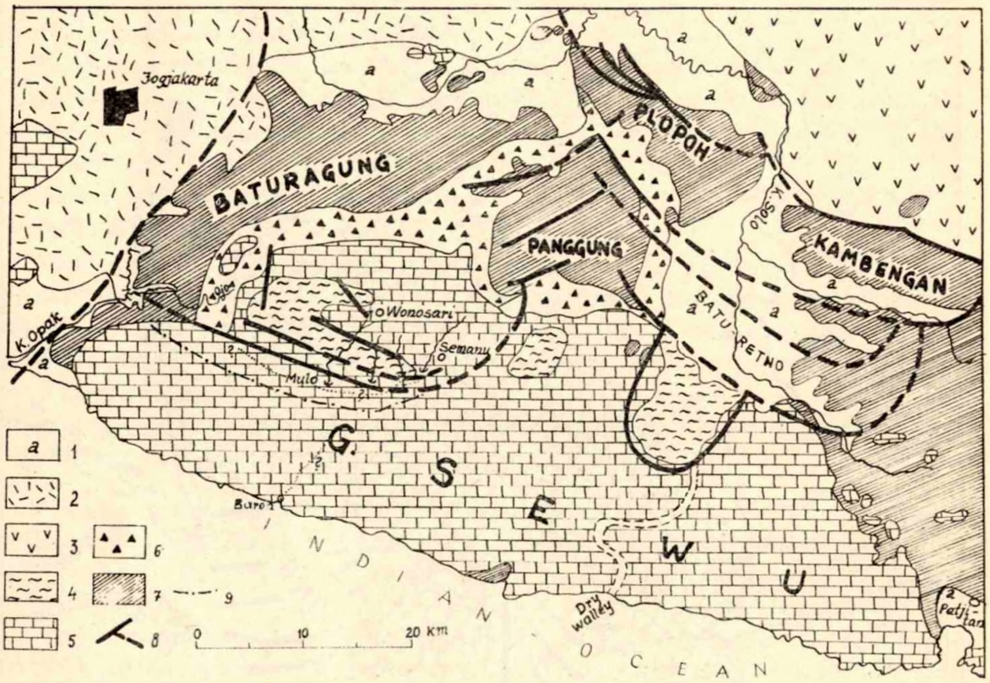


Fig. 14. Geological map-scheme of Gunung Sewu (by courtesy of R. W. VAN BEMMELEN) 1. Alluvial 2. Young volcanoes 3. Older volcanoes (breccia) 4. Kepek Beds 5. Wonosari Limestone 6. Ojo Beds 7. Old andesite formations 8. Normal faults and flexures, inverse faults 9. Secondary watershed (according to FLATHE and PFEIFFER)

Hydrography. It is evident from the geographic situation of *G. Sewu* that the waters of the karst region are received by the Indian Ocean — base level bordering the region on the east — and that only the rivers of the *Baturetno* basin region run northwards to join the *Solo* river emptying into the *Java Sea.* Despite the near-by main base level of erosion, the inner hydrographic system of the karst region is not yet satisfactorily explored.

The surface waters of the northern mountain range of *G. Kidul* and, in part, of the *Wonosari Basin* are drained by *K. Opak* and its tributary, *K. Ojo*, emptying into the Indian Ocean. The infiltrating part of the meteoric waters falling on *G. Sewu*, flows — in line with the region's karst-type hydrographic pattern — through subsurface channelways toward the Indian Ocean and emerges in karst springs of varying size along the coast. (The largest karst spring is the *Baron* spring on the central south border of the karst plateau, its yield varying between 25 and 500 m^3 a minute.) Earlier students of the karst region (Daneš, H. Lehman, etc.) believed that the rivers plunging underground on the southeast and south borders of *Wonosari Basin* were also drained, via karst passageways, immediately into the Indian Ocean. Geoelectric measurements by Flathe and Pfeiffer (28, 29), however, have shown that because of the upwarping of the impervious *Ojo Beds* in the central part of the plateau, the swallowed waters cannot flow southwards, but they migrate westwards, through a subsurface river called *Mulo*, past the south edges of the basin, to flow into the *Ojo* river at a point still unknown. Whereas the earlier students suggested the presence of an intermediary watershed between the *Ojo* river and the ocean, a dividing line stretching to the west from the villages *Giring* and *Warang* and to the north and northeast of the townlet of *Wonosari* in the basin of the same name, Flathe and Pfeiffer traced this secondary dividing line underground in the northern one-third of *G. Sewu*. This new point of view, however, cannot be adopted until warranted by investigations into sink-hole versus spring relationships.

An interesting feature of *G. Sewu*'s hydrography is the presence of many doline-lakes or *telagas* as local people call them. In the depressions of the karsted plateau and on the south edges of *Wonosari Basin* there about 460 minor lakes and ponds vary in between 50 and 300 m in diameter. The "Telaga Register" compiled upon a Jogjakarta order includes information on 372 lakes and ponds. As shown by this document, 2/3 of all the lakes run dry in the dry season and only 144 can preserve the rainy season's waters round the year.

Morphology. The surface of *G. Sewu* is featured by thousands of conical hills (40,000 as put by an estimate). This peculiar type of landforms has passed as "G. Sewu type" into morphologic glossaries. Similar forms occur in many a region of the tropical belt (*the Antilles*, *Southeast Asia*, etc.). The peculiar relief forms drew attention of early research workers and since the ivestigations of Junghuhn (1836), first student of the problem, many workers described them or tried to decipher the process of their evolution.

According to H. Lehmann (42), late in Neogene time and early int the Pleistocene, the area of present-day *G. Sewu* emerged hardly a few meters high above sea level and karstification could not yet begin that time. When the Javanese geoanticline began to uplift again, the area of *G. Kidul*- being tilted to the south, was also set into motion. The stream which drained the north part of the block flowed southward, across what is now the karst region, cutting deep valleys into the emerging surface, a process particularly intensive in the case of the paleo-Solo. (Now already dry, this ocean-bound valley runs from *Giritontro* southwards.) Toward the end of the *Pleistocene*, with quicker emergence of the southern limestone zone, giving rise to *Wonosari* and *Baturetno* basins, the waters from these basins could not keep pace with the high rate of uplifting and sought for drainage possibilities to the west and north, plunging in part underground. The limestone areas were witnessing large-scale denudation which has brought about the rounded, conical features of present-day topography.

In their report on the German hydrogeological expedition of 1961., Flathe and Pfeiffer disapprove the use of the term "Kegelkarst", as the contours of the karst mounts and hills of *G. Sewu* are sine-lined rather than cone-shaped. On the basis of striking, convincing illustrations, they proposed to use the term "sinoid" for such sine-contoured karst hills. In reality, however, the number of regular sine-contoured hills and mounts is reduced, whereas forms of transition between hemisphere and sinoid are rather abundant within one and the same karst region, so in *G. Sewu* too. It does not seem to be advantageous to name a karst region as a whole for any geometric form or shape (cone-featured karst, "sinoid" karst, etc.). Instead, we should speak simply of a "tropical karst" and notify within it the presence of predominant mountain forms (pinnacles, towers, etc.).

The process of evolution of present-day relief has been illustrated on a block-diagramme by H. Lehmann (42). The first stage in this process is represented by N-S trending surface drainage channels — ravines and gullies — developed on the slowly rising surface (Rumpfläche). During the accelerated uplifting of the area, they are cut deeper and deeper, giving rise to the primary pattern of what is termed "gerichteter Karst" in German literature. Surface erosion is concentrated on the development of linear depression features, while the intermediary, more resistant rock slabs are carved out to form cones. During the subsequent emergence of the karst region a hydrographic network is developed. According to certain theories (54), a primary role in the initial stage of development of some of the karst cones is played by the so-called biohermes -coral colonies growing near transgressive coasts. These are rather compact and become emergent during regressions.

Of the negative karst features ("Hohlformen"), we find in the intermontane depressions of G. Sewu, the broad doline forms — typical features of the temperate belt (the telagas occur usually in these depressions). Most of the depressions, however, are represented, here too, by narrow karst canyons reminding quasi of the past evolution of the karst. These continuous karst valleys penetrate from the ocean coast for some 3 to 5 km into the karst-hilled topography, providing episodically for the surface drainage of precipitations during the rainy season.

Typical feature elements of the northern karst borderland are the deep canyons of the plunging rivers ending in broad-entranced, high cave recesses. Collapse sinks — deep karst pits — are frequent here. Senile and youthful caves can be encountered throughout the karst mountains, but the huge cavern systems of the northern underground passageways are still unexplored.

Along the oceanic coast of *G. Sewu* schoolexamples of the corrosive effect of abrasion can be observed. In some places, the abrasion benches and their underwash recesses penetrate 3 to 8 m deep below the coastal reefs. They are continuously lashed by surf and combined physical and chemical wearing away of rock has been proven by horizontal denudation at the height of sea level. Abrasion of coast is a rapid process, well illustrated by the conical hills cut asunder, quasi sliced up (sinoids!), and by the huge limestone blocks standing in water on the broadening abrasion terrace. (Fig. 15).

b) Nusa Barung

The *Nusa Barung* island off southeast coast of Java does not belong to the largest karst regions. Its area is only 80 km^2 — 17.3 km long (W-E) by 4 to 6 km wide (N-S). (Fig. 16). Despite its reduced size, it seems to be worth of dwelling on this karsted island, as its morphologic pattern is different from that of *G. Sewu.*

Geology. The island of *Nusa Barung* is an integral part of the Tertiary belt stretching across south Java and abunding in karst phenomena. The island is made up of Middle Miocene coral-reef limestones which can be identified with the *Wonosari Beds* well-known in *G. Sewu*, though this correlation is not yet completely proven. The massive beds

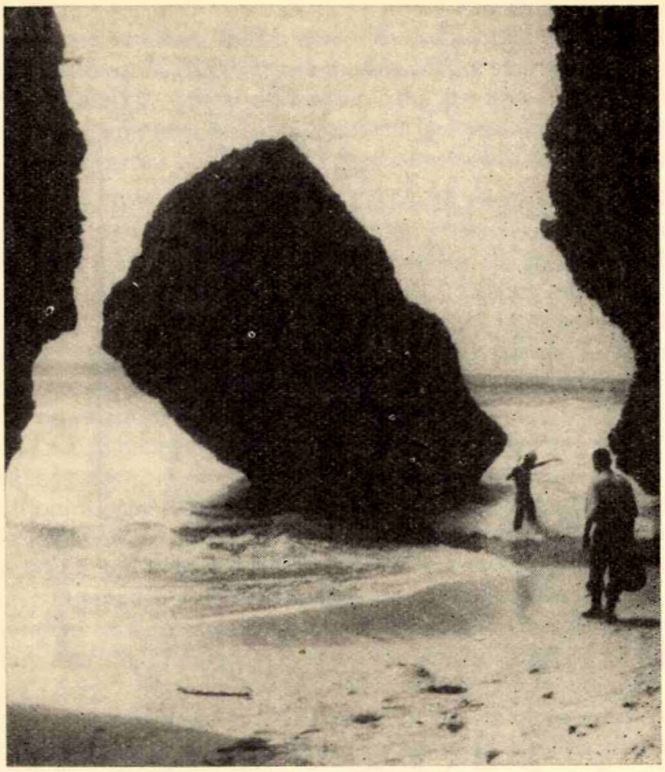


Fig. 15. Huge blocks fall down into the sea from the limestone walls, assaulted heavily by the abrasion (Gunung Sewu, Central Java).

of the rather compact, hard limestone mass dip southwards at a low angle. The north border of the island, rising about 300 m high and precipitating with a sharp edge into the ocean, indicates the presence of a W-E-trending fault, zig-zagged by the formation of abrasion klippens especially in the northeast part.

Hydrography. The island is characterized by a distinct, surface drainage system and a primitive subsurface drainage pattern. The surface drainage is represented by a dense network of "dry valleys" which, issuing from the high north border net the whole island along NE-SW lines. Dry valleys are being developed by fluvio-erosional way, for a considerable part of precipitation (see data of "Puger" station in Table 2) falls in form of heavy showers characteristic of the tropics and the water masses rushing down the valleys are essentially more powerful denudation agents than the chemical erosion of meteoric water is. There is not a single true karst spring on the island, only a few minor springs issuing from the outcrops of deep-seated strata are known. The infiltrating portion of meteoric waters flows southwards, along bedding planes, via narrow joints, to emerge to daylight merely at the base of deeper-seated boulders of some dry valleys. The deep penetrating waters nowhere concentrate into a large spring, as far as it is known to the author, but they leave the karst massif in a scattered pattern, mostly below sea level. The scant hydrographic pattern of the island may have been responsible for that the population of

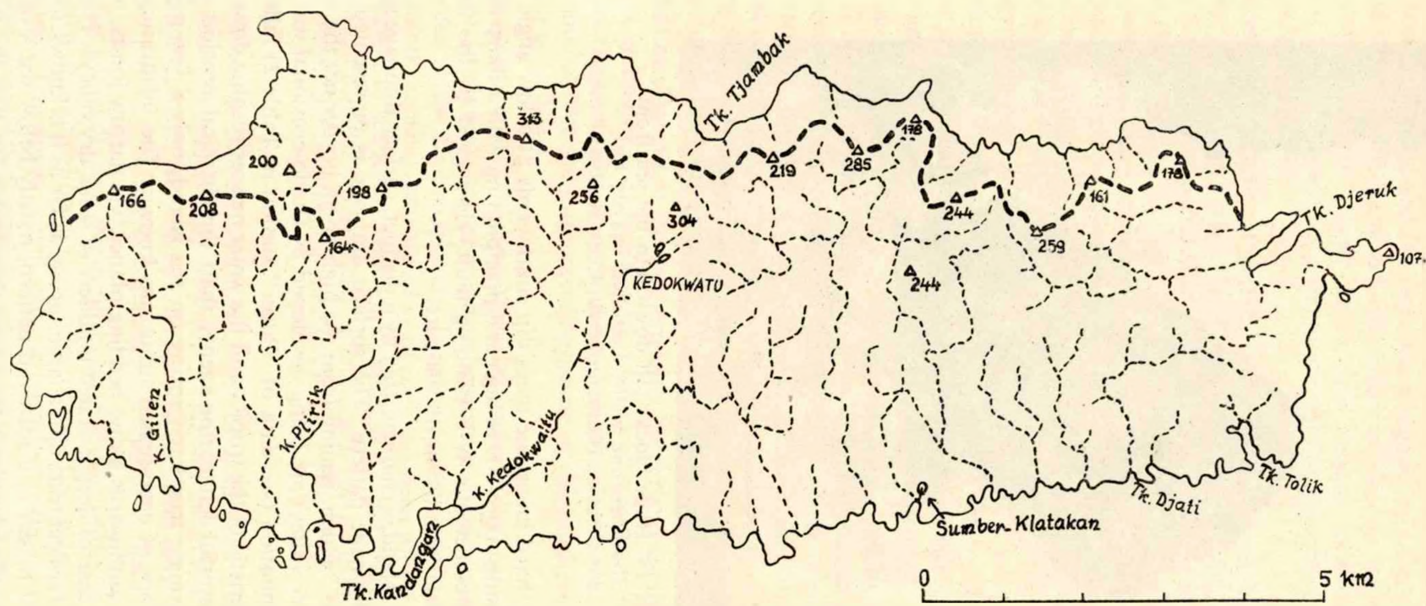


Fig. 16. Dry valleys of the Nusa Barung

near-by Java have not sought for possibilities of settlement on the island, so that the latter is completely unpopulated to this date. The deep-reaching roots of tropical plants, howerver, can find water enough to warrant the presence of a dense primary forest throughout the island, a vegatation typical of the tropical karst areas. On the island live many representatives of big game (elk, wild-hog, varanus, giant snake, etc.) drinking from stagnant waters of deep canyons and from minor springs active mainly in the rainy season.

Morphology. The initial development of the island may have been much the same as was suggested for *G. Sewu* by H. Lehmann. The fragmented blocks of *Miocene* deposits in the south part of the island emerged above sea level as early as the end of Miocene time, but their low relief did not permit full development of karstification till *Quaternary* time. The rate of emergence was then not so high as was in the case of *G. Sewu* — incision of valley could always keep pace with the work of endogenic agents. So, closed drainless depressions could nowhere develop, and even though subsurface hydrography is more prominent today, no large, broad subsurface drainage caverns (caves) could be formed because of the comparatively low relief and of the valley-dissected pattern of the landscape.

The formation of cone features typical of the tropical karst areas is still in its initial stage. The development of cones on the low hill ridges stretching NE-SW between the dry valleys has begun, but these are still connected by comparatively high saddles in most places. We have counted about 400 embryonic cones forming rather closely spaced, oriented chains ("gerichterer Karst" as called by Lehmann). Completely detached cones occur only near the south coast, where both fluvial erosion and abrasion are tending to form "inselbergs" from the lower, southern, members of the cone chains.

The *Nusa Barung* island is a good example of the comparatively youthful stage of tropical karstic evolution. Similar forms are encountered in other places too, along the south coast of Java.

3. Nusa Tenggara (Little Sunda islands)

The young orogenic belt extending throughout *Sumatra* and *Java* — and characterized by heavy volcanism — can be traced off east coast of Java, where it is split up into islands. The narrowing range is joined from the south by the upwarps of the outer arch. Van Bemmelen has referred the islands to three physiographic units:

a) inner, volcanic, zone,

b) central, interdeep, zone (from which emerges the *Sumba* island), and

c) outer, sedimentary, zone *(Timor)*.

Compared to *Java*, the *Little Sunda islands* have rather lagged behind in geological exploration, particularly the geological maps of *Sumbawa and Sumba* have many white spots. Most of research has been concentrated on the young volcanoes, substantially less attention has been paid to the more complex, non-volcanic or combined, volcanic-and-sedimentary, areas such as *Lombok*, *Sumbawa*, and the south parts of *Sumba*. The sedimentary areas show exposures of limestone facies in many places, but no continuous karst areas can be encountered in any of the islands but *Sumba*.

a) Bali-Romang Volcanic Arch

Large islands from west to east are *Bali*, *Lombok*, *Sumbawa*, *Flores*, *Solor*, and *Alor* islands, *Wetar* and *Romang*. The three western islands are in structural composition similar to eastern Java, being quasi a continuation of the latter, except for that the northern

Neogene-Quaternary zone lacks almost completely or it is buried by later, volcanic, formations. The *Tertiary* zone of Java, however, can be traced as far as *Sumbawa.* The surface of *Flores* and of the islands to the east of it is dominated by volcanics, spotted by sporadic representatives of sedimentary deposits.

Bali

The volcanic masses accounting for the bulk of the island are linked by a narrowing alluvial bridge with the southern peninsula — *Bukit Badung* or *Tafelhoek* in its old Dutch name. *Bukit Badung* is an extension of Java's southeastern, karsted peninsula — the *Blambangan.* It is also made up of older, Neogene limestones lifted to some 200 m height a. s. l. by orogenic forces subsequent to the formation of Java's Southern Mountains. Covering some 85 km^2 area, the island-like limestone peneplain is 7 km wide (N-S) by 15 km long (W-E). Its surface is covered by terra rossa. Although the total annual amount of precipitation is high (1,600 mm), hardly any rain does fall for months in the dry season. This seems to be one of the main causes of that the natural vegetation of the island is represented merely by alang-alang instead of a tropical karst forest. Culture vegetation is insignificantly scant. Population numbers 2,500 to 3,000.

The hydrographic conditions of *Bukit Badung* are yet less known. Much of the rainfall of the rainy season is drained into the ocean by the deep erosion valleys and gullies; the rest is swallowed by the primitive cavern system of the limestone massif, to emerge finally in minor coastal, or submarine, springs. In the dry season, from June to September, all streams run dry. (26).

The morphology of the island is rather monotonous. Conical forms of modest development are restricted to the southwest parts of the island. Depression features (dolines), large sink-holes and caves are also absent. The landscape is characterized by flat, savanna-clad, karsted hill ridges dissected by deep ravines and gullies.

Nusa Penida

An eastward continuation of *Bukit Badung* is the *Nusa Penida* island. Built up of *Miocene* limestones, the about 200 km^2 large island is geologically, hydrologically, and morphologically very similar to the south peninsula of *Bali*, so we may dispense with its any detailed description.

Lombok

Mantled by older volcanic rocks, the south part of the island shows a number of outcrops of *Miocene* limestones (e. g. *Pantjoran)* forming no large karst area but some minor cone ranges.

Sumbawa

The *Miocene* limestones occur at a number of points of the south half of the island, but no continuous karst area is known.

Flores

On *Flores* and the islands to the east of it, only minor karst blocks are associated with the predominant volcanic rocks.

b) Interdeep zone (Sumba)

Van Bemmelen's "interdeep zone" consists of two marine basins (*Wetar-Sawu Basin* and *South-Lombok-Bali Basin)*, between which emerges the upwarped *Sumba* island, quasi linking the inner volcanic zone with the outer sedimentary one.

Of 12,000 km^2 area, the island in its north half is composed mainly of *Neogene* limestones and marls. The tree-less, grassy plateaus vary in elevation between 400 and 600 m. Forest has been preserved merely in the valleys and on a few karst cones. Precipitations show a very irregular distribution — 1,800 to 2,500 mm on the plateaus (long-range average) and 800 to 900 mm along the northeast border of the plateau. The June-to-September period is very dry.

The hydrography of the northern karsted area (about 3,000 km^2) was studied, on behalf of the Indonesian government, by Laufer and Kraeff, for a lot of cattle is lost every year for lack of water (40). Beneath the large karst plateaus underground river systems like that of *G. Sewu* have developed, which carry the abundant water of the rainy season quickly into the sea.

The karsted landscapes are dominated by thousands of monotonous, barren cones. Their relative height is 50 to 80 m. They surround irregularly running dry valleys. The higher-sited plateaus include dolines as well as polje-like depressions 50 to 100 m deep, 10 to 15 km long, and 5 to 10 km broad. Such are the *Waikabubak*, *Anakalang*, and *Lewa* basins (Fig. 17). These karst features are associated with numerous caves of varying size.

c) *The outer zone (Timor)*

The westernmost member of the outer, sedimentary, arch is the small *Dana* island, followed by islands of progressively increasing size — *Raidjua*, *Sawu*, *Roti*, *Semau*, and, finally, *Timor* (32,000 km^2). Although the geological exploration of the latter has been undertaken by a number of outstanding specialists, the structural setting of the island is not known exactly even today, which is due to the extremely complex structure of the island. Its geological composition includes — along with crystalline rocks and products of *Tertiary* volcanism — varied, marine and sedimentary, sequences ranging in age from the *Permian* to the *Quaternary*. *Permian* and *Mesozoic* and *Tertiary* sediments occur in a number of places, though no large karst area has so far been recorded in geolological descriptions.

4. Kalimantan (Borneo)

The geology of this island — third largest of the planet and second of the East-Indian Archipelago — covering an area of 734,000 km^2 is known but in rough lines. The western one-third of the island is part of the *Sunda Massif*, a southeast outpost of the Asiatic continent, while the more extensive east parts of the island belong to the Tertiary geosynclinal zone. Northern and central Kalimantan is traversed by Tertiary orogenic ranges issuing from the *Philippines* and diverging in a NE-SW strike. Within the northeast stretch of these ranges has intruded the *Kinabalu* Granodiorite Massif which is the highest part of the island (4,200 m).

On eastern Kalimantan the main tectonic line is represented by a NNE-SSW-striking upwarping. It begins on the south with the pre-Tertiary *Meratus* Mountains and continues to the north with the *Samarinda* anticline which includes mainly Tertiary sediments.

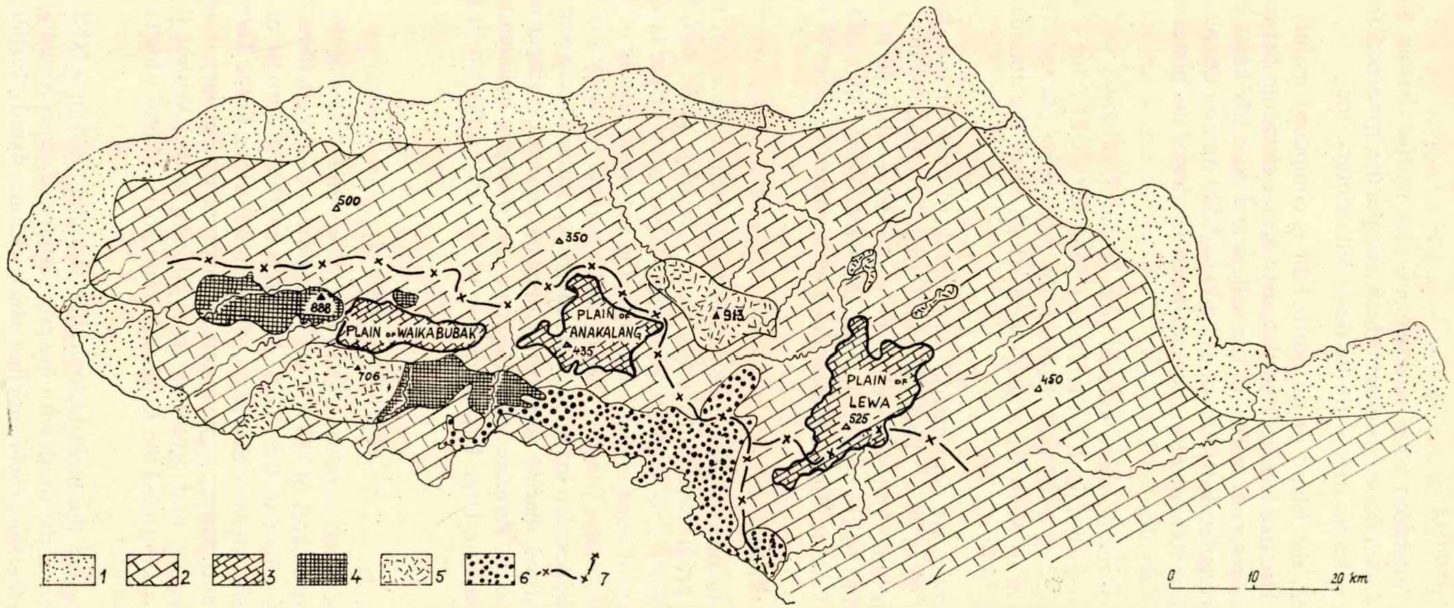


Fig. 17. Geomorphological map-scheme of West and Central Sumba (by courtesy of Laufer and Kraeff) 1. Quaternary coastal coral terraces 2. Neogene limestone karst relief with deep canyons, caves, sink-holes and primitiv conical hills 3. High and flat limestone plateaus 4. Mountains of Early Neogene volcanic rocks (ruffs, basalts) 5. Mountains of Pre-Tertiary igneous rocks 6. Pre-Tertiary slate formation 7. Chief watershed

The *Meratus-Samarinda* range is the result of Tertiary orogeny, just as are the *Sarawak* Mountains of northern Kalimantan.

It follows from the geology of Kalimantan that the west, south, and central parts are poor in limestone, whereas the east zone includes vast, still rather unexplored, karst regions. On the middle stretch of the *Barito and Mahakam (Kutai)* Interfluve geological investigations have shown several occurences of *Upper Paleogene* and *Lower Neogene* limestone exposures (Fig. 18). Several large karst areas are known in northern Borneo, near *Sarawak, too.*

The largest karst areas of the island occur within the *Samarinda* anticline. The up-warping is cut by the broad, antecedent valley of the *Mahakam (Kutai)* river. North of the cutting, the Tertiary limestones, locally more than 1,000 m thick, form vast karst zones. The largest karst zone lies at the eastern tip of *Mangkalihat Peninsula.* The 300 to 700 m high, tropical-forest-clad, Miocene limestone plateaus cover some 800 to 1,000 km^2 area to the east of the *Pulai Mountains.* Another, larger karst region stretches between *Gubar*, *Badju*, and *Mehisi* over some 700 to 800 km^2 area. On the average 300 to 500 m high, this cone-featured Miocene limestone plateau has its highest peak attaining 1,110 m on the west side. Additional karsted zones are found in the *Njapa Mountains* between the low stretch of the *Segah* (Berau) river and the upper stretch of the *Karang* river, near the source of the latter, on the shore of *Golok* Bay, northeast of *Lubukutung*, in the middle stretch of the *Segah-Kajan* Interfluve's mountain ridge, etc. All these combined give a total karst area of 1,500 to 2,000 km^2.

No details as to the genesis and the variety of forms of the karst areas are available. The maps locally show rivers plunging underground and depressions. For lack of roads, or even paths, it is very difficult to visit the karst areas. Intensive karstification is suggested by the orographic position of the region, by the presence of karstification-inclined rocks and by the abundance of rainfall (2,000 – 3,000 mm per annum).

5. Sulawesi (Celebes)

Island of K-like shape suggesting a composite geological structure, *Sulawesi* of 172,000 km^2 area ranks fourth among the islands of the Indonesian Archipelago. Its northern, long-stretching peninsula is connected with the *Philippines* through the medium of the volcanic *Sangihe* island range, whereas the mountain ranges of the southern, southeastern, and eastern peninsulae appear to be linked with the arches of the *Sunda Volcanic Belt* (Sumatra-Java-Little Sunda islands), arches recurving off *Sahul Shelf.* The four large peninsulae are separated by bays penetrating deep into the island's body. (*Tomini*, *Tolo*, and *Bone* bays). The centre of the island is formed by solid cratogene made up of early rocks and dissected by faults (*Fossa Sarasina Graben* with Lake *Poso*, etc.). Active volcanism occurs in *Tomini* Bay and on the north peninsula (*Minahassa*).

In Tertiary time much of the peninsulae as well as the west coast were parts of a geosyncline, so that calcareous sediments of considerable thickness could be accumulated. On the narrow *north peninsula*, the sea-facing slopes of the high mountains composed of crystalline schists, granites and eruptive rocks are locally covered (over comparatively small areas) by reef limestones emerging 500 to 1,000 m high. Considerably larger are the karsted landscapes of the *northeast peninsula*, where karst plateaus and peneplains are made up of *Permo-Carboniferous*, *Triassic*, *Jurassic*, and *Tertiary* limestones. The hig-hest karsted elevation is the *Tokala* Mountains (2,630 m). The west part of the northeast

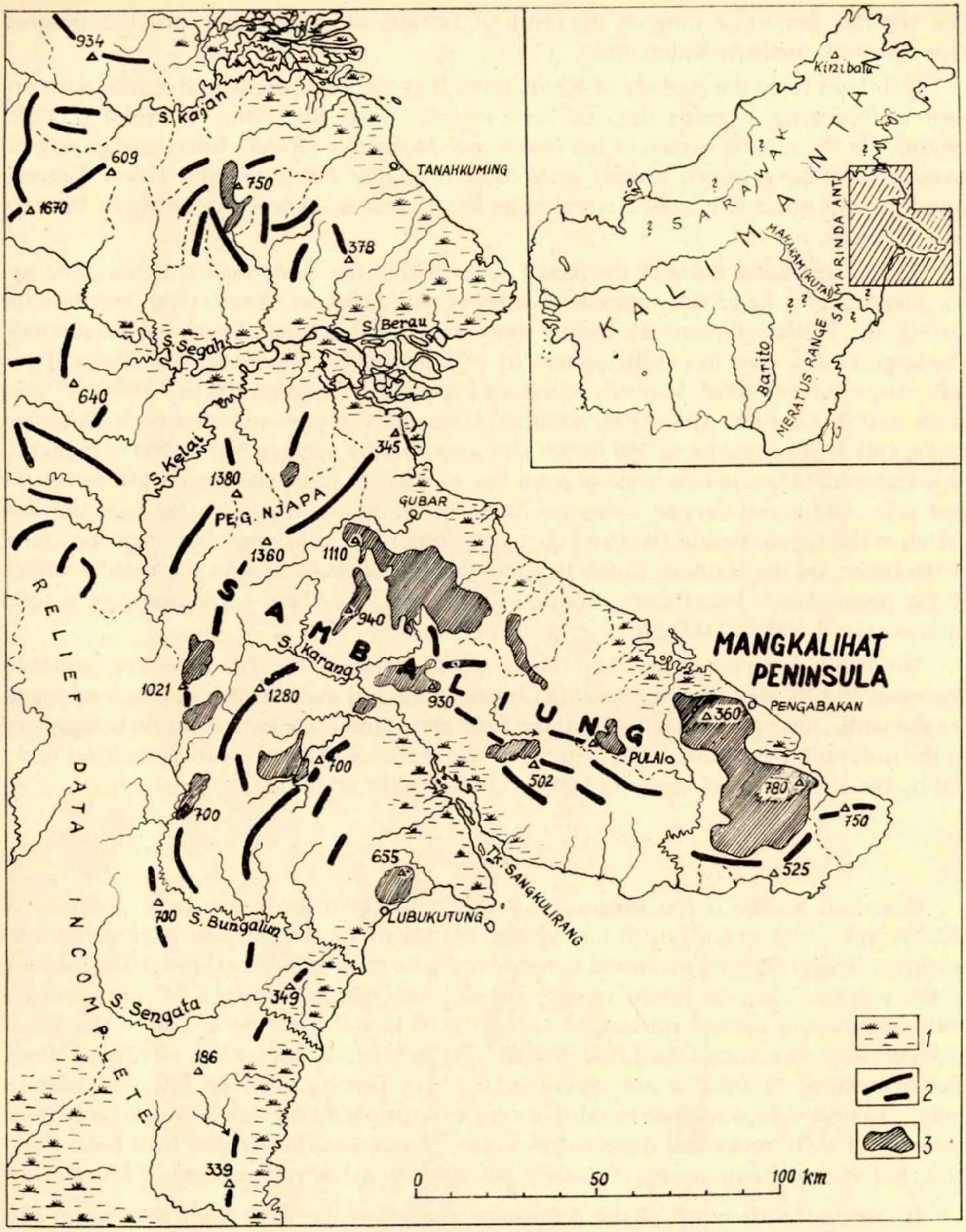


Fig. 18. Karst regions in East Kalimantan (Sambaliung-Area) 1. Quaternary coastal swamp 2. Tertiary folded mountain range 3. Tertiary (Miocene) karst regions

peninsula of *Sulawesi* — *Tokala* Mountains, northern *Bungku*, and *Bongku* — was explored and described in 1933—34 by Hungarian geologist L. Lóczy. On the *southeast peninsula* the sedimentary rocks are predominated by the *Cretaceous* limestones which are exposed on the *Buton* island farther southeast, but there, and on the adjacent *Muna* islands, mainly *Neogene* coral-reef limestones cover the surface.

The most marked karst features of Sulawesi occur on the *southwest peninsula*. In recent years detailed descriptions of the *Maros* and *Bone* karst areas have been given by H. Lehmann and M. A. Sunartadirdja (60, 61). (Fig. 19).

a) *The Maros Karst Area*

Sulawesi's largest karst area stretches east of the line of the towns of *Maros* and *Pangkadjene*, along an arch which can be described by a 30 to 50 km radius to the northeast of *Makassar*. The length of the karst area along a NNW-SSE axis attains 55 to 60 km, its diameter of NE-SW direction being 10 to 20 km. Irrespective of the marginal plain of indistinct outline, the karst landscapes cover some 400 km^2 area. Farther east-and northward, a number of additional,minor karst zones can be traced (with a total of 200 to 250 km^2 area).

Geology. At the centre of Sulawesi's southwest peninsula a deep tectonic trough of N-S orientation, called *Walanae-Tempe Depression*, has developed. Its name comes from the *Walanae* river, flowing over the full length of the depression, and from Lake *Tempe* in the north part of the trough. The south part of the trough is barraged by the products of an extinct volcano — *Lompobatang* (2,891 m). On the west, the trough is bordered by a mountain range consisting of Late Tertiary marine sediments volcanic breccias, and tuffs, rising 1,000 to 1,500 m high a. s. l. On its south and southwest edges has developed the *Maros* Karst Area consisting of several blocks.

The bedrock of the karst area is represented by thick-bedded, subhorizontal, comparatively pure, *Eocene* nummulitic limestones underlain as suggested by van Bemmelen (?), by crystalline schists and gneisses as well as locally by *Cretaceous* ophiolitic volcanics. Vertically walled on the west, the karst peneplains are surrounded by denuded karstic edges, alluvial plains and, farther on, by a mangrove-grown shore.

Hydrography. The western feet of the *Maros-Pangkadjane* karst range lie immediately at the base level of erosion. The flattened coastal plain rises not higher than 2—5 m above sea level, so that the springs of the karstic edge emerge, for the most part, at the same level. As a result of the considerable latitudinal extent of the karst area, the role of exogenic rivers in the hydrographic regime of the area is more reduced than in the case of *G. Saribu*, Sumatra. The streams of the high land surfaces bordering the karst on the east mostly skirt the area (*Lampe* or *Pangkadjene* rivers) and only the waters of a comparatively small impervious area can join, through the sink-holes of the east border, the hydrographic system of the peneplain. In spite of this fact, large underground channels, trending usually NE-SW, have developed in the interior of the karst block. They emerge to daylight as huge *Vauclusian* springs. (One of the largest karst springs is the *Towakkalak* near *Bantimurong*. The yield of the main spring varies between 80 and 150 m^3 per minute.) The catchment areas of the springs and their relationships with the sink-holes of the east edges and the inner depressions are still uncleared. During chemical analyses of spring water samples the highest values of water hardness (9—10 degrees of German scale, i. e. 160—180 mg per liter of $CaCO_3$) were found here. The annual amount of precipitations averages 3,000 to 3,500 mm with a wide range of seasonal fluctuations.

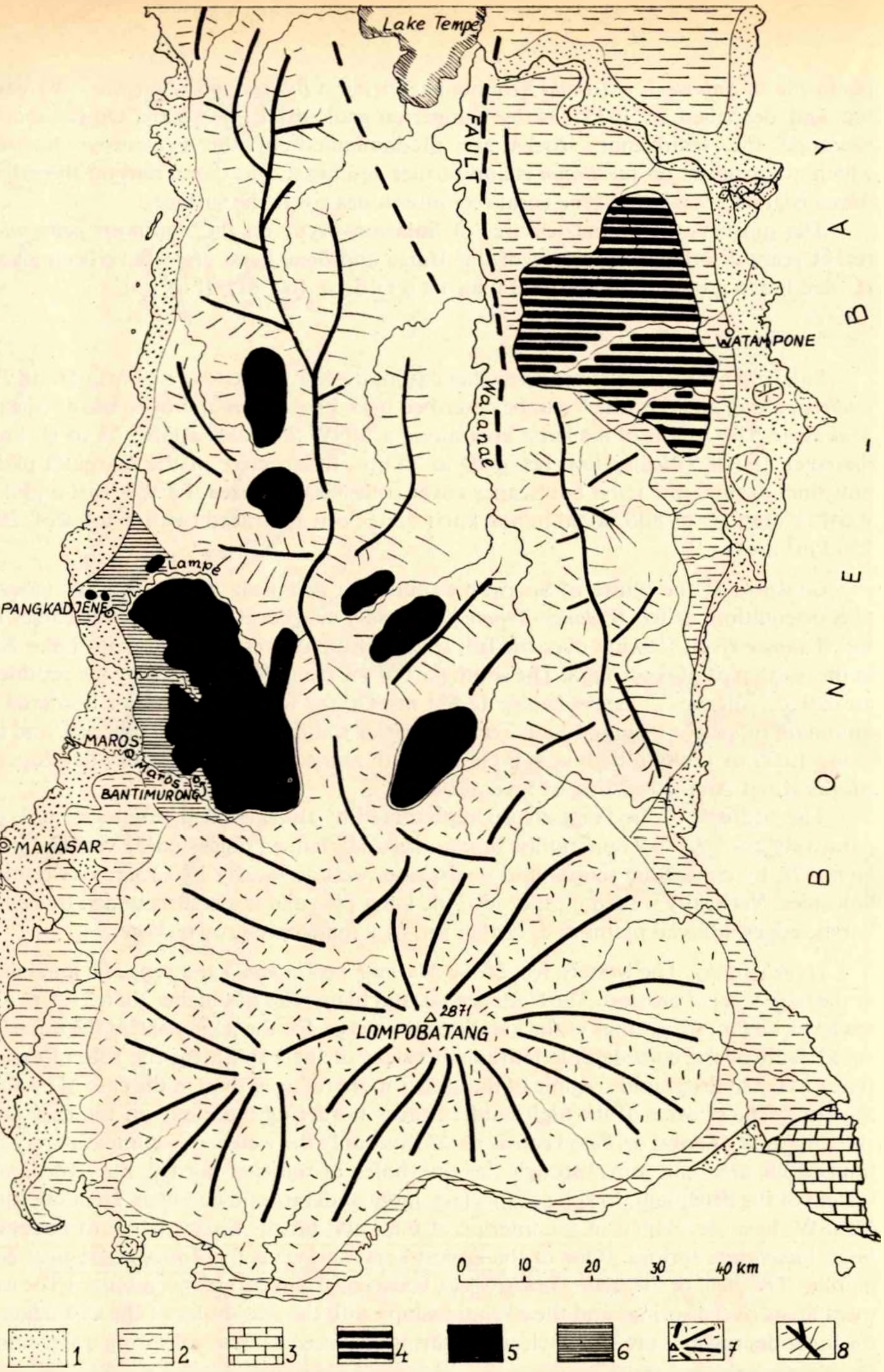


Fig. 19. Geomorphological map-scheme of SW-Sulawesi (simplified after A. SUNARTADIRDJA) 1. Late Quaternary coastal plain (swamp and paddyfields) 2. Late Neogene and Pleistocene terraces (hilly relief) 3. Pleistocene coral karst relief without conical hills (Bira Peninsula) 4. North-Bone karst region, mainly plateaus, but also karst hills 5. Tipical "Turmkarst", pinnacled karst, Eocene limestone 6. "Karst-Randebene" — West of Maros-Pangkadjene pinnacled karst region 7. Lompobatang volcanic complex 8. Non-karsted mountain ranges (Late Tertiary sediments and volcanic rocks)

Morphology. H. Lehmann distinguishes two basic types of tropical karst. One of them is the "Mogoten-Typ" — a karst plateau consisting of steep-walled pinnacles of sharp contours; the other one is the "Gunung Sewu Typ" represented by gentle karst hills of rounded, conical outline. The *Maros* Karst Area belongs to the "Mogoten Typ" whose representatives occur in the *Sierra de los Organos* Cuba, in South China, Vietnam, along the *Sinamar-Kvantan-Takung* rivers of Sumatra, etc.

The emergence of the area began at a marked rate about the middle of *Miocene* time, so that karstification could set in only afterwards. As termed by Lehmann, the initial period of karstification is "post-Mittelmiozän".

Viewed from the coastal plain, the karst area shows plateau features, but as one comes closer, one will find that the seemingly uniform plateau is dissected by deep clefts, canyons and, in some places, by bay-like depressions. The western, vertical edge walls are 100 to 200 m high; to the east, the limestone pinnacles rise gradually higher, to attain 700 m height, so that their average height rarely exceeds 200 to 300 m. The walls have been markedly undercut by the combined chemical and physical erosion of the running-off surface waters and karst springs; now and there hanging rock spurs have been formed, waters precipitating from which have yielded stalactites and tufa-draperies. (Fig. 20).

Fig. 20. 2—5 meters long outdoor stalactites hang down from the ceilings of the limestone wall concavations. The hills are mostly inaccessible because of the dense thicket. (Karst region of Maros, near the fountain Towakkalak)

According to H. Lehmann, the formation of steep-walled karst edges is due to corrosional underwash (Lösungsunterschneidung) at soil level. On the west borderlands, however, this process has been promoted by abrasion, for the accumulation of marine lamellibranches at the foot of rock walls and in cave entrances suggests that the sea transgressed up to the karst edges in Quaternary time.

Main landform elements of the karst area are the pinnacles which are densely packed, separated at most by collapse-sinks, and grown by dense tropical vegetation. In some places they are separated by minor depressions – dolines. At the bottom of the collapse-sinks marking the one-time underground channels of the *Towakkalak* river near *Bantimurong* there are minor ponds. When interlinked with one another, the dolines may exhibit uvala-like configurations. L e h m a n n and S u n a r t a d i r d j a described two large polje-like depressions *(Daimanggala* and *Bontobonto)* on the basis of a topographic map. These depressions are not completely closed, but the emerging karst waters vanish through sink-holes. The edges are usually formed by steep walls due, as believed by L e h m a n n, predominantly to corrosional underwash, a process responsible for the broadening of the depression itself. In the steep rock precipices the one-time drainage channels – cave passageways – are readily exposed. The several-kilometer-long cave labyrinths are still unexplored – the earlier caverns are filled with masses of dripstones which handicap man's penetration.

On the west border of the karst area, scores of single, 100 to 200 m high pinnacles emerge above their karst-border-plain background (Karst-randebene). These are remnants of the one-time contiguous karst plateau. The most scenic, cave-hollowed "inselbergs" occur north of *Pangkadjene*, a region markedly resembling the "inselberg"-studded karst regions of *South China* and *North Vietnam*.

b) *North-Bone Karst Region*

On the southwest peninsula of *Sulawesi*, in the north part of the *Bone Highland* west of the town of *Watampone*, a karstic landscape has developed. Its descriptions can be found in papers by M. A. S u n a r t a d i r d j a and H. L e h m a n n (60, 61). As to karst development and variety of landforms, this region substantially differs from the *Maros* Karst area already described.

Geology. As shown by T'H o e n, Z i e g l e r, and R u t t e n, the limestone sequence is made up of *Upper Pliocene* coral reef limestones resting unconformably on similarly marine *Upper Neogene* sediments and tuffs. The karst region under consideration was uplifted above sea level in *Late Pliocene* and *Pleistocene* times.

Hydrology. The hydrographic conditions of the karst area has been little studied so far. The main watershed of the *Bone Highland* stretches near the high ridge bordering the *Walanae* depression on the east. Rivers issuing from here and carrying their waters into *Bone Bay* have cut their channels through the young karst peneplain, thus draining its waters as well. On the karsted surfaces, peculiar valley configurations have been carved out by erosion in the interspaces of the oriented rows of low cones ("gerichteter Karst"), though most of these valley are only episodically active. Meteoric waters are swallowed by the karst, to reach the deep-cut local base level of the rivers, by transmissions through the microjoints of the porous, unconsolidated rock.

Morphology. Basic landforms of the *North-Bone Karst Region* are the karst cones scattered by the thousands throughout the region or, in some areas, arranged into rows. These cones resemble the forms studied in *G. Sewu*, features held for one of the leading types of tropical karst landforms by the authors of papers on karst morphology. Cone – featured karst of similar type has developed in *Jamaica* ("Cockpit country"), in *Puerto Rico*, but similar landforms can also be encountered in other parts of the Indonesian Archipelago *(Ajamaru Karst*, West Irian, etc.). The relative height of the cones varies between 50 and 150 m, their contours are sine-lined, though regularly hemispherical forms may also occur. The flats surrounding the individual cones or cone-rows are made up of the same rock facies as the cones themselves. Another interesting phenomenon is that air-surveying has shown but minor remnants of cones, if any, over the half of the karsted area. These karst platforms emerge 100 to 300 m high above local base level developed by incising river channels.

H. Lehmann makes a comparison between the mount features of the *Maros* Karst Area and the *North-Bone* Karst Region. In his criticism of J. Corbel's tropical karst denudation models, he concludes that the landform type of the *North-Bone* Karst Region can by no means be called such a senile "stage" of karst evolution as was drawn by Corbel on a block-diagramme for the landscapes having been karsted since *Cretaceous* time and showing features very similar to the pattern of Bone. The relief type of *North Bone* also confirms the lack of a direct relationship of this kind between the variety of landforms of a karst region and the age of the constituent rock strata. As believed by Lehmann, the contrast of *North-Bone's* low cone features against the steep pinnacles and vertical rock precipices of *Maros* is due to the reduced thickness of limestones that covered the non-karsting sediments underneath, conditions under which saturation by karst water may have hindered additional subsidence of the limestone zone of *North-Bone*. The difference between the karst types of *Maros* and *Bone* must be, however, much more complex a phenomenon, where the lithologic characteristics and, first of all, the different circumstances of the emergence of the two areas may have been largely involved.

6. Maluku islands

In the interspaces of the sea basins bordered by *Sulawesi*, *Timor* and *Irian-Barat* there are hundreds of islands of different size, which are collectively named *Maluku islands*. The name "Molucca" was first used by Portuguese sailors to denote the northern islands, from where they shipped various sorts of spices to Europe (Spice islands).

The northern *Maluku Islands (Morotai*, *Halmahera*, *Ternate-Tidore-Makian* volcano islands, *Batjan*, *Obi*, etc.) are tectonically interconnected with the *Philippines* to the north and with *Sulawesi's* east peninsula to the west, and, most evidently, with *Irian-Barat's Doberai* and *Bombarai* peninsulae to the east *(Vogelkop)*. The *central Maluku* islands *(Buru*, *Ambon*, *Uliasser*, *Seram*, *Banda)* and the *southeast Maluku* islands *(Kai*, *Tanimbar*, *Babar*, etc.) form the east arch of the *Sunda* mountain system, being arranged semicircularly on the edges of the more-than-7-km deep depression of the *Banda Sea*. The *Aru* islands, belonging administratively still to southeast *Maluku*, lie already on the Australian continental basement *(Sahul Shelf)*.

Advanced disintegration and tectonic fragmentation of the islands and, first of all, the extremely rapid tectonic movements, have not permitted the formation of any large karst region or of any distinct major karstic surface landform. Surfaces built of loose reef limestones can be encountered in many places; emerging to several hundred meters, they locally form embryonic karst reliefs (karst sacs, karst precipices, minor caves, rock-pendants, sink-holes, collapse-sinks, etc.). Unmature karst surfaces like these occur on Ambon's *Hitu* peninsula, on the west and east coats of *Haruku* and *Seram*, but the largest ones are known to occur on the *Tanimbar* islands and *Kai-Ketjil* as well as on the west half of *Kobroör* — large central member of the *Aru* group (Fig. 25). These young coral-reef karst areas are characterized by water shortage — rain water will immediately

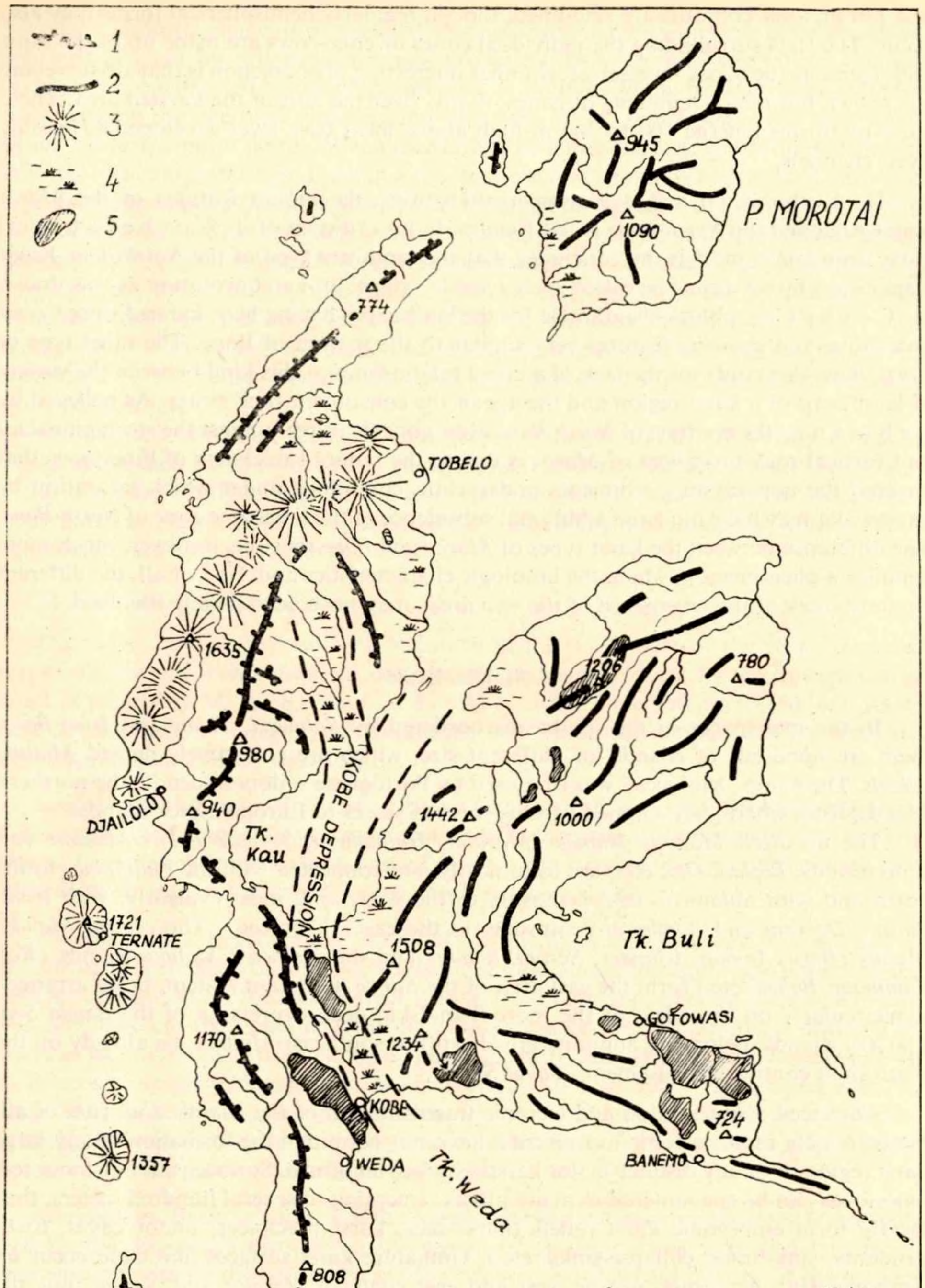


Fig. 21. Karst regions of Halmahera (North Maluku) 1. Tilted fault-blocks 2. Rolling uplan areas 3. Volcanoes 4. Quaternary coastal plains 5. Karst areas

vanish into the brittle, porous coral-reef matter, as it falls on the surface; and transmitted by myriads of microjoints and caverns, it will flow underground toward the base level of erosion. Concentrated streams are scarce. Thus low-yield seepages rather than large karst springs emerge at the edges of the peneplains. The loose structure of the rock makes impossible the formation of large cavern systems — caves.

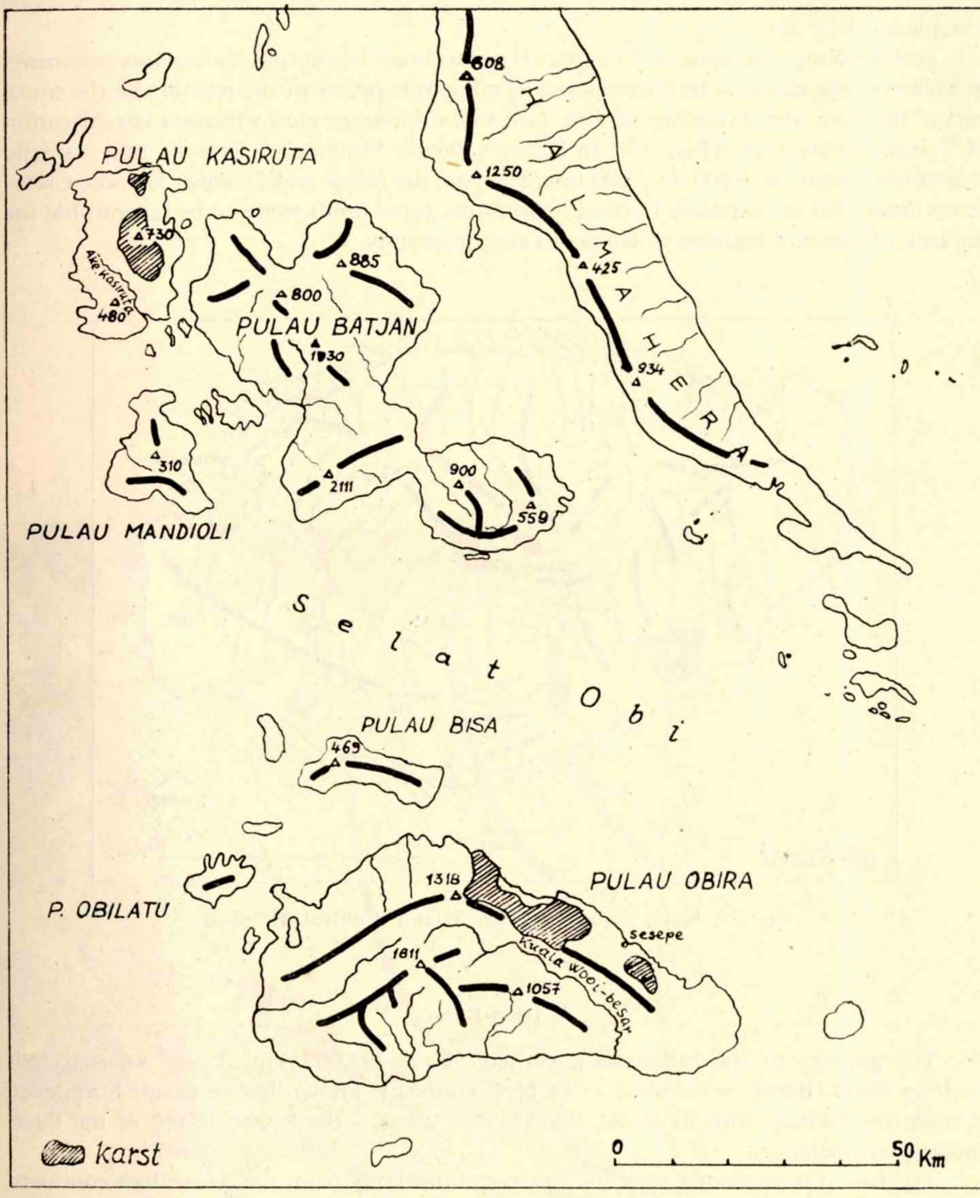


Fig. 22. Karst regions in the Kasiruta and Obira Islands (North Maluku)

Cone-featured karst areas studded with cones 200 to 500 m high have developed on the northeast and, particularly, the east peninsulae of *Halmahera*. (Fig. 21). Made up of *Neogene* limestones, these are structurally the westward extensions of the Neogene zone of Irian Barat's *Doberai* peninsula. The largest karsted landscape on the east peninsula extends to the southeast of *Gotowasi* (about 300 to 400 km^2). The 100 km^2 large karst area, lying at the issue of the peninsula, northeast of *Gemat*, is characterized by broad and deep depressions and underground rivers. West of locality *Kobe* and in the depression between *Kau* and *Weda* Bays, as well as the *Kasiruta* and *Obira* islands too, there are karsted peneplains (Fig. 22).

Beside young, Neogene and Quaternary, coral-reef limestones, calcareous sediments of *Mesozoic* age can also be encountered at numerous points of the islands. So the south part of the *Buru* island (regions of *Tifu*, *Lek Sulam Namrote*, etc.) witnesses karstification of Triassic limestones; (Fig. 23). In Seram's *Binaja* Mountains, Triassic and Jurassic limestones occur at 2,000 to 3,000 m a. s. l.; on the *Babar* and *Taninbar* islands, Cretaceous limestones are exposed. In these regions too, rapid uplift seems to be responsible for the lack of classical features of tropical karst orography.

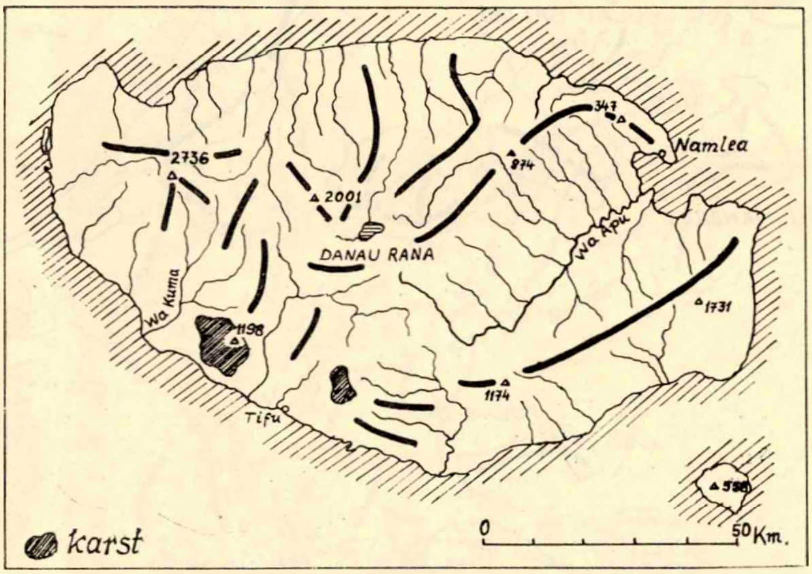


Fig. 23. Karst regions in Buru Island (Central Maluku)

7. Irian-Barat

The geology of the Indonesia-governed about 394,000 km^2 large, western half — *Irian Barat* (Barat = western) — of New Guinea is known but in rough lines, even though *New Guinea*, with its about 785,000 km^2 area, is the largest island of the East-Indian Archipelago.

The island is separated by a shallow sea water body from the Australian continent which had dryland communication with the island as late as *Pleistocene* time. The macro-

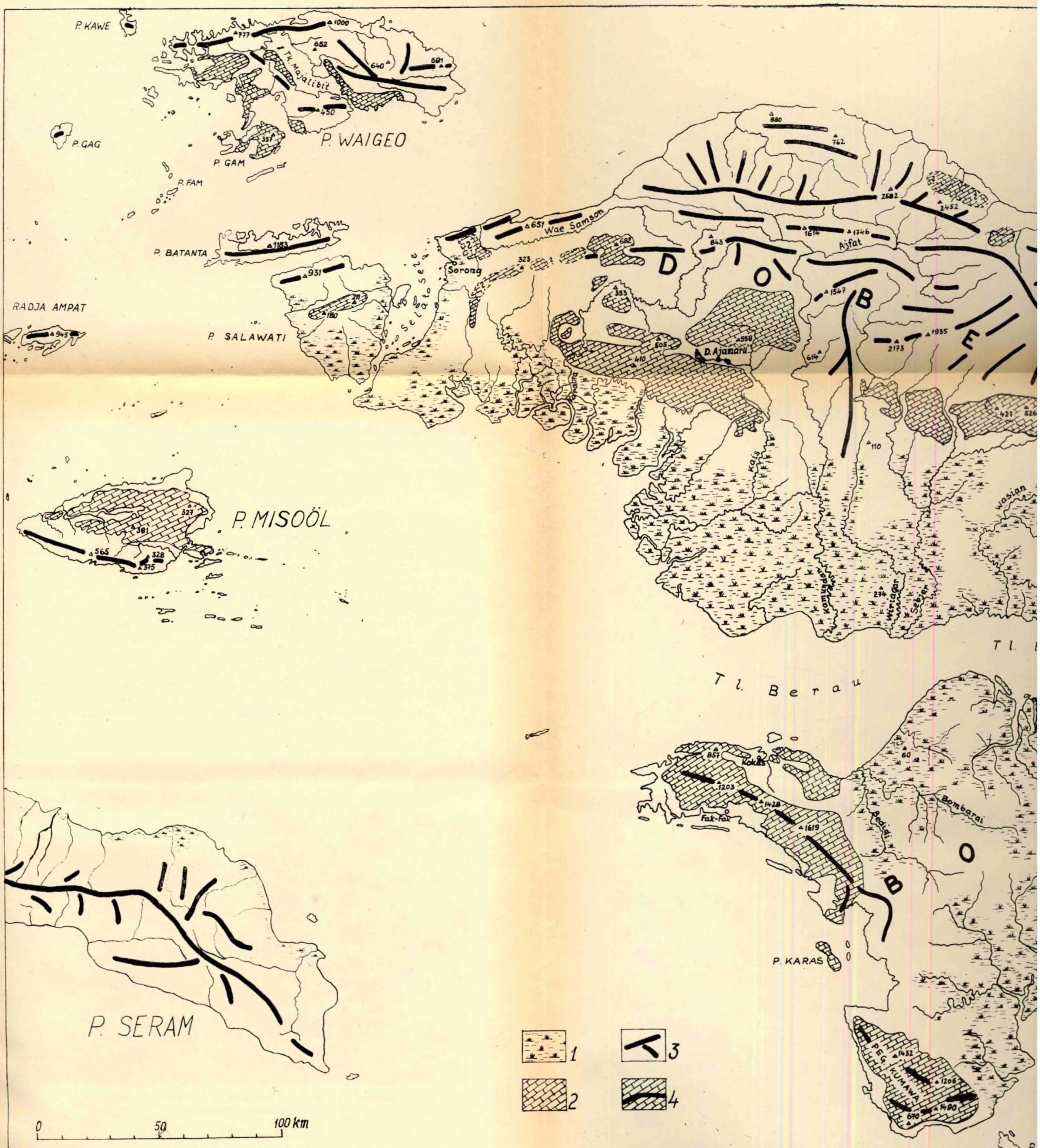


Fig. 24. Karst regions of Vogelkop (West Irian). Waigeo and Misoöl Islands. 1. Late Quaternary coastal plain 2. karst region (mainly conical hills) 3. Non-karsted mountains 4. Limestone mountains

Karst regions of Vogelkop (West Irian). Waigeo and Misoöl Islands. 1. Late Quater-
astal plain 2. karst region (mainly conical hills) 3. Non-karsted mountains 4. Limestone mountains

tectonic subdivision of *New Guinea* is simple — its surface is characterized by a distinct, W-E-oriented parallelism. The island is rimmed by a broad, swamped coastal plain facing the *Arafura Sea* on the south and the *Papua Bay* on the east; to the north of this plain, follows the Central Range forming the marrow of the island and consisting of a number of parallel zones; then the Pacific-facing edge of the island is formed by the Northern Coastal Range.

In the west part of the bird-shaped huge island, the "bird's" head — *Vogelkop* — is composed of two large peninsulae — *Doberai* and *Bombarai* (Fig. 24). In the structure of these, four elements can be distinguished. In the northern coastal, parts of Doberai stretches a Neogene-to-Quaternary *volcanic* zone of basaltic, andesitic, and trachytic composition, whose connection with *Halmahera* can be traced through the island of *Kofiau*. To the south of it, rises a markedly *folded, pre-Tertiary sedimentary mountain range* of 1000 to 2000 m height, which, skirting *Sarera Bay* (Geelvink Bay), is continued by the *Northern Dividing Range (Peg. V. Rees)* emerging in the central part of the island. On the west, in the south foreland of this mountain range, *karsted peneplains* made up of Neogene limestones feature the *Doberai* peninsula. Passing the broad alluvial plain and the *Berau Bay (Mac Cluer Bay)*, one will reach Irian-Barat's forth tectonic unit — the *young karsted mountain system* extending from *Misoöl* island, through Bombarai's southwest shores. It is also composed of Neogene sediments and can be traced farther through the *Adi* island, the *Aru* islands, and along the so-called *Merauke* Range.

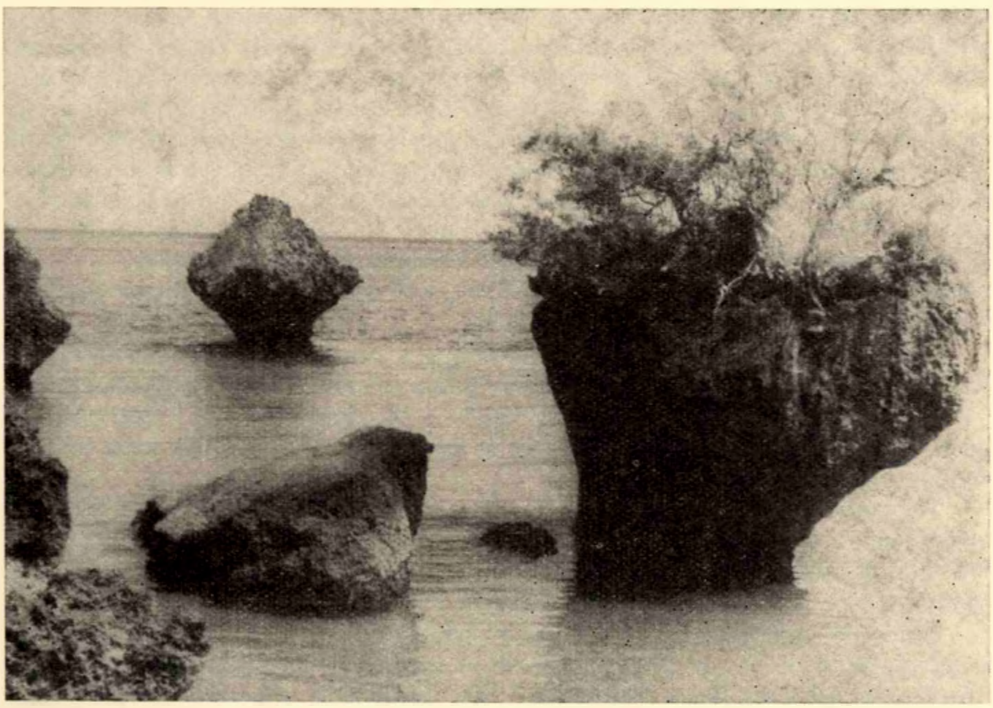


Fig. 25. Abraded rocks built up of Mesozoic limestone, off Teneman Island (Tanimbar islands)

According to present-day knowledge, the largest karst region of Irian-Barat lies in the centre of the *Doberai* peninsula around *Lake Ajamaru* or *Amaru* (referred to as *Ajamaru Karst Region* henceforth). Featured by typical tropical karst landforms, the region covers an area of about 2300 km^2. The karsted plateaus are, on the average, 300 to 500 m high a.s.l. Made up of the so-called Klasafat Limestones of the Miocene, they underwent very slight folding in Pliocene time, to become block-faulted and uplifted in Late Pliocene and Early Quaternary times.

Consequently, the process of karstification could not set in earlier than the end of Pliocene time. Given the favourable climatic conditions, it has been, however, very effective. As testified by Table 1, the karst region receives 4500 to 5000 mm of precipitation a year. The existing karsted orographic features resemble the low-cone-featured karst of *North Bone*, whose evolution was sketched by Pannekoek (50). The countless karst cones are covered by a dense primary, tropical forest.

The cone-studded karst plateaus are separated by depressions of different size. Largest is the *Ajamaru Basin* — or even polje as you like it — containing three contiguous lakes. The water level of the lakes is 50 to 55 m high a.s.l. The polje is about 20 km long (W-E) and 5 to 6 km broad (N-S).

The eastward continuation of the *Ajamaru Karst Region* is testified by several minor karst plateaus, on which, however, no description or detailed information is available (about 2000 km^2).

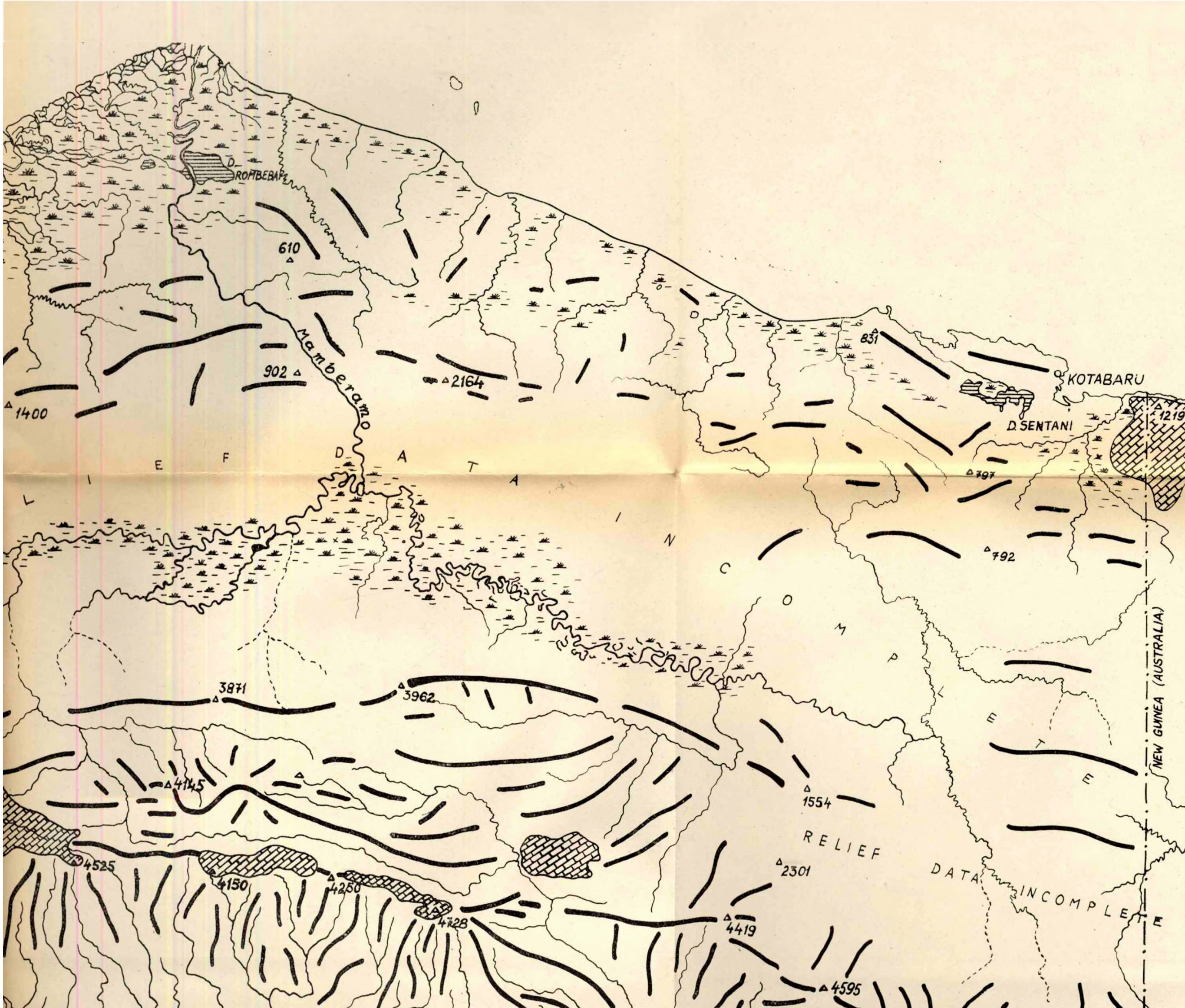
The next large karsted zone of the west sector is the so-called *Fak-Fak Karst Region* on Bombarai's northwestern *Onin peninsula*. The *Fak-Fak Mountains* are composed of markedly folded and fractured Neogene limestones and marls which have locally have been lifted even 1500 m high by rapid Late Tertiary and Quaternary tectonic movements. This fundamental geomorphologic setting has defined the characteristic relief pattern of the local karst: in contrast with the *Ajamaru Karst Region*, what we can find here are no gentle-contoured, rounded, conical forms, but hosts of striking karst pillars with impenetrable joints, precipices, and, of course, with a dense tropical vegetation. Because of the favourable orographic setting, this area is even more abundant in precipitations (about $>$ 5000 mm) than was found on the *Ajamaru Karst* (Table 1). The area featured by exposed karstic landforms measures some 1900 km^2. As shown by descriptions, the karst region is characterized by plenty of caves, pits, collapse-sinks, and corroded rock ridges.

Farther southward, the *Fak-Fak Mountains* is continued by the peanut-shaped *Karas* island which is, again, a rugged tropical pinnacle-studded karst. Farther southeastward, follows Irian-Barat's largest karst region — the *Kumawa Karst* on the island of equal name. Geologically and morphogenetically, this karst is altogether identical with the *Fak-Fak Mountains*.

The rugged pinnacle-studded karst emerges, here too 1000 to 1400 m high and covers some 1100 km^2 area. Its hydrography is unexplored, nearly half of the 3000 to 4000 mm of annual precipitation must be drained via unknown subsurface channels — huge cavern systems — into the *Banda Sea*.

Beside the karst areas described above, minor (80 km^2) karst surfaces are shown to the northeast of *Sorong* and to the south of the middle stretch of the *Wae Samson* river by "USAF Operational Navigation Chart". This latter appears to extend southward up to the *Klamagun Mountains* and eastward to *Sainkeduk*. Northwest of *Manokwari*, a 200-km^2 area northeast of the river *Prafi* is similarly built up of *Miocene* limes-

Fig. 26. Karst regions in the Central Mountains of West Irian. 1. Late Quaternary coasta plain (swamp, mangrove) 2. Non-karsted mountains 3. Karst relief



26. Karst regions in the Central Mountains of West Irian. 1. Late Quaternary coastal plain (swamp, mangrove) 2. Non-karsted mountains 3. Karst relief

tones, whose karst features — densely wooded, 300- to 400-m-high rounded, isolated karst cones — remind us of the *Ajamaru* Karst. To the west from there, south of *Wefiani*, powerful tectonic stresses have lifted the Miocene limestone sequence as high as 1500 to 2000 m, where a dense-vegetation-clad, rough rocky country, similar to the *Fak-Fak* Karst, has developed ("heavily wooded, rugged limestone mountains" as specified by the map of 1 : 250 000 scale).

On the west shore of *Sarera* Bay (Geelvink Bay) and of a minor secondary embayment — *Wandammen* Bay — even larger karsted surfaces can be found. South of the eastern tip of the volcanic *Arfak Mountains*, at the latitude of the *Rumberpon* island there are *Miocene* limestones of 500 to 700 m height, being attacked by karstification ("low hills, drainage indeterminate"). On the 1 : 250 000-scaled map scores of plunging rivers and surface-drainless karst lakes are shown. Farther south on the coast hundreds of square kilometers are occupied by similarly high, 500 to 800 m, karst plateaus, consisting of supposedly Jurassic limestones. The map shows, here too, rivers plunging underground "rough broken limestone terrain with many sink-holes and depressions". This area too is altogether inaccessible to man.

The karsted Paleogene limestone ranges striking north-northwest to northwest between *Arguni* and *Lakahia* Bays represent a 2000- to 2500-m-high discontinuous karst terrain. At a number of places, polje-like, closed depressions with subsurface hydrographic systems have developed. Doline- and polje-lakes are frequent. The highest points of the karsted plateaus lie at 1000 to 1500 m.

In the intrusion-interlaced, Hercynian-folded principal zone of the about 150- to 200-km-wide *Central Mountain Range (Pegunungan Saldju*, recently — *Peg. Maoke*; in Dutch papers — *Sneeuwgebergte)* Mesozoic and Lower Tertiary limestones and sandstones, locally thrust up to heights of 4000 to 5000 m, are predominant (Fig. 26.).

Information on the geographic location of the karst areas has been provided by the 1 : 1 000 000-scaled sheet ONC-M-13 of "USAF Operational Navigation Chart". As shown by the map, the southerly, highest zone of the huge alpine mountain range is featured by limestone pillars and high-mountain karst plateaus over nearly 300 km length to the east of Lake *Paniai*. *Puntjak Ngga Pulu* (Carstens) — Irian's highest peak with its 5030 m — is also made up of limestones. Its northeast slope carries an about 10-km-long glacier. Farther northeast, in the middle of the 25- to 30-km-wide limestone zone, stretches a deep depression with a minor river vanishing in sinkholes. The revelant remark on the map is: "numerous sink-holes". In the more-than-4000-m-high chains continuing eastward *(Nassau*-Gebergte) the limestone zone is 5 to 15 km wide; here is the second highest peak of the island — *Puntjak Iniaga* (one-time *Vilhelmina Peak*, 4750 m) which is, again, a karsted mountain.

At an air-distance of 30 to 40 km northeast of *Puntjak Iniaga*, lies the fertile, densely populated basin of the *Baliem* river. The east flank of the basin borders on a westward-sloping, karsted plateau of 2000 to 2500 m height (relative elevation — 400 to 800 m) and about 400 km^2 area.

Within the *Central Mountain Range*, Indonesia's easternmost karst region is the eastward-sloping plateau leaning against the southeast foot of *Pegunungan Digul* (its highest peak is *Puntjak Digul*, 4700 m, shown as *Juliana Peak* on old maps). The karst covers an area of 800 to 900 km^2 and is characterized by plunging rivers and depressions.

A large karst area is shown by the afore-mentioned map on the north coast, southeast of *Humboldt Bay* (town of *Kotabaru* or *Hollandia)*. It covers about 1200 km^2 area, but its larger part belongs to the area protectorated by Australia.

The map shows scores of spots dedicated "Relief data incomplete", where thousands of square kilometers of karsted surface may be still undiscovered.

On the relief forms of the karsted mountains and plateaus, lying at 4000 to 5000 m and difficult to approach, of the Central Mountain Range, few information is available. Nevertheless, some correlation with the alpinc high-mountain karst occurrences can be traced. The mean annual temperature of West Irian's high-mountain karst plateaus ranges from +3 to −3°C. Snow and ice have locally become permanent, precipitations amount to 4000 to 8000 mm a year. Since, under colder climate, corrosion is more effective, this circumstance, coupled with abundant precipitations, may contribute to the development of particularly rugged, poorly-plantcovered, impenetrable rocky country.

After discussing the karst areas of central *Irian Barat*, now I shall briefly deal with the karst phenomena of the major satellite islands.

The largest karst area can be found on the *Misoöl island.* As mentioned above, the island's orographic system is the western member of the *Fak-Fak — Kumawa — Adi*, etc. range. The endogenic stresses here have not lifted the Miocene limestone so high, and have not folded, nor faulted them to such an extent, as in the *Fak-Fak* Mountains for instance. The northeast one-third of the peninsula is made up of "heavily wooded limestone pinnacles" rising 200 to 400 m high, the plunging rivers reach the Seram Sea through an unexplored surbsurface hydrographic system. The area of the karsted terrain is about 800 km^2.

At the centre of *Salavati island* the tropical forest cover hides a range of 200-m-high karsted limestone cones of SW-NE strike. The strikingly dissected *Waigeo island* is predominated by eruptive rocks, though on the west peninsula and on the coast of *Majalibit Bay* the impenetrable tropical jungle locally hides 300- to 500-m-high karst plateaus. *Gam island* is almost entirely karsted (a total of 650 km^2).

Numfor island is a coral-reef karst of 150 to 250 m elevation, covered by a dense primary forest, its hydrography being indeterminate. The centres of *Biak* and of *Supiori* island, almost completely welded with it, are dominated by tropical karst features. The coast are made up of Quaternary corallium, the central parts consist of Neogene limestones with the typical variety of landforms of rugged, tropical, forested karst regions hiding a labyrinth of caves.

* * *

At the end of the above short review of the karst landscapes of the Indonesian Archipelago, *Table 3* is to present the essential morphologic data of the major karst areas, a tabulation which, I hope, may help the reader draw correlations.

Limited space and incomplete references have not allowed the author to dwell exhaustively on the matter. Large regions of the archipelago still lack basic geologic exploration. As for the karsted areas of little economic importance, they cannot boast of hardly any detailed information even concerning the geologically mapped sectors. What is known about these latter is largely restricted to the knowledge of mineral deposits, as prospecting has not been coupled with morphologic research. (The only exception to the rule seems to be in this respect Java's *G. Sewu.)* This fact is all the more regrettable as the archipelago could be made a colossal natural laboratory, where terrains of different geologic structure, different hydrographic pattern, having been karsted for different times, should be subjected to a detailed, comparative genetical analysis

Table No. 3.

Name of karst region	Island, geographic situation	Surface area km²	Average peak height m		Origin of rocks	Petrophysical characteristics	Beginning of karstification	Hydrological and morphological characteristics		Literature
			absolute	relative						
Sinamar-Kvantan-Takung Karst Region	Central Sumatra	200	500—900	150—300	Carboniferous	very hard crystalline limestone	Pliocene	well developed subsurface cavern system, with transient rivers	karst pinnacles with surrounding depressions	7, 44
Kalapanunggal Karst	Western Java	55	300—500	100—150	Miocene	rather hard compact reef limestone	Early Pleistocene	surface and subsurface runoff	plateau-type karst with rare cone-shaped hills	7, 49
Karangbolongi Gunung Sewu	Central Java	40	300—400	100—150	Miocene	rather hard compact reef limestone	Late Pliocene Early Pleistocene	well developed surface and subsurface drainage	hundreds of cone-shaped hills on a sloping surface	7
Gunung Sewu	Central Java, SE of Jogjakarta	1300	300—500	50—150	Miocene	rather hard compact reef limestone	Late Pliocene Early Pleistocene	well developed surface and subsurface drainage with transient underground rivers	thousands of karst cones, dolines and surface valleys	7, 13, 20, 21, 54, 55 25, 28, 29, 31, 32, 64 34, 35, 36, 42, 51
Eastern Gunung Kidul	Eastern Java	2000	350—450	100—150	Miocene	rather hard compact reef limestone	Late Pliocene Early Pleistocenc	well developed valleysystem, non-karsted type	cone- and pinnacle-shaped forms lacking, karst features scant	7
Nusa Barung	Island off SE Java	80	200—300	80—150	Miocene	rather hard compact reef limestone	Late Pliocene Early Pleistocene	well developed valleysystem, underdeveloped subsurface hydrologic system	developing serial cones without depressions	7
Blambangan	Southeastern peninsula of Java	about 420	250—350	50—150	Miocene	rather hard compact reef limestone	Late Pliocene Early Pleistocene	well developed surface and subsurface drainage system	adult or developing conical forms, few depressions	7
Bukit Badung	S peninsula of Bali	85	150—200	150—200	Miocene	less hard stratified reef limestone	Post-Pliocene	mainly surface runoff in deep karst valleys	flat monotonous grassy karst plateau without dolines	7, 26
Nusa Penida	island betw. Bali and Lombok	about 200	200—500	100—300	Miocene	less hard stratified reef limestone	Post-Pliocene	mainly surface runoff in deep karst valleys	flat monotonous grassy karst plateau without dolines	7
Northern Sumba	Sumba Island	about 3000	500—600	100—200	Miocene	less hard stratified reef limestone	Pliocen	well developed surface and subsurface drainage	savanna grown monotonous karts plateau, with dolines and some polje-like depressions	7, 40
Sambaliung-Mangkalihat Karst Region	Eastern Kalimantan	about 3000	500—1000	150—400	Neogene & Paleogene	hard well-karsting limestone	?	unexplored		7
Maros Karst Region	SW Sulawesi	about 300	300—550	100—250	Eocene	hard, pure, compact nummulitic limestone	„Postmittel Miozän" (Lehmann)	well developed subsurface hydrologic system	host of isolated and contiguous pinnacles and horsts with vertical walls and internal depressions	7, 58, 60, 61
North Bonei Karst Region	SW Sulawesi	about 300	250—500	30—80	Pliocene	loose reef limestone	Early Pleistocene	surface hydrographic system	isolated or serial rounded cones	7, 60, 61
Hitu Karst Plateau	Ambon Island	35	200—400	150—300	Pleistocene	loose crumbling coral and shell material	Late Pleistocene	primitive surface and subsurface drainage system	karr-patterned surface of a young plateau	7, 10
Ajamaru Karst Region	Irian Barat Doberai Peninsula	about 2300	300—500	100—250	Miocene	comparatevely hard compact limestone	Late Pliocene, Pleistocene	mainly surface runoff	rounded cones, cone reves rows with polje-like depressions	7, 50, 52
Fak-Fak Karst Region	Irian Barat Onin Peninsula	about 1900	1000—1500	300—600	Miocene	comparatevely hard compact limestone	Pliocene	surface drainage and markedly well developed subsurface hydrologic system	karst cliffs and rifts of high mountains	7, 50
Kumawa Karst Region	Irian Barat Kumawa Peninsula	about 1100	1000—1400	300—500	Miocene	comparatevely hard compact limestone	Pliocene	surface drainage and markedly well developed subsurface hydrologic system	karst cliffs and rifts of high mountains	7, 50

under approximately the same climatic conditions (except for Irian Barat's high-mountain karst terrains). Such systematic geomorphologic investigations would provide plenty of useful information not only for a better understanding of the given area, but for the solution of many open questions of climatic karst morphology as well.

Beyond promoting the progress of science, these studies would explore possibilities for the utilization of these vast areas and pave the road of social and cultural development of the peoples living there.

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KARSTGEBIETE IN INDONESIEN

von

D. BALÁZS

Zusammenfassung

Zwischen dem Massiv Südost-Asiens und dem australischen Kontinent ist eine gewaltige geosynklinale Zone eingeschlossen in deren zeitlich und räumlich sehr veränderlichen Meeresbecken, von den alten Zeiten her, eine Sedimentmasse von mehrere tausend Meter Mächtigkeit abgelagert ist. Diese Formationen wurden durch die endogenen Kräfte, in Form von Inseln, an mehreren Stellen über die Meeresoberfläche gehoben und die begonnen Verkarstierungsprozesse unter dem Einfluss des günstigen tropischen Klimas in den karbonatischen Gesteinen.

Der Verfasser dieses Artikels hat — im Laufe seiner Studienreise in 1964/65 — mehrere Karstgebiete der Inselwelt besucht, und gibt — teils auf Grund dieser Studien, teils mit der Benützung literarischer Materialien — ein Gesamtbild der grössten Karstgebiete. Der Aufsatz beschränkt sich auf die Inseln Indonesiens und beschäftigt sich nicht mit den zu den Philippinen bzw. zu Malaysien gehörenden Teilen des Ostindischen Archipels.

Die indonesische Inselwelt selbst besteht aus ungefähr 13 000 Inseln, deren Gesamtoberfläche (West-Irian einbegriffen) ungefähr 1 904 000 km^2 ausmacht. Aus dieser Oberfläche bedecken die Karstoberflächen mehrere 10 000 km^2 (annähernd 2–3% der Gesamtfläche).

I. Allgemeine Darlegung

1. *Stratigraphie.* Die ältesten, an der Oberfläche liegenden, sich verkarstenden Kalksteine stammen aus der Permo-Karbonzeit und bilden nur in Sumatra bedeutendere Karstgebiete. Die Kalksteine des Mesozoikums sind schon häufiger (hauptsächlich in West-Irian und auf den Maluku-Inseln), grössere Karstgebiete konnten sich aber auch in den Gesteinen dieser Ära nicht entwickeln, zufolge der häufigen Krustenbewegungen. Weniger gefaltet und zerbrochen sind die ausbeissenen karbonatischen Sedimente des Tertiärs, die grossen Karstgebiete von Java, Sulawesi, Ost-Kalimantan und West-Irian sind in diesen jungen Kalksteinen entstanden.

2. *Geochronologie und Tektonik.* Die Geologen unterscheiden im allgemeinen zwei junge orogene Phasen, den Beginn der ersteren setzen sie in die Kreide, den der letzteren ins Miozän. Die orogenen Kräfte waren auch in der plio-pleistozänen Zeit periodisch, intensiv tätig und haben die Grundlagen der heutigen Karstgebiete geschaffen. Im Pleistozän hab es auf diesem Gebiet keine wesentlichen Klima-Veränderungen, welche auf die Ausbildung der Karste bewirken können hätten.

3. *Klimatische Verhältnisse.* Die Inselwelt ist durch den Äquator in der Mitte geschnitten, das Klima ist dementsprechend feucht und tropisch (äquatoriales Klima). Die jährliche Normaltemperatur ist an der Meeresoberfläche 26–27°C, mit einer sehr geringen Jahresschwankung. Die Verteilung des Niederschlages ist — von der Lage der Inseln abhängig — differenzierter, im allgemeinen schwankt sie zwischen 1000 und 5000 mm (durchschnittlich 2500 mm). Die östlichen Inseln befinden sich unter einer starken Monsun--Wirkung, das Jahr teilt sich auf eine Regen- und eine Trocken-Periode. An den beiden Seiten des Äquators sind die Zeitpunkte der feuchten und trockenen Jahreszeiten verwechselt (Tabellen 1 und 2). Die Klimaverhältnisse sind für eine intensive Verkarstung besonders günstig.

4. *Pflanzen- und Tierwelt.* Die freiwachsende Pflanzendecke der Karstplateaus und Hügelländer besteht im allgemeinen aus tropischem Regengehölz, die nur auf einigen weniger feuchten Gebieten der Kleinen Sunda-Inseln durch Savannen mit Alang-Alang-Gras abgelöst wird. Da die Erosion des tropischen Bodens auf den ausgerotteten, ausgebrannten Waldgebieten ein ausserordentlich rascher Prozess ist, erneuert sich an der Stelle der aufgestörten primären Wäldern — auch bei einem bedeutenderen Niederschlage — nur eine niedrige, dichte, buschige Vegetation. Mit Ausnahme der dichtbevölkerten Java gibt es keine Kulturvegetation auf den Karstgebieten (ausser dem bedürfnisslosen Kassava). Namhafte Tiere der Tierwelt sind Tiger, Panther, Affe, Hirsch, Wildschwein, Riesenechse, usw.

5. *Hydrographie.* Die Schwankung der Karstwasserspiegel ist — wegen der saisonmässigen Niederschlagsverteilung — sehr stark. Über Einsickerung und Abfluss haben wir keine sicheren Angaben. Der Abfluss-Faktor ist übrigens sehr veränderlich (25–50%). Physikochemische Angaben der untersuchten Karstquellen: Wassertemperatur = 23,3–27,6°C, pH = 6,8–7,3, gelöste $CaCO_3$– Gehalt = 114,2–415,8 mg/l, Karbonathärte = 6,4–23,3 dH° (Durchschnittwert dieser letzteren: 11,0 dH°).

6. *Karstdenudation.* Anhand der auf den vier untersuchten Karstgebieten gesammelten Angaben beträgt die durch Auflösung des Gesteinsmateriels bedingte Denudation jährlich 0,083 mm, d.h. 83 m^3 pro km^2. Nach den Beobachtungen dürfte die mechanische Erosion (flächenmässige Denudation) das Vielfache dieses Wertes erreichen (0,1 – 0,4 mm pro Jahr).

7. *Morphologie.* Die Ausbildung der charakteristischen Turm- und Kegelberge der tropischen Karstlandschaft ist das Ergebnis der Tätigkeit des reichen und intensiven Niederschlages, die Entwicklung dieser Formen steht aber auch mit vielen anderen Umständen in Zusammenhang (petrographische, tektonische, zeitliche und räumliche Faktoren), die vom Verfasser in einem speziellen Aufsatz besprochen werden. Die beiden klassischen tropischen Karsttypen: der *Kegelkarst* von *G. Sewu* und der *Turmkarst* von *Maros* sind nur an einigen Stellen in vollendeter Entwicklung auffindbar, der Formenschatz des grösseren Teiles der Karstflächen weist nur eine Übergangs (oftmals embryonale)-Phase auf ohne die sehenswerteren grösseren Formen. Auch für die hiesigen tropischen Karste ist im allgemeinen das Überwiegen der positiven Formen (Vollformen) gegenüber die Depressionen (Hohlformen) charakteristisch (wenige Dolinen, Polje).

II. Regionale Darlegung

Der Verfasser gibt eine schematische Schilderung der grössten Karstgebiete der Inselwelt, von Sumatra bis West-Irian. Über diese Gebiete führt er auch eine tabellarische Zusammenstellung mit den wichtigsten charakteristischen Angaben (Tab. 3.) an.

КАРСТОВЫЕ РАЙОНЫ В ИНДОНЕЗИИ

Д-р ДЕНЕЩ БАЛАЖ

Резюме

Между массивом юго-восточной Азии и континентом Австралии вклинивается огромная геосинклинальная зона, где в весьма неодинаковых по возрасту и боъему морских бассейнах отлагался до наших дней масса отложений мощностью нескольких тысяч метров. Эти образования на многих местах были подняты эндогенными силами в виде островов над уровнем моря и под влиянием благоприятного трописческого климата наступило карстообразование в карбонатных породах.

Автор данной статьи в течение научной командироваки в 1964/65 гг. посетил несколько карстовых районов архипелага и — с использованием этих исследований с одной стороны и с помощью литературных материалов, с другой — он дает обзор наибольших карстовых областей. Работа ограничивается описанием островов принадлежащих к Индонезии и не останавливается на принадлежащих к Филиппинским островам или к Малайе частях Восточно-Индийского архипелага. Индийский архипелаг сам состоит из около 13 000 островов, общая площадь которых (вместе с западным Ириа-

ном) составляет около 1,904.000 квадратных километров. Из этой площади на долю карстовых районов приходится несколько десятков тысяч км² (около 2—3%).

I. ОБЩЕЕ ИЗЛОЖЕНИЕ

1. Стратиграфия. Самые древние, выходящие на поверхность и подвергающиеся карстовой эрозии известняки относятся к пермо-карбонской системе и образуют только на территории Суматры знаменитые карстовые зоны. Мезозойские известняки пользуются уже более широким распространением (главным образом в западном Ириане и на островах Малаку), но какие-нибудь значительные карстовые зоны не могли сформироваться даже в мезозойских породах этого времени, из-за частых движений земной коры. Менее складчатыми и раздробленными являются выходы карбонатных отложений третичного периода; большие карстовые области островов Ява, Сулавеси, восточного Калимантана и западного Ириана развивались на этих молодых известняках.

2. ГЕОЛОГИЧЕСКАЯ ИСТОРИЯ И ТЕКТОНИКА

Геологии обычно выделяют две молодых орогенических фазы, начало первой они относят к меловому, а второй — к миоценовому периоду. Орогенические силы периодически интенсивно действовали и в плио-плейстоценовое время и фундаменты современных карстовых областей формировались в это время. В плейстоценовое время значительных изменений климата — способных влиять на развитие карстов — на данной площади не было.

3. КЛИМАТИЧЕСКИЕ УСЛОВИЯ

Экватор рассекает архипелаг посередине, следовательно его климат является влажным, тропическим (экваториальный климат). Средняя годовая температура на уровне моря составляет 26—27 C°, с очень малым годовым колебанием. Распределение атмосферных осадков — в зависимости от положения отдельных островов — является более дифференцированным, оно колеблется вообще от 1000 до 5000 мм (в среднем около 2500 мм). На восточных островах монсунное влияние сказывается сильнее, год делится на дождливый и сухой периоды. На обеих сторонах Экватора время наступления влажного и сухого периодов изменяется. (Табл. 1 и 2). Климатические условия очень благоприятны для имтенсивного карстового процесса.

4. ФЛОРА И ФАУНА

Естественным растительным покровом карстовых плато и холмистых рельефов является вообще тропический дождевой лес, который сменяется лишь на нескольких менее осадочных площадях Малых Зондских островов саваннами и травой аланг-аланг. Так как эрозия тропической почвы происходит чрезвычайно быстро, в разрушенных, опаленных областях, на месте уничтоженных первичных лесов — даже при большом количестве осадков — вообще возобновляется только низкий, густой кустарник. За исключением густонаселенной Явы, культурной вегетации в карстовых областях нет, (в крайнем случае нетрудоемкая культура кассава). Самым большими представлями фауны являются тигр, пантера, обезяны, олень, кабан, комодовые драконы, и .т. п.

5. ГИДРОГРАФИЯ

Зеркало карстовых вод — из-за сезонного распределения осадки — очень изменчиво. Относительно количества просачивающихся осадков и величины стока мы не имеем никаких надежных данных. Коэффициент стока впрочем очень изменчив (от 25% до 50%). Физикохимическая характеристика изученных карстовых источников: температура воды — 23,3 — 27,6 C°; pH — 6,8 — 7,3; растворенный $CaCO_3$ — 114,2 — 415,8 мг/л; карбонатная жесткость — 6,4 — 23,3° по немецкой шкале) средняя величина последней — 11° (по немецкой шкале).

6. КАРСТОВАЯ ДЕНУДАЦИЯ

На основании собранных данных в четырех исследованных областях вызыванная выщелачиванием денудация составляет ежегодно 0,083 мм, т. е. 83 м³ на км². Соответственно наблюдениям механическая эрозия (площадная денудация(может составлять в несколько раз больше данной величины (0,1 — 0,4 мм/год).

7. МОРФОЛОГИЯ

Развитие характерных для тропического карста конусообразных и башенных форм связано с большой влажностью климата, но формирование таких форм также зависит от многих других условий (петрографические, тектонические, геохронологические и стратиграфические условия), которым автор посвящает специальную статью. Два характерных типа тропического карста: „Кегелькарст" из Г. Севу и „„Турмкарст" из Мароша наблюдаются только очень редко в полном развитии, подавляющее большинство карстовых форм почти всюду находится в переходной (часто эмбиональной) стадии развития, с отсутствием каких — нибудь наглядных крупных форм. Для здешных тропических карстовых районов также характерно всеобщее преобладание положительных форм (Фоллформен) по отношению к депрессиям (Голформен) (мало долин, польев).

II. РЕГИОНАЛЬНЫЙ ОБЗОР

Автор дает схематическую характеристику самых больших карстовых регионов архипелага от Суматры до западного Ириана. В прилагаемой им таблице содержатся важнейшие показателя и данные (табл. 3).

KARSTREGIONOJ EN INDONEZIO

D. BALÁZS:

Resumo

La aŭtoro studis kelkajn karstregionojn de la Indoneza Insularo en la jaroj 1964/65. Li desegnas resuman bildon pri la plej grandaj karstregionoj de Indonezio, parte lau siaj studadoj parte laŭ literaturaj indikoj. La aero de la Indoneza Insularo konsistanta rondcifere el 13 000 insuloj estas ĉirkaŭ 1 904 000 km² (kune kun Okc. Iriano). El tiu ĉi aero estas karsta surfaco kelkaj 10 000 km² (ĉ. 2–3%).

I. Ĝenerala konigo

1. *Stratigrafio.* La plej maljunaj, surface situantaj karstiĝantaj kalkŝtonoj originas el la periodo karbono-permo. Nur en Sumatro ili formas pli signifajn karstregionojn. Mezozooaj kalkŝtonoj estas jam plurloke troveblaj (ĉefe en Okc. Iriano kaj sur la Malaku--insuloj), sed el ili ne povis elformiĝi pli grandaj karstregionoj sekve de oftaj krustomovoj. Estas malpli cifitaj kaj rompitaj la terciaraepokaj karbonataj sedimentoj. La grandaj karstregionoj de Javo, Sulavezo, Or. Kalimantano kaj Okc. Iriano formiĝis sur ĉi tiuj junaj kalkŝtonoj.

2. *Geohistorio kaj tektoniko.* La geologoj determinas de junajn montkreajn fazojn: en la kretaceo kaj en la mioceno. La montkreaj fortoj efikis periode, intense ankaŭ en la plio-pleistoceno, tiam elformiĝis la fundamentoj de la hodiaŭaj karstregionoj. Dum la pleistoceno en tiu ci areo gravaj klimatoŝanĝoj, influantaj la karstformiĝon, ne okazis.

3. *La klimato.* Estas malseka-tropika, ĉar la insularon tranĉas tra la mezo la ekvatoro. La jara meztemperaturo ĉe la marnivelo estas ĉ. 26–27°C, kun minimuma ŝanĝo dum la jaro. La jara kvanto de precipitaĵo laŭ la situo de insuloj estas inter 1000–5000 mm-oj (meze 2500 mm-oj). Sur la orientaj insuloj forte efikas la musono (1-a kaj 2-a tabelo). La klimato bonege taŭgas por la intensa karstformiĝo.

4. *Flaŭro kaj faŭno.* La karstajn altebenaĵojn kaj montetarojn kovras ĝenerale tropika pluv-arbaro, kiun nur en kelkaj regionoj de la insuloj Malgranda-Sundo ricevantaj nemultan precipitaĵon anstataŭas la savano, la herbo „alang-alang". En la loko de elhakitaj aŭ forbrulintaj arbaroj kreskas ĝenerale nur malalta densa arbusta vegetaĵo, car tie la erozio de la tropika tero estas rapida. En la karstregionoj kulturvegetaĵaro ne estas trovebla (maksimume la modesta „kassava"), escepte la insulon Javo. La pligrandmezuraj specoj de la flaŭro estas la tigro, pantero, simiospecoj, cevro, apro, giganta lacerto ktp.

5. *Hidrografio.* Laŭ la sezona ŝanĝo de la precipitaĵo la karstakvoniveloj grandmezure ŝanĝiĝas. Ne ekzistas fidindaj indokoj pri la mezuro de la enfiltriĝo kaj forfluo. La koeficiento de la forfluo estas tre varia (20–50%). Fizikaj-kemiaj indokoj pri la ekzamenitaj karstaj fontoj: temperaturo de akvo 23,3–26,7°C, pH 6,8–7,3, malmoleco 6,4–23,3 (meze 11)° germ.

6. *Karsta denudacio.* En kvar ekzamenitaj karstregionoj la denudacio pro solviĝo estas jare 83 m³/km² (0,083 mm). Laŭ la observadoj la meĥanika erozio kelkloke povas esti multoble pli granda (0,1–0,4 mm/-jaro) ol tiu grado.

7. *Morfologio.* La elformiĝo de tipaj tur- kaj konusformaj montoj en la tropika karsto estas konsekvenco de la abunda kaj intensa precipitaĵo, sed la disvolviĝo de tiuj formoj havas ankaŭ multajn aliajn kondiĉojn, kiujn la aŭtoro pritraktas en aparta traktato. La du klasikaj tipoj de la tropika karsto: la „Kegelkarst" de G. Sewu kaj la „Turmkarst" de Maros estas nur kelkloke troveblaj en plena disvolvo. Multfoje la formoj de la karstaj surfacoj montras mezan (eĉ embrian) etapon de la evoluo, sen spektaklaj grandformoj. Estas ĝenerale tipa en la Indoneziaj tropikaj karstoj la supernombro de la pozitivaj formoj (Vollformen) kontraŭ tiuj negativaj (Hohlformen) .

II. Regiona konigo

La aŭtoro skematike prezentas la plej grandajn karstregionojn de la insularo, de Sumatro ĝis Okc. Iriano, ankaŭ en tabelo (tab. 3-a).