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The development of karst landscapes in Vietnam

ABSTRACT: The main factors controlling the development of tropical karst landscapes in Vietnam are: structural and lithological properties of carbonate rocks, tectonic movements, and the position of ground-water levels. Corrosional undercutting and the subsequent gravity collapse of rocks is the chief mechanism involved in the retreat of karst walls and the formation of flat-floored karst depressions. This mechanism comes into action when the negative forms produced by vertical corrosion reach the ground-water level and it is effected by agressive swamp waters or, at sea level, by subsaline marine waters. The role of tropical climate is important in providing huge amounts of solvent by means of heavy rainfalls and by elimination of frost splitting, which in temperate climatic zones is the most effective factor acting upon the exposed limestone walls.

INTRODUCTION

The origin of tropical landscapes is still controversial. The controversy is centered around the role played by climatic, structural, and biogenic factors in the development of such landscapes. Authors following the morphoclimatic school of LEHMANN (*see* SWEETING 1972) maintain that karst forms in different climates have independent modes of development and that the climatic factors are here of primary importance. Other investigators emphasize the significance of structure and lithology of the rocks involved. They insist that the climatic factors influence only the intensity and speed of dissolution but it is the character of limestones itself that gives rise to specific karst forms (KLIMASZEWSKI 1958, JENKO 1959, KOZARSKI 1963, VERSTAPPEN 1964, PANOŠ & STELCL 1968). There are also investigators who claim that large accumulation of organic matter derived from luxuriant vegetation in tropical zones plays a decisive role in the development of karst forms (JAKUCS 1977). With recent trend towards biologic corrosion and "phytokarst" phenoména (SMYK & DRZAŁ 1964), some authors consider the possibility that "such humble and inconspicuous creatures as boring algae were responsible for some of the world's most curious landscape art" (FOLK & *al.* 1973, p. 2359).

The present paper is a preliminary report from work in progress on karst forms in the nothern part of Vietnam. It aims to demonstrate the influence of rock structure and neotectonic movements on the development of karst landscapes in tropical zones. The following considerations are based upon observations gathered from three representative regions: Huong Tich, Ha Long, and Bac Son (*see* Text-fig. 1).

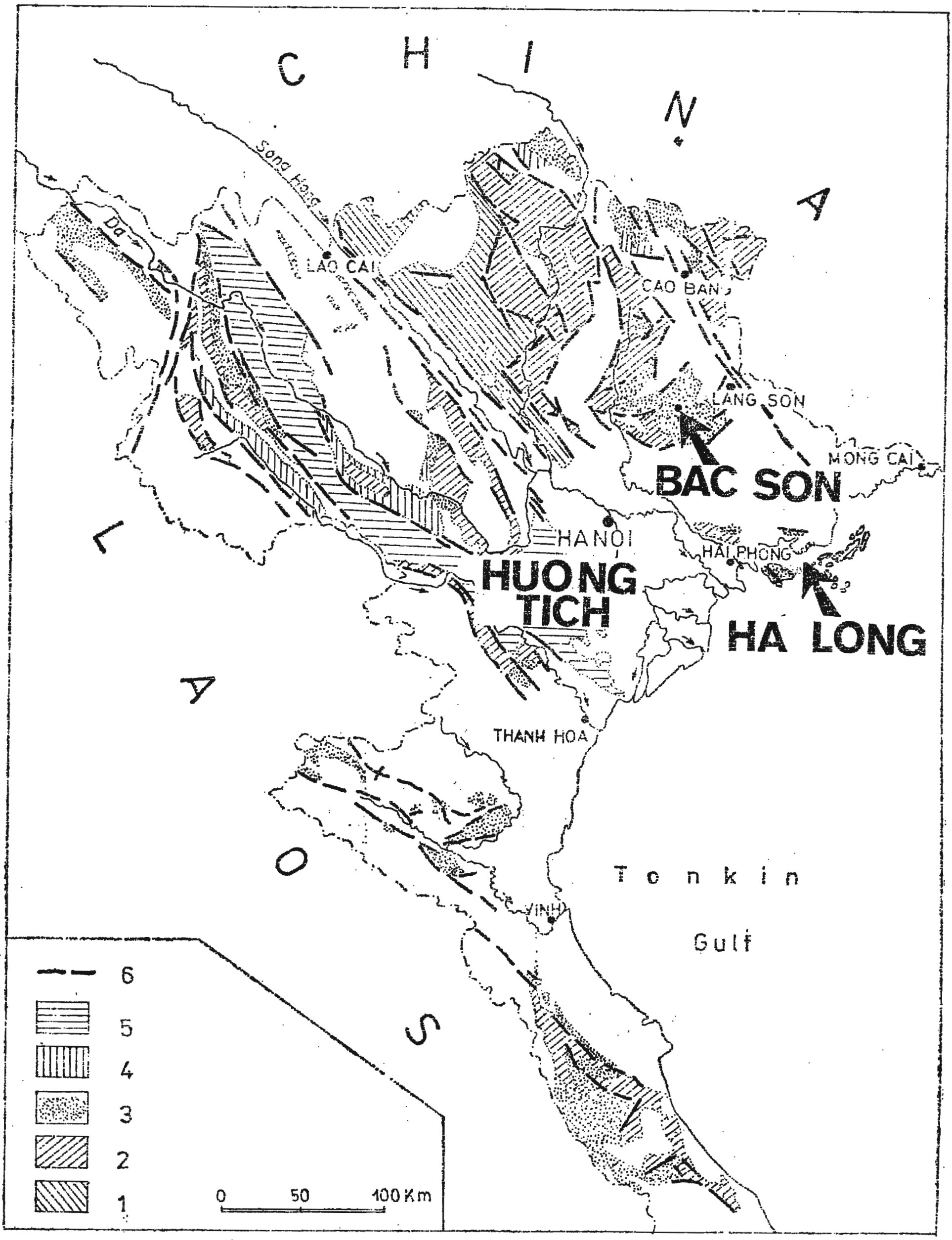

Fig. 1. Distribution of carbonate rocks in Vietnam

1 — Cambrian, **2** — Devonian, **3** — Upper Carboniferous through Lower Permian, **4** — Upper Permian, **5** — Triassic; **6** — faults

REVIEW OF PREVIOUS INVESTIGATIONS

The karst features of Vietnam have been mentioned in a number of publications (for references *see*: TRI & *al.* 1977). There are, however, only few comprehensive studies devoted specifically to this subject (BLONDEL 1929; ZUBASHCHENKO 1960; ŠILAR 1965; GŁAZEK 1966, 1970; THUY 1972; MY & *al.* 1976). All these authors stress the importance of young tectonic movements for the development of karst features though they differ in their evaluation of the role played by the climate. For instance, BLONDEL (1929) does not recognize in the Vietnamese karst any features which would be diagnostic of tropical climates. Other authors instist that these landscapes could only have formed under humid and hot conditions (ŠILAR 1965, THUY 1972, MY & *al.* 1976).

It is to be recalled that the karst terranes of Vietnam are part of the world's largest karst area which includes a considerable portion of southern China. The karst of China is still far from being adequately investigated, but a number of observations already made on this subject (KLIMASZEWSKI 1958, KOZARSKI 1964, ŠILAR 1965, JENNINGS 1976) are also of interest for the study of karst in Vietnam.

CLIMATE

The climate of North Vietnam is of the sub-tropical monsoon type with a dry season lasting from October to March. Mean annual temperature is about 20°C, air temperatures average 28°C for July and August with maxima reaching 43°C, and 12—15°C for January. In mountaneous region of Bac Son, the minimal winter temperature may occasionally drop to 0°C. Annual rainfall varies from 1500 to 2000 mm with maxima up to 3500 mm (Ha Long). The mean air humidity is 77—85%.

GEOLOGIC SETTING

The karst landscapes under consideration developed chiefly in higly folded carbonate rocks ranging in their stratigraphic age from the Middle Carboniferous to the Lower Permian. The rocks in question consist of medium and thick bedded limestones with sporadic intercalations of massive limestone bodies. In most of the areas investigated, the limestone layers are steeply dipping or vertical, and are cut by abundant joints and fractures, and also by numerous faults. The dislocations are associated with zones of breccias and highly tectonized rocks. The thickness of the carbonate sequence amounts up to 1000—1300 m in Bac Son.

The level of summit heights of karst ranges in northern parts of Vietnam is inherited from a former extensive planation surface which is generally regarded as Paleogene in age. Well preserved but not completely developed planation surfaces which morphologically acquire much lower position date back to Pliocene time. In many inland areas such surfaces have been differentially uplifted by neotectonic movements. This uplift resulted in the incision of rivers and the formation of waterfalls.

HUONG TICH REGION

The landscape of Huong Tich is that of tower karst with variously shaped vertically-sided and rugged karst hills rising up to 150 m from the swampy plains of marginal poljes (Pl. 1, Figs 1—3). The groundwater level coincides here with the surface of the plains. Consequently, the agressive swamp waters are in permanent contact with the base of karst hills. In such situation, the basal sapping, *i. e.* the corrosional undercutting (*Losungsunterscheidung* of LEHMANN 1963) is very active. It is evidenced by deep solutional notches at the foot of karst hills. The undercutting leads to recurrent episodic collapses whereby large portions of vertically disposed limestone layers and/or joint-bounded blocks become dislodged and fall onto the swampy ground (Text-fig. 2). Here, the broken rock fragments are subject to rapid dissolution by rain and swamp waters. With the disappearance of rock fragments, the corrosional undercutting is renewed and the conditions conducive to collapse and rockfalls are reinstated.

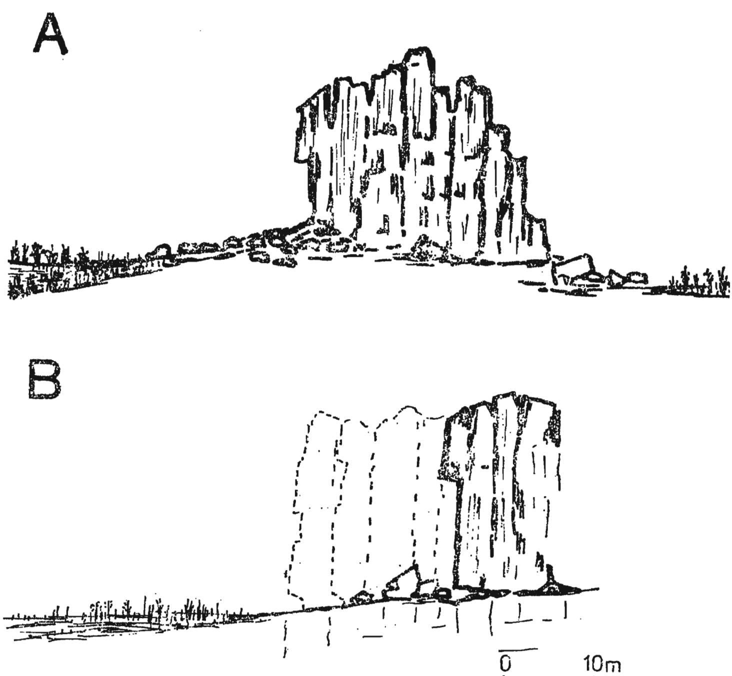

Fig. 2. Karst hills rising from swampy plain in Huong Tich: wall retreat by corrosional undercutting of vertically dipping layers of limestones (*cf.* Pl. 1, Fig. 1)

The solutional undercutting results in a progressive retreat of karst cliffs and lateral reduction of positive forms. The rapid recession is clearly demonstrated by fresh scars on the walls of karst hills and by the absence or scarsity of rillkarren and other minor solution features on the newly exposed rock surfaces. It is also evidenced by the rock debris at the foot of karst hills. In a further development, the retreat of walls leads to a lateral extension of negative forms and, ultimately, to the formation of the solution planation surfaces. The receding walls, however, retain their precipitous character so that the tower karst once formed is perpetuated (*cf.* SWEETING 1971).

HA LONG REGION

The region of Ha Long is presumably the world's most spectacular example of inundated karst landscape (Pls 2—3). The Holocene Flandrian transgression affected the already mature karst topography with isolated mogotes which now rise out from a very shallow bay in the form of picturesque cliffs, stakes and miniature islands (*archipelkarst* of THUY 1972). The corrosional undercutting at sea

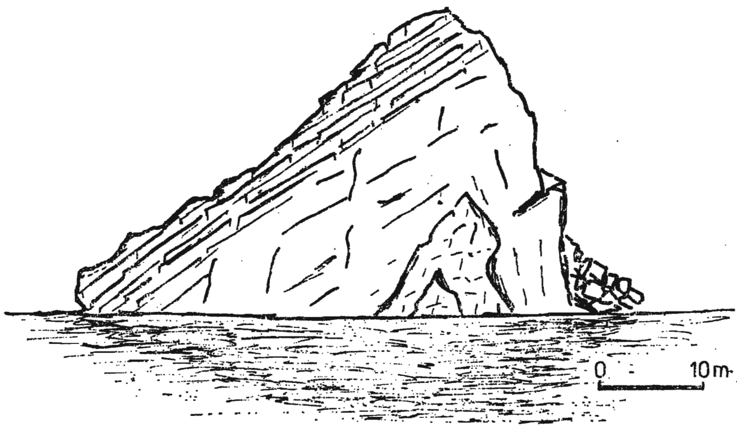

Fig. 3. Asymmetric karst hill in Ha Long

level is here exceptionally intensive. The dissolution of limestones is evidenced by deeply incised corrosion notches which may proceed several meters back from the walls of karst hills. In places, the corrosion acting from opposite sides of karst towers cuts through the towers to produce flat and shallow sea arches (Pl. 3, Fig. 2).

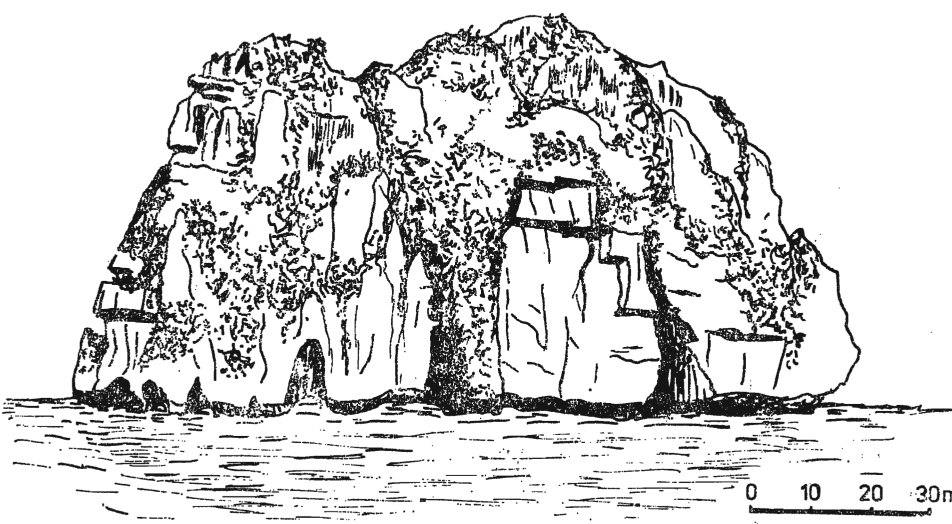

Fig. 4. Fresh scars on walls of karst hill and corrosional notches at sea level (*cf.* Pl. 3, Fig. 2) in Ha Long

The reasons for the unusual agressiveness of the Ha Long bay waters with respect to limestones are as follows. Firstly, the bay waters are much less saline than it is the case with normal sea waters. Within the limits of 10 m isobath, the salinity of the Ha Long waters varies between 0.91% and 3.10‰, with lower values close to the surface. This is chiefly due to the abundant influx of fresh waters supplied by large rivers (Hong and Bach Dang) emptying into the bay. The mixture of marine and fresh waters, notably that with the salinity values between 0.5% and 1.0‰, is a highly effective solvent of limestones and its role in the formation of coastal karst forms is the same as it was demonstrated by RUDNICKI (1980) in Italy. Secondly, the shallowness of the bay (the depth of waters generally does not exceed few meters) reduces the surge and spray activity so that corrosion is concentrated within the interval between high- and low-water mark which is about 2 m.

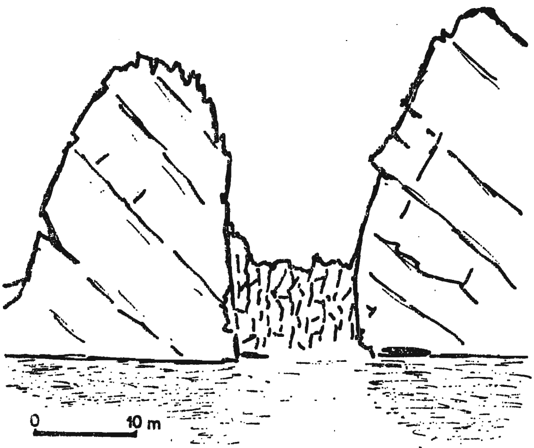

Fig. 5
Pass in a karst hill, produced along brecciated zone in Ha Long

The intensive undercutting by subsaline waters results in conspicuous and widespread collapse phenomena. The walls of karst hills show fresh scars (Text-fig. 4) and are commonly devoid of rillkarren and related dissolution features (*cf.* RÓŻYCKI 1984). Under the present conditions the steep walls of karst hills are subject

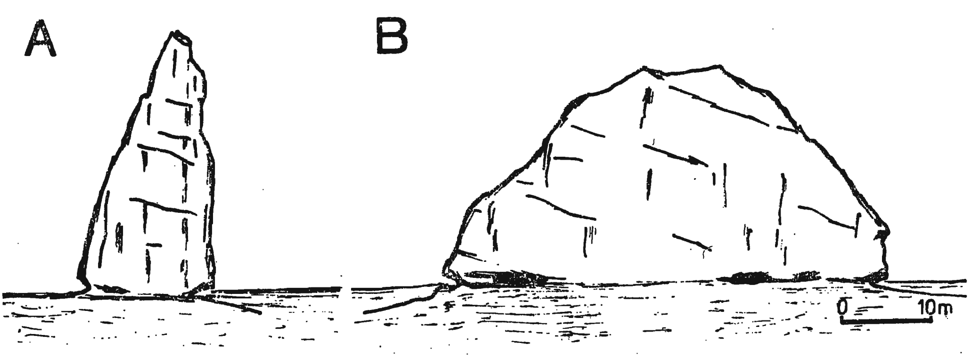

Fig. 6. "Chapeau bras" type of karst hill in Ha Long: A — transverse view, B — longitudinal view

to rapid parallel retreat and the landscape is undergoing substantial lateral transformations. The passes in karst hills usually develop along the zones of brecciation (Text-fig. 5).

The karst hills of Ha Long vary in size and shape and rise above sea level up to 200 m. The domed hills are very rare. Apart from rugged pinnacles and towers there are karst hills which in longitudinal sections reveal plano-convex and in transverse section wedgelike profiles. Such forms are here indicated as the "chapeaux--bras" type of karst hills (Pl. 2, Fig. 2, and Text-fig. 6). Where the limestone layers are less steeply inclined the karst hills show distinctly asymmetrical longitudinal profiles (*see* Text-fig. 3 and Pl. 2, Fig. 3) with the gentler slope following the dip of strata (*cf.* KLIMASZEWSKI 1958, KOZARSKI 1964).

BAC SON REGION

The landscape of Bac Son is that of "polygonal karst" of WILLIAMS (1971). The closed depressions, known as "lungs"*, are distinctly polygonal in plan view and their contours follow the tectonic pattern of the region. The lungs tend to develop at the intersection of major tectonic fractures which are commonly associated with zones of breccias. Such zones, being susceptible to vertical solutional degradation, are expressed in topography in the form of low, easily accessible passes incised into the karst ranges separating the neighboring lungs (Text-fig. 7).

The flat bottoms of lungs are covered with a thin mantle of soil and karst residues. In most instances, these bottoms are located above the ground-water level. They are dry or inundated only temporarily during heavy rains (Pl. 4, Fig. 2). Consequently, there is no evidence of any significant solutional undercutting at the foot of karst hills and no trace of active retreat of karst walls. The process of intensive lateral transformation of the karst landscape and the extension of karst depressions has virtually ceased. However, beneath the soil cover of lungs there is a solutional enlargement of fissures and, at least a localized lowering of the limestone surface manifested by the appearance of sinkholes.

The positive karst features of Bac Son differ from those regarded as characteristic of tropical karst zones. Steep-sided pinnacled karst towers and "sinoid" hills (*sensu* PFEIFFER, *see* SWEETING 1972) are absent or rare. The most common forms are karst pyramids (*sensu* JAKUCS 1977) showing roughly polygonal contours and more or less uniformly sloping sides (Text-figs 8—9 and Pl. 4, Fig. 1). These karst forms are developed in vertically disposed well-bedded and jointed limestones. Marked irregularities in the shape of karst pyramids occur where the rock sequence contains interbeddings of massive limestones.

The origin of pyramidal karst hills in the Bac Son region is open to discussion. At the time of intensive lateral expansion of lungs, these hills might had been and,

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* The *lung* (plural: *lungs*), it is a common Vietnamese name for a karst form which may be defined as a large sinkhole, with gentle slopes, and attaining a diameter up to 1 km; the *lungs* develop preferentially in bedded limestones. In all these features, the *lungs* differ from the *hoyos* of the Cuban karst (*see* GRADZIŃSKI & RADOMSKI 1965, 1967).

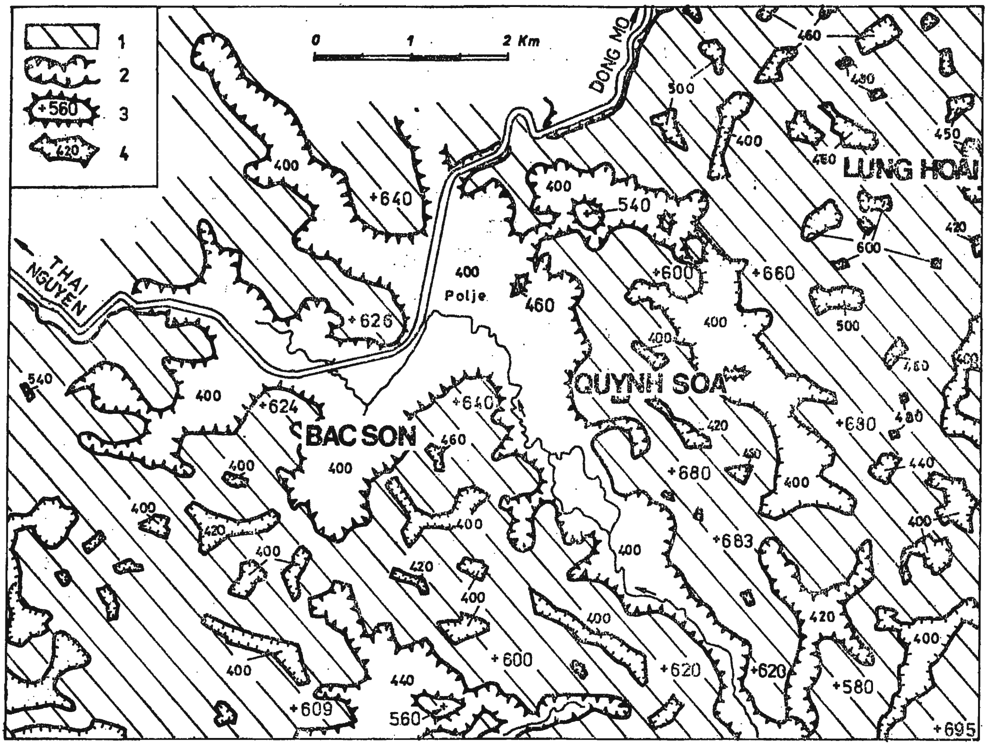

Fig. 7. Investigated region of polygonal karst in Bac Son
1 — karstifying limestones, 2 — poljes, 3 — karst hills, 4 — lungs; height in meters a.s.l.

presumably, were steep-sided. However, after the lowering of ground-water level and in the absence of active corrosional undercutting, the primarily precipitous hill slopes have been rendered less steep. Here again, the reduction of steepness

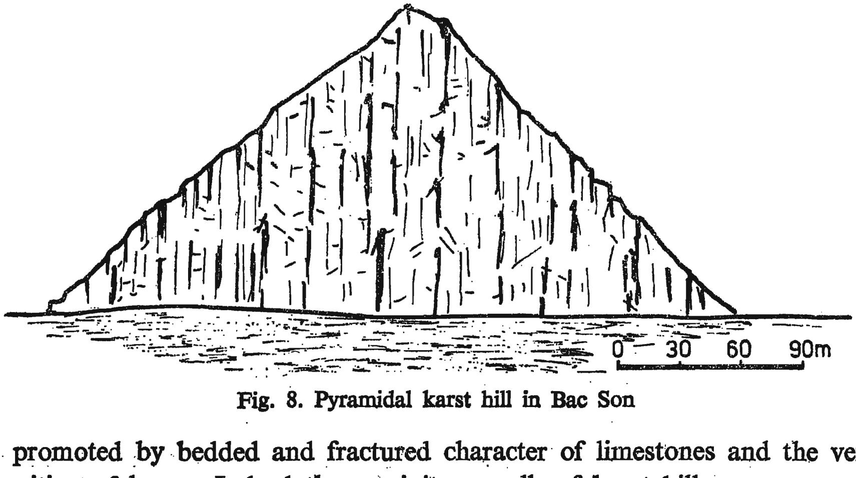

Fig. 8. Pyramidal karst hill in Bac Son

was promoted by bedded and fractured character of limestones and the vertical disposition of layers. Indeed the precipitous walls of karst hills are seen only in those places where the margins of lungs are made up of massive limestones. Such walls are fluted by rillkarren and reveal the presence of vertical karst chimneys. There is, however, no sign of any significant recession of slopes produced by slow dissolution by rain-waters washing the cliff faces (surface runoff).

Fig. 9. Landscape of karst pyramids in Bac Son

FORMATION OF FLAT-FLOORED KARST DEPRESSIONS

From the foregoing data it appears that corrosional sapping combined with gravity collapse is the chief mechanism promoting the recession of karst slopes and the formation of flat-floored depressions. This mechanism comes into action where the bottoms of karst depressions coincide with regional or general base-levels and are occupied by swampy or subsaline waters. The recession brings about a progressive extension of lungs and, ultimately, may lead to the appearance of planation surfaces with isolated mogotes. This conclusion is confirmed by experimental studies conducted by DŻUŁYŃSKI, GIL & RUDNICKI (*personal comunication*). The rapid retreat of karst walls is greatly facilitated by vertical disposition of stratified limestones. One can envision that in horizontally disposed rocks or in massive limestones, the slope recession is slower. However, the formation of extensive karst planation surfaces and the destruction of residual hills require a prolongued period of tectonic quiescence and the stability of base levels.

The process of corrosional sapping comes to its end when the ground-water level is lowered and the karst depressions become dry. In such situation, the lateral corrosion is reduced to minimum and is exclusively effected by surface runoff of rain water. In massive limestones, the steep faces of cliffs may survive for a long time but in vertically disposed well-bedded limestones the precipitous walls are transformed into more gently inclined slopes.

Generally, the surficial karst processes begin with the uplift of limestone terrains and the lowering of karst watertable. It is the vertical corrosion that dominates in the incipient stage of karstification. The lungs start to develop when the karst holes produced by vertical corrosion reach the ground-water level.

ALTITUDINAL RELATIONSHIPS BETWEEN POSITIVE AND NEGATIVE KARST FORMS

The present karst massifs of Vietnam are rised to various altitudes above sea level. However, their relief is essentially the same and varies from 50 to 300 m. This is clearly demostrated by a series of transverse (Text-fig. 10) and longitudinal sections (Text-fig. 11) through the karst massifs. The sections were constructed by plotting the summits of karst hills and the bottoms of lungs respectively. The resulting curves (*see* Text-figs 10—11) are roughly parallel to each other. In other

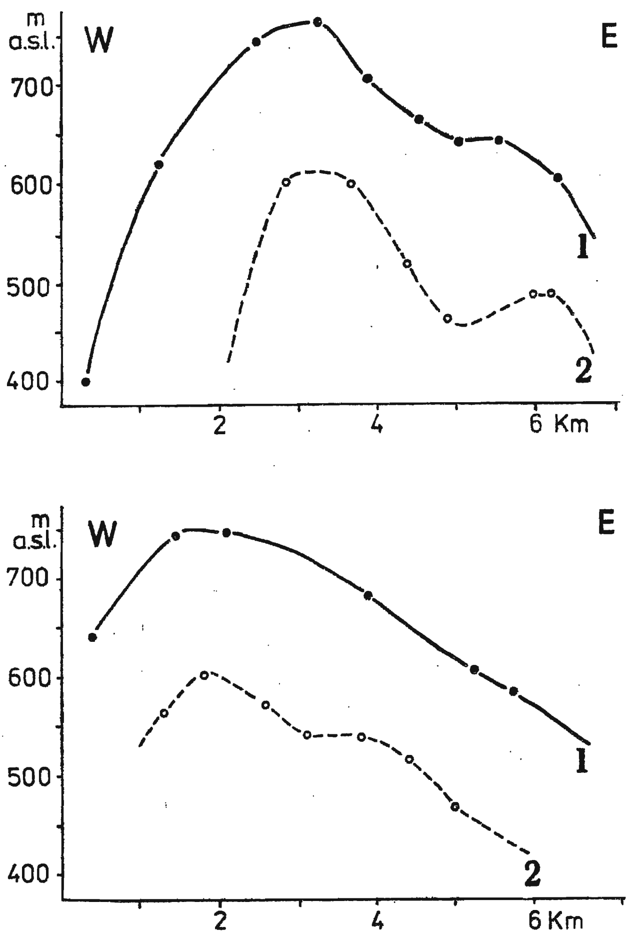

Fig. 10. Dependence between the altitude (in meters a.s.l.) of: 1 — summits of karst hills, and 2 — bottoms of lungs in the Bac Son region, taken in latitudinal direction (*cf.* Text-fig. 7)

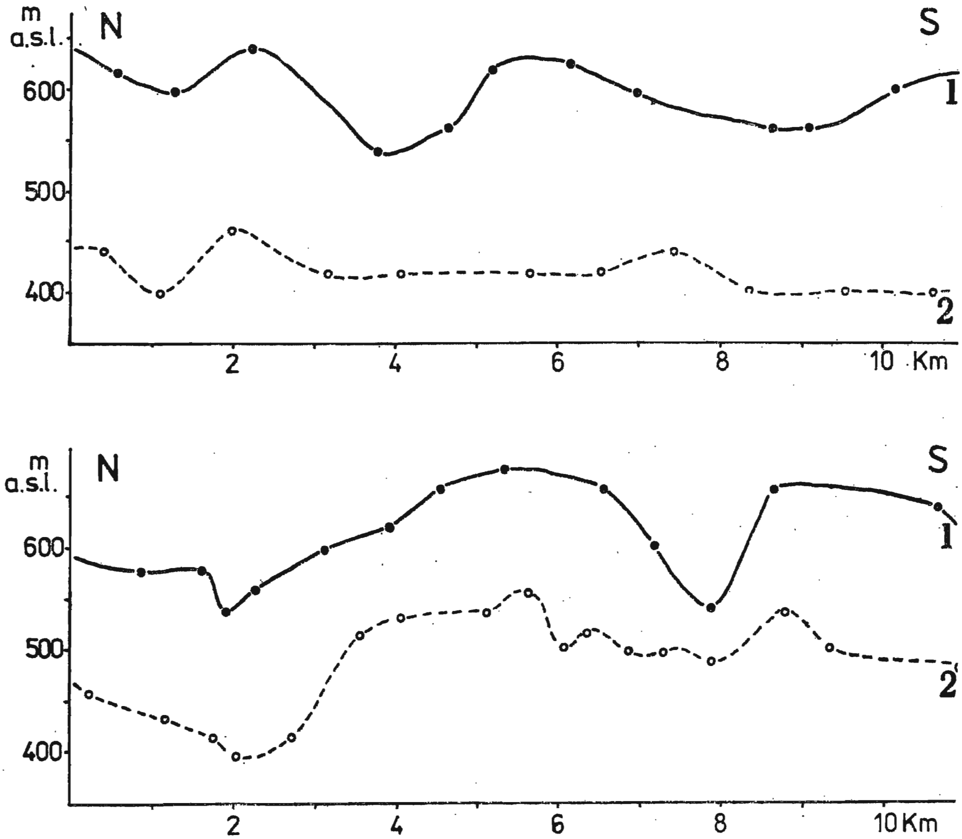

Fig. 11. Dependence between the altitude (in meters a.s.l.) of: 1 — summits of karst hills, and 2 — bottoms of lungs in the Bac Son region, taken in meridional direction (*cf.* Text-fig. 7)

words, whatever be the altitude of karst massifs, the elevation of karst hills above the bottoms of adjacent lungs varies always within the same limits. The above relationships may reflect the interruption of a karst cycle by differential tectonic movements (neotectonic movements) which have rised the once corresponding karst planation surfaces (bottoms of lungs) into new different positions higher in the landmass.

FACTORS CONTROLLING THE DEVELOPMENT OF KARST LANDSCAPE

The factors controlling the development of karst are variously classified and assesed but are generally held to include: lithology of the rock involved and their spacial situation, structural properties, changes in base-levels, biologic and climatic factors. The role of lithology and the significance of the spacial situation of karst massifs is beyond the scope of our considerations. The latter term, as it is understood by some authors, includes not only the position of karst massifs within the regional geological framework (GRADZIŃSKI & RADOMSKI 1963, GŁAZEK 1970), but also tectonic deformations predating the karstification. As noted previously, such deformations control the location of negative forms (lungs) and the shape of positive forms. In this connection, attention is once again focused on the apparent scarcity or absence of domelike "kegelkarst" hills in the study area. The scarcity of such forms is linked with the predominantly vertical arrangement of limestone layers and the absence of large bodies of massive limestones. It is to be recalled that the best known examples of kegelkarst occur in massive and/or flat--lying or gently dipping carbonate rocks (*e. g.* Jamaica, Cuba, Gunung Sewu in Indonesia).

From the foregoing considerations it is evident that any changes in the groundwater level resulting from tectonic and/or eustatic movements may alternately influence the shaping of karst landscapes. In this respect, the conclusions confirm the opinion that different "stages" in the development of karst relief may result from petrographic-structural differences and the position of the controlling base-levels (*see* KLIMASZEWSKI 1958). The changes in the position of base-levels are, in most instances, the result of neotectonic movements which are, thus, among the decisive factors determining the development of karst landscapes.

The question that needs comments is the role played by biogenic factors in the development of Vietnamese karst terrains. This role appears to be limited. Despite the luxuriant vegetation there is no soil cover nor any significant accumulation of plant litter on positive karst features. Also the dry lungs contain little accumulation of organic matter and consequently, the humic acids. These latter, however, become an important factor increasing the agressivenes of swamp waters.

In view of the lasting controversy, the role of climatic conditions deserves particular attention. This role is to be considered in terms of rainfall, temperature, and air humidity. The heavy tropical rains bring into the contact with limestones huge amounts of water which in such situation seldom if ever becomes saturated with $CaCO_3$. Accordingly, the humid tropical zones provide particularly favorable conditions for the development of karst forms. Such conditions, are hardly met with in other climatic regions. In addition, the temperature in tropical zones (with the exception of very high mountains) is persistently above 0°C. This eliminates the action of thaw-and-freeze which in temperate regions with frequent temperature oscillations around 0°C is the most important factor acting upon the exposed limestone surfaces. For instance, in the Cracow Upland in southern Poland the frost splitting is the dominant process which promotes the retreat of karst walls and inhibits the development of rillkarren (POKORNY 1963).

Moreover, in contrast to mid-latitude regions, the climate of tropical zones has not much changed since the beginning of the Neogene. Accordingly, the karst processes have been operating over a long time interval without any appreciable interruptions.

The air humidity affects only some minor karst forms. It varies not only with seasons but also in different tropical or sub-tropical regions. In Vietnam the air humidity is high even during the dry months. This accounts for the ubiquitous appearance of transverse dissolution wrinkles (karst ripples *sensu* WALL & WILFORD 1966) which in some other regions (*e. g.* the Caribbean) are relatively rare (RUDNICKI, *personal communication*).

It is worth while to illustrate in a simple diagram the role of various factors controlling the development and the form of karst features. Following the classification used by other authors (GRADZIŃSKI & RADOMSKI 1963, GŁAZEK 1970; *cf. also* JIMENEZ & *al.* 1984, p. 90) the controlling factors are grouped into three categories: climate, character of rock, and spacial position. For the sake of comparison with the diagram presented by GŁAZEK (1970), the last mentioned group of factors includes also the tectonics. The order of importance of the groups of factors differentiated is indicated by numerals. The diagram (Text-fig. 12) makes also the distinction between the development of karst forms and the forms themselves.

	R. GRADZIŃSKI & A. RADOMSKI (1963)			J. GŁAZEK (1970)			P. KHANG (1985)			
Factors / Groups of karst forms	Climate	Spatial situation	Rock character	Climate	Spatial situation	Rock character		Climate	Spatial situation	Rock character
Large surface forms				1	2	3	Development	2	1	3
							Shape	3	1	2
Small surface forms	+	-	-	1	3	2	Development	1	3	2
							Shape	3	2	1
Caves	-	+	-	3	1	2				
Rate of influence:	+ prevailing - second			1 = prevailing, 2 = second, 3 = third						

Fig. 12. Factors controlling the karst development in the tropics,as compared to the previous data

The diagram (Text-fig. 12) shows separately the influence of the controlling factors upon the development of karst features and their form. From this diagram it appears that the climate is of primary importance only for the development of minor karst features the form of which is, however, chiefly dependent on the petrological character of the rocks involved. With respect to large karst features it is the spacial situation (in the above given meaning) that is of primary importance.

EVOLUTION OF KARST LANDSCAPES IN VIETNAM

It is concluded that the development of karst landscapes in Vietnam was initiated during Triassic time. There is the evidence of fossil lapiez crevices filled with the Triassic sands (MY & *al.* 1976). However, any major karst forms which might had existed during pre-Paleogene time were apparently obliterated by the Paleogene planation and are not discernible in the present-day topography. The development of the observed karst landscapes started in the Miocene, and the karst processes have been uninterruptedly in operation since that time. Like many other tropical karst regions, the area of Vietnam was not exposed to changing climatic conditions during the Pleistocene.

The Neogene tectonic movements created favorable conditions for the development of karst landscapes by the uplift of limestone terrains and the formation of new, and/or the rejuvenation of ancient fault and fracture zones. These zones have determined the distribution and pattern of the present-day karst features. In the first stage of karstification, the prevailing vertical corrosion resulted in the dissection of the uplifted massifs and the appearance of landscapes characterized by the predominance of positive forms. With the diminished tectonic activity in the Pliocene, the bottoms of many negative forms have reached the controlling base-levels providing thus premisses for lateral corrosion.

The increased tectonic activity during Quaternary time has interrupted the process of lateral transformation of karst landscapes in the uplifted areas. Such transformation is still going on in places where the controlling base-levels occupy the same position or, at a higher level, in places of subsidence. The karst processes and notably the lateral transformation of karst landscapes have not proceded uniformly within specific massifs. The most extensive transformations occurred at the margins of the karst massifs (GŁAZEK 1970) and in their lower portions where the vertical corrosion had earlier reached the controlling base-levels. The present-day karst landscapes of Vietnam are thus in different stages of development. Such stages however, do not correspond to specific time-succession of events in a single karst cycle.

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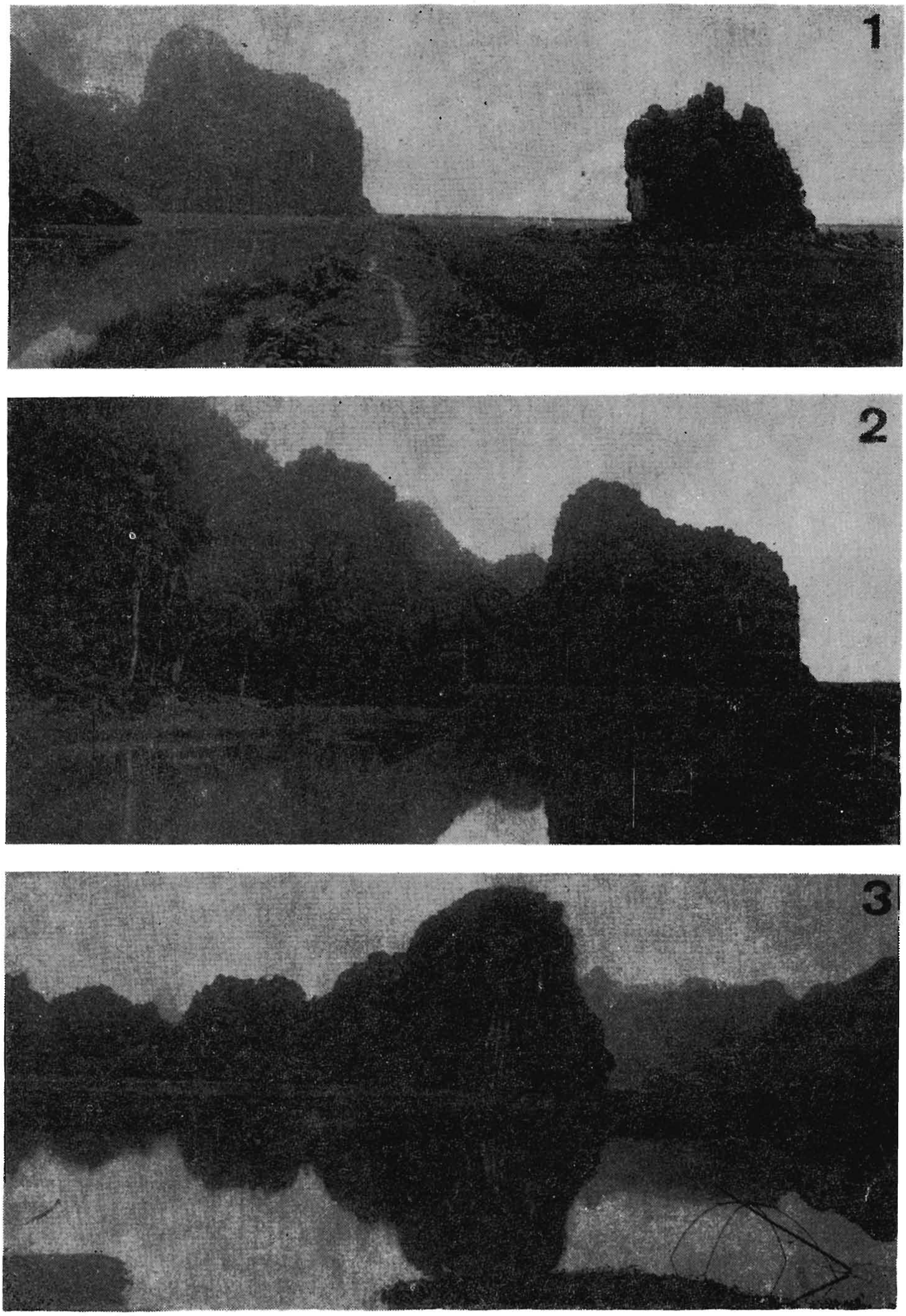
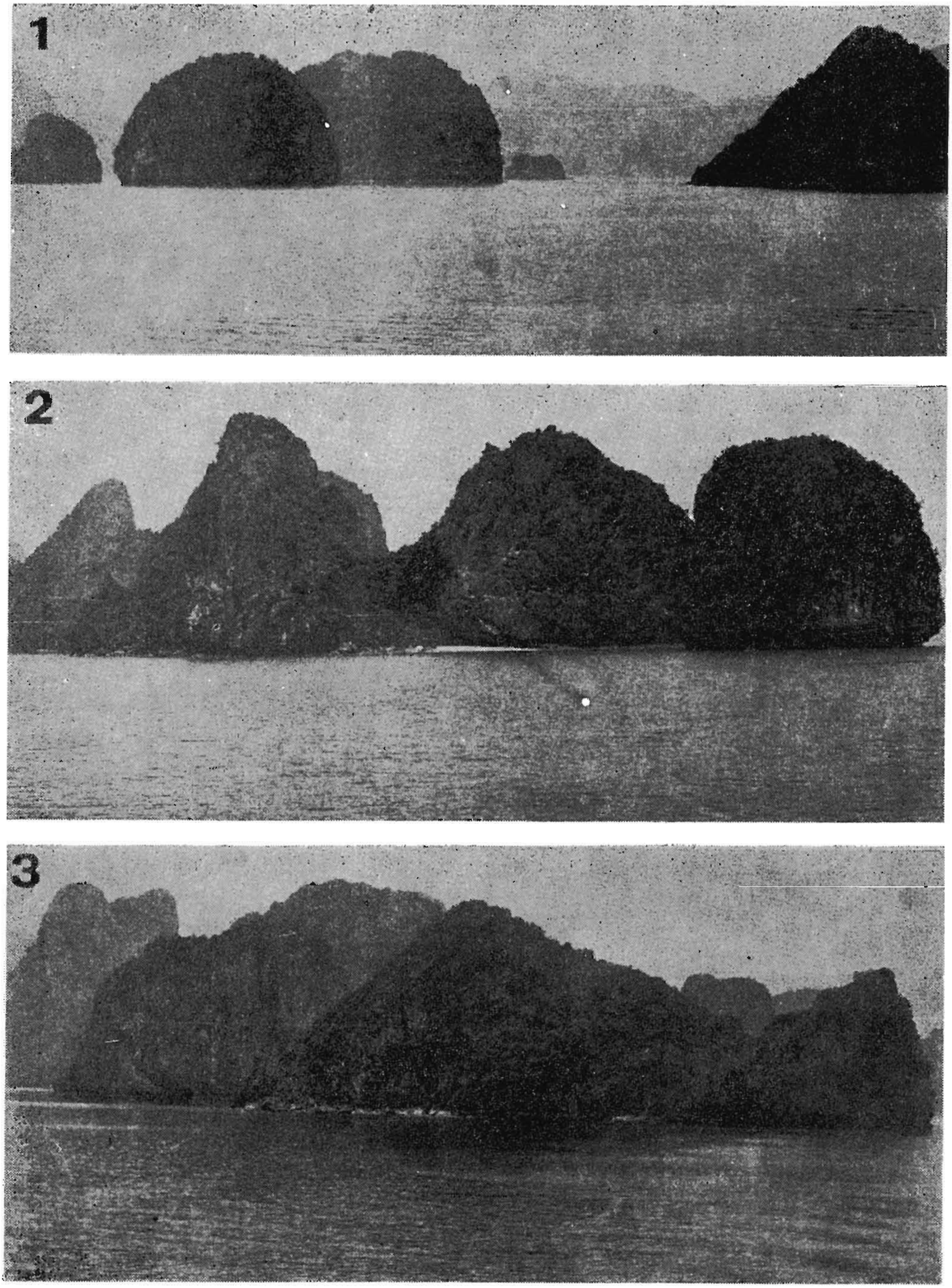


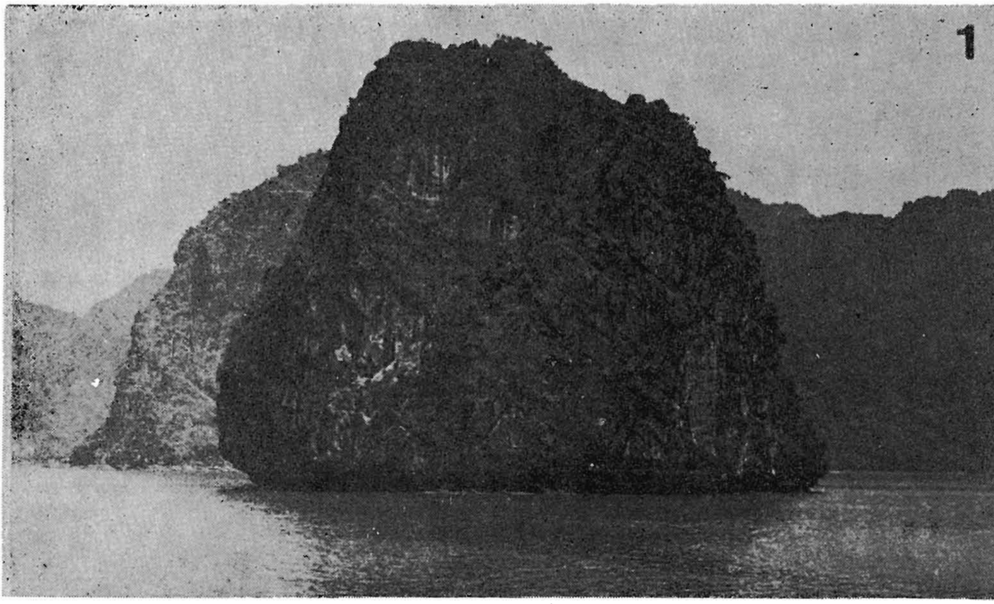
Karst landscape of Houng Tich region

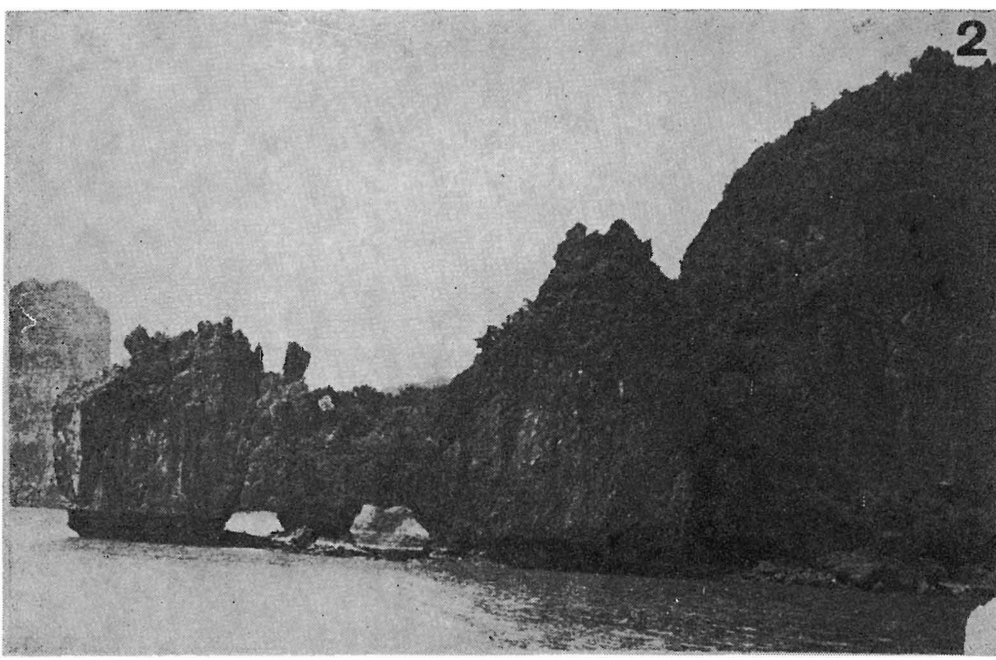
1 — Karst hill on the bottom of karst marginal plain
2 — Pinnacle karst hill
3 — The bottom of central polje concordant with regional groudwater level



Karst landscape of Ha Long region

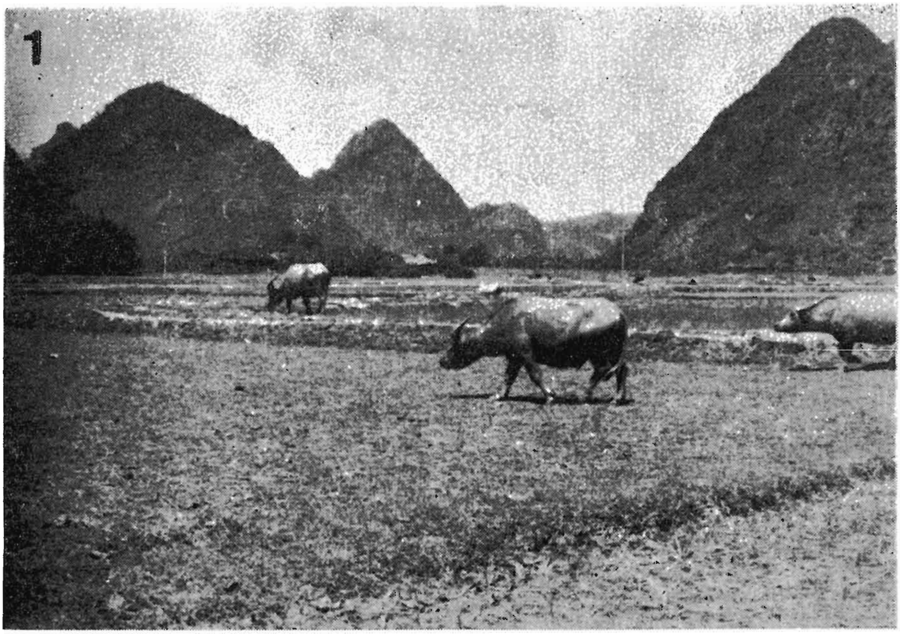
1 — Inundated karst landscape
2 — "Chapeau bras" type of karst hill
3 — Asymmetric karst hill

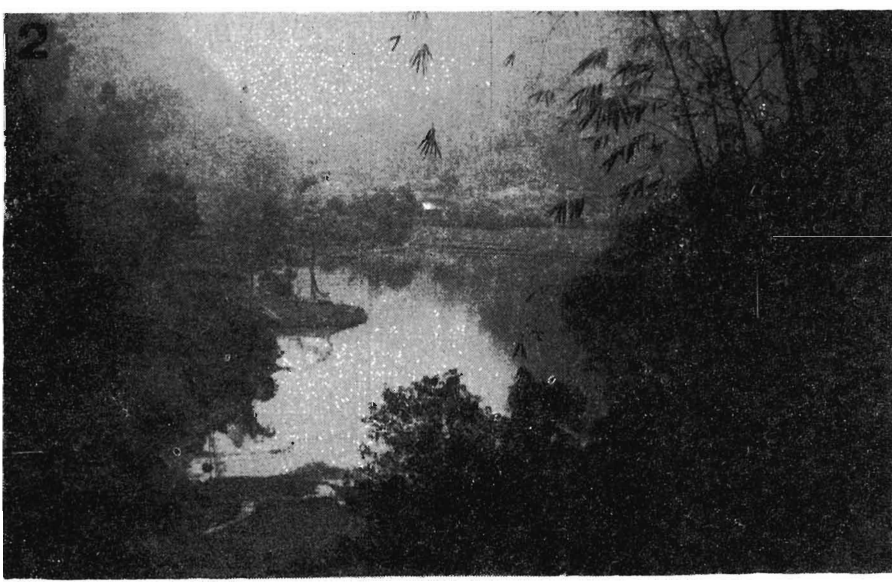




Karst landscape of Ha Long region

1 — Karst hill in massive limestones
2 — Two arches in massive limestones





Karst landscape of Bac Son region

1 — Pyramidal karst hills, in the foreground a dried central polje is visible

2 — A temporary lake in the lung