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LANDFORM DIFFERENTIATION WITHIN THE GUNUNG KIDUL KEGELKARST, JAVA, INDONESIA

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The Gunung Kidul karst is the western part (65%) of the larger Gunung Sewu (Thousand Hills) karst area, which is generally considered a type example of cone- or kegelkarst (Lehmann, 1936). This classification is an over-simplification, however, in that the karst landscape within the Gunung Sewu is considerably differentiated in terms of landform morphology and genesis. In the Gunung Kidul, this differentiation is evident from aerial photographs, which provide basic information about landform patterns, including lineament information. These observations were confirmed by field investigation, which incorporated landform measurement and acquisition of lithological information. These detailed studies distinguish three Gunung Kidul karst subtypes: labyrinth-cone, polygonal, and residual cone karst. The labyrinth-cone subtype occurs in the central Gunung Kidul karst where hard, thick limestones have undergone intensive deformation. Polygonal karst has developed in the western perimeter on hard but thinner limestone beds. The residual cone subtype occurs in the weaker and more porous limestones (wackestones or chalks), despite considerable bed thickness.

Herbert Lehmann’s (1936) research on the karst of the Gunung Sewu (Thousand Hills) in south-central Java (Figure 1) was the first modern work on humid tropical karst (Sweeting 1981; Jennings 1985) and it made a significant contribution to understanding both the development of the Gunung Sewu landscape itself and tropical karst in general. Subsequent research has revealed that tropical karst morphology varies considerably, particularly as a result of differing geologic environments and hydrologic regimes (Sweeting 1972, 1980; Jennings 1972, 1985; Trudgill 1985; White 1988; Ford & Williams 1989) and the karst of the Gunung Sewu itself demonstrates this differentiation.

Lehmann and more recent workers have described the Gunung Sewu landscape as cone- (or kegel) karst, characterized by sinusoidal or hemispherical hills (kuppen) interspersed with enclosed star-shaped depressions or interconnected valleys (Lehmann 1936; Flathe & Pfeiffer 1965; Balazs 1968, 1971; Verstappen 1969; Waltham *et al*. 1983). These descriptions of the Gunung Sewu landscape as kegelkarst generalize what is really a variety of different residual hill morphologies, with the conical form not actually being the most characteristic (Flathe & Pfeiffer 1965). The Gunung Sewu karst covers an area of more than 1300 km², and incorporates over 10,000 individual hills (Balazs 1968 estimated 40,000), at densities of about 30/km², whose morphology varies considerably more than previous studies suggest.

The diverse forms of residual hills in tropical humid karst are generally considered to be the result of “…structural factors in the broad geomorphological sense.” (Jennings 1985, p. 205). Many individual factors govern carbonate karst development in specific locations, including lithology and structure, which influence the efficacy and the distribution of the dissolution process within the rock mass (Sweeting 1980; Trudgill 1985; White 1988). The objective of this research is to begin to identify the geologic variations and the associated karst landform differentiations within the Gunung Sewu karst, thus refining geomorphological understanding of this classic karst landscape. Because of the paucity of existing data, no specific hypotheses are tested in this initial phase of the research, but it is anticipated that such hypotheses will be developed and tested subsequently.

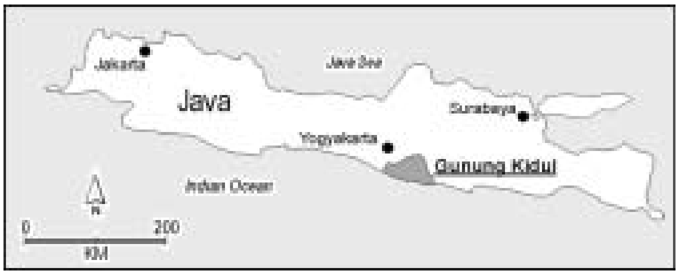

Figure 1. Location of the Gunung Kidul.

THE STUDY AREA

The research documented herein focuses upon the western two thirds of the broad Gunung Sewu karst area, in the Gunung Kidul Regency of Yogyakarta Special Province, Java, Indonesia between 7°57’ and 8°12’ South latitude (Figure 1). We refer to this study area henceforth as the Gunung Kidul (Southern Hills) karst, reflecting previous and more geographically correct usage (Balazs 1968).

The Gunung Kidul area is adjacent to the Indian Ocean on the south central coast of Java (Figure 1). Elevation range is between zero and 400 m above mean sea level, with resurgence springs such as Baron being at sea level and the highest portions centrally located about 25 km from the coastline.

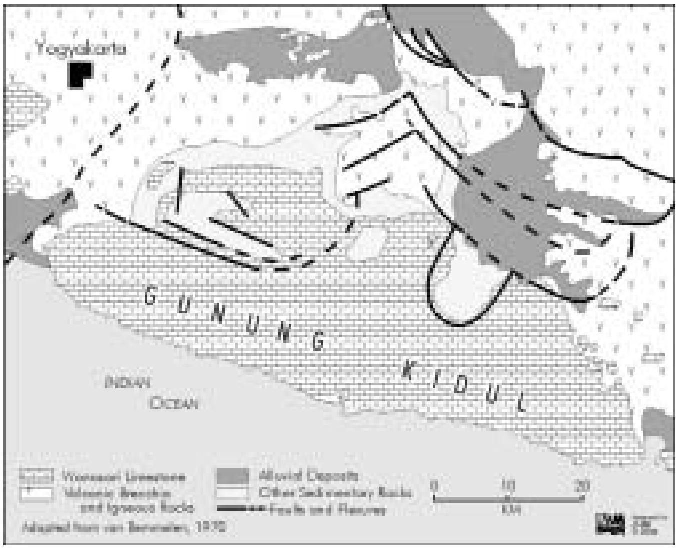

Figure 2. Geology of the Gunung Kidul area (after van Bemmelen, 1970).

Physiographically, the Gunung Kidul karst is part of the southern plateau of Java Island (Pannekoek 1948), which extends some 85 km east-west and slopes gently, at approximately a 2% gradient, southward, being marked by a high (25–100 m) cliff along the south coast.

Geologically, the study area is dominated by Miocene limestones of the Wonosari Formation, which consists of massive coral reef limestones in the south and bedded chalky limestones in the north (Balazs 1968; van Bemmelen 1970; Waltham *et al*. 1983; Surono *et al*. 1992) (Figure 2). Total thickness exceeds 650 m, and the limestones are underlain by volcanic and clastic rocks (Waltham *et al*. 1983). The coral reef limestone is lithologically highly variable, but dominated by *rudstones*, *packstones*, and *framestones*. Breccias with a clay matrix are not uncommon, biohermal structures are identifiable, and lenses of volcanic ash are interspersed among the carbonates (Waltham *et al*. 1983). The bedded, chalky limestones become more prominent towards the north and northeast, and dominate the Wonosari Plateau (Figure 2).

The Wonosari Formation was uplifted during the late Pliocene and/or early Pleistocene and dips gently southward at about a 2% gradient (Balazs 1968; van Bemmelen 1970; Surono *et al*. 1992; Sutoyo 1994). North-south compression associated with tectonic plate convergence produced deformation including intensive northwest-southeast and northeast-southwest jointing and faulting (Balazs 1968; van Bemmelen 1970; Surono *et al*. 1992; Sutoyo 1994). The structure is most complex along the northern boundary, and the northeastern part was downfaulted, forming the Wonosari Basin, within which karstification is limited.

The karst surface within the valleys and depressions is mantled by deeply weathered clays, up to 10 m in thickness, which are remants of volcanic ash intermixed with weathering residue from the limestones (Waltham *et al*. 1983). On the hills, soils are shallow, patchy rendzinas or vertisols, but the karst is intensively cultivated, particularly the red-brown clays in the valleys and depressions, with terracing, irrigation and sophisticated manipulation of available water resources (Uhlig 1980; Urushibara-Yoshino 1993).

Karst development in the Gunung Sewu has been influenced by paleoclimatic conditions (Urishibara-Yoshino & Yoshino 1997). Dry valley formation appears to have been associated particularly with the lower sea levels and the cooler, drier conditions of the last glacial stage 18,000 B.P. By contrast, cone karst development was apparently promulgated during subsequent warmer and wetter periods.

The prevailing contemporary climate in the Gunung Kidul is strongly influenced by the Northwest and Southeast monsoons, which produce a distinct wet season from October to April and a dry season, which may be extremely arid, between May and September. The annual rainfall is about 2000 mm; records from 14 local rain gauge stations between 1960 and 1997 vary between 1500 mm and 2986 mm annually. An earlier mean annual rainfall, based on 33 years of record was quoted as 1809 mm (Balazs 1968). Mean annual temperature is about 27° C. Seasonal drought is a serious economic problem, because over 250,000 people live within the Gunung Sewu karst, at a density in excess of 300/km² (Uhlig 1980; Waltham *et al*. 1983).

METHODOLOGY

Broad scale interpretation of the karst landforms was based upon 1:50,000 scale black and white panchromatic aerial photography from September 1993. The aerial photographs were used to produce an uncontrolled photo mosaic, which then was used to identify overall landscape patterns, including visible lineaments, and individual landform morphologies within the study area. On this visual basis, three distinctive broad areas of landform assemblages and patterns were identified and, within each of these, 10, 22 and 29 km² sample areas were selected non-randomly, on the basis of photographic quality (absence of clouds) and accessibility, for morphometric analysis and field survey. Valley lineaments were measured from the air photographs, with field verification, and the significance of preferred orientations was tested using one-way analysis of variance.

Fieldwork was conducted in November 1999 in order to verify the results of the initial interpretation of the air photographs. Sites were selected non-randomly to correspond with the sample areas within the different landform patterns that had previously been identified on the aerial photographs. The fieldwork involved observation and measurement of individual landforms, together with macroscopic lithological identification and determination of Schmidt Hammer hardness (Day & Goudie 1977; Day 1980, 1982). Rock porosities were determined from thin-section analysis (Curtis 1971).

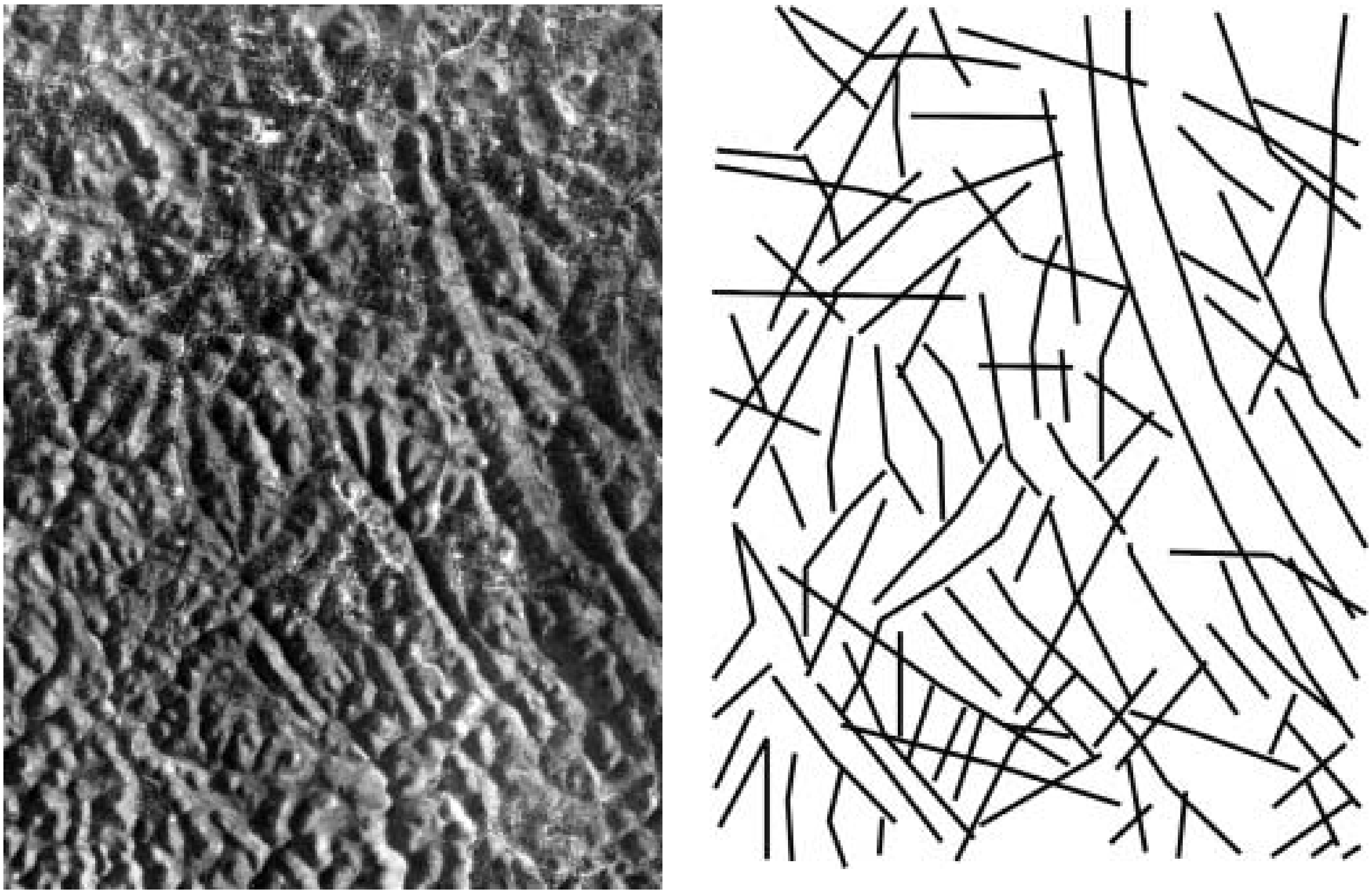

Figure 3. Labyrinth-cone karst: air photograph (left) and lineaments (right).

RESULTS

Although the Gunung Sewu karst is generally classified as kegelkarst, detailed analysis of the aerial photography and field observation in the Gunung Kidul reveals that there are three distinct landscape subsets, which we refer to as labyrinth-cone karst, polygonal karst and residual cone karst. This terminology incorporates a descriptive element (cone) into existing terminology (Ford & Williams 1989).

Labyrinth-Cone Karst

Labyrinth karst (Figures 3 and 4 [page 60]) "…is a landscape dominated by intersecting solution corridors and solution canyons." (White 1988, p. 116) or, alternatively, "…aligned or intersecting corridor topographies." (Ford & Williams 1989, p. 391). Specifics notwithstanding, labyrinth karst development is distinctly linear, incorporating meandering valleys rather than enclosed depressions, and is dominantly controlled by faults or major joints. In the Gunung Kidul area the valley linearity is combined with intervening conical hills, hence we refer to this landscape as labyrinth-cone karst. The labyrinth-cone landscape type is characterized by two series of joint-controlled valleys, which are dry under normal circumstances. In the 29.2 km² study area, the dominant trend of the valleys is northwest-southeast, with a secondary trend northeast-southwest (Figure 3). Lineations in the classes 31–40°, 41–50°, 301–310°, 321–330° and 331–340° are statistically significant at the 0.001 level. Valleys extend up to 4.5 km in length, and are typically 50–250 m wide, bordered by steep to moderate slopes on both sides. Most valley thalwegs are thoroughly disordered, with only minimal evidence of descending tributary-trunk sequences. Between the valleys are elongated, interfluvial residual hills, 80–100 m in height, which form long, serrated, ridge-like chains of conical or flat-topped hills without intervening closed depressions (Figure 4 [page 60]). Enclosed depressions are uncommon within the labyrinth-cone karst, although some have developed within the valley network, where they tend to be large and elongated (Table 1).

The slopes of the residual hills in the labyrinth-cone karst are generally steeper than those in other parts of the Gunung Kidul karst, generally ranging between 60 and 70 degrees. Dry valley sides may be near vertical, although in some localities they grade imperceptibly into the cone slopes. The slope steepness may be attributable to lithological factors. The carbonate lithology of the labyrinth-cone karst comprises *floatstones*, *packstones* and *rudstones*, which are usually dense, hard limestones. Whereas the mean regional Schmidt Hammer hardness

Table 1. Enclosed depression measurements in labyrinth-cone karst of Gunung Kidul (All measurements in meters).

Doline Order	Length Range	Mean Length	Width Range	Mean Width	N
0	100–238	161	75–200	124	42
1	150–600	445	100–200	152	15
2	600–925	750	175–625	332	5
3	1225–1650	1427	250–650	426	5

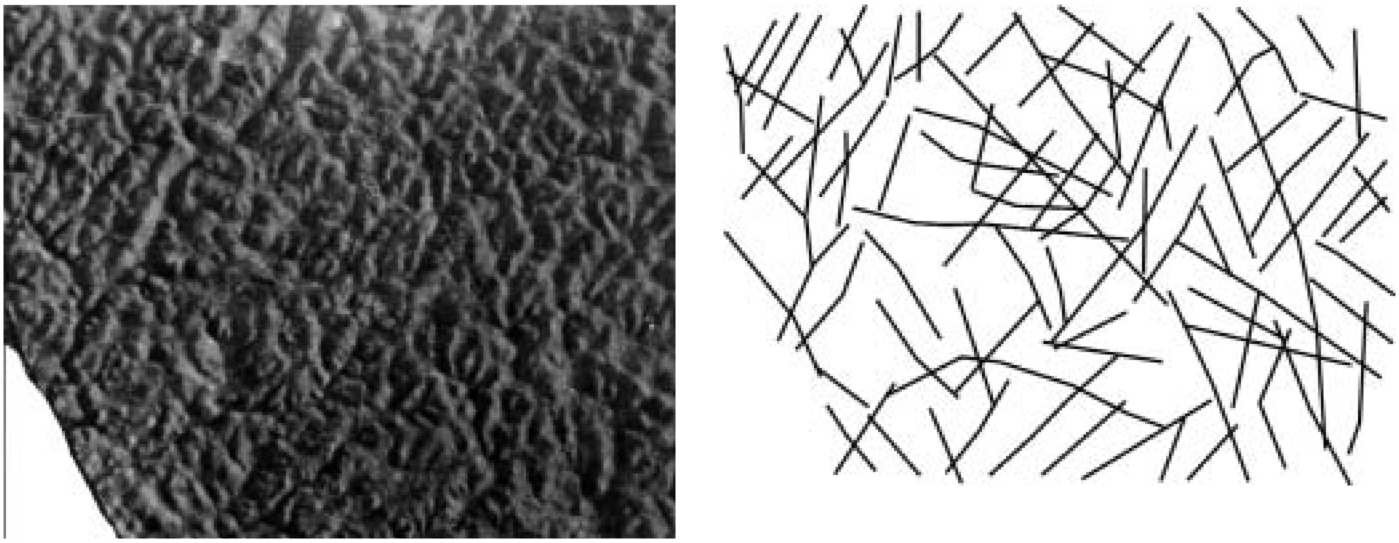

Figure 5. Polygonal karst: air photograph (left) and lineaments (right).

value for the limestones is 40.5 (n=80) for weathered surfaces and 21.2 (n=60) for fresh exposures (Day 1978), the corresponding values for limestones in the labyrinth-cone landscape are 44.3 (n=20) and 24.6 (n=15). Porosity of limestones from the labyrinth-cone karst ranges from 13.0 to 16.6% (n=3), which is quite high for diagenetically mature limestones. More importantly, the bedding is massive, commonly exceeding 5 m.

The labyrinth-cone karst is most pronounced in the southern portion of the Gunung Kidul, where the carbonates are most intensively jointed and faulted. This area was subject to the maximum displacement as a result of the compressional stresses associated with the subduction zone of the Australian Plate (Tjia 1966; Dwiyana 1989).

Polygonal Karst

The most characteristic polygonal karst in Gunung Kidul occurs in the western part of the area (Figures 5 and 6 [page 60]). Polygonal karst is characterized by densely packed or coalesced depressions (cockpits), such that the entire karst landscape, including the residual hills marking the polygonal divides, is consumed by them, and the ratio between closed depression area and karstified area approximates unity (Williams 1971; White 1988).

Although owing much to dissolution, the polygonal karst of Gunung Kidul appears to be strongly influenced by fluvial processes and by the general southerly slope of the plateau. Although enclosed depressions dominate the landscape, dismembered meandering valley networks are also present, and these may become activated during intense wet season rains. Whereas surface flow within the depressions is centripetal, flow within the valley segments is dominantly towards the south. Increased discharge from epikarstic springs is of particular importance in generating this channel flow (Haryono, in preparation). Thirty-two springs have been identified to date, 28 close to the margins of the karst, from which they discharge surface runoff in channels, and four in central valleys, where they generate surface runoff that subsequently sinks into valley beds.

Polygonal karst is particularly well developed in the western part of the Gunung Kidul karst, where the enclosed depressions in some localities resemble the cockpits of Jamaica and Papua New Guinea (Williams 1971 1972a,b). Elsewhere, the depression slopes are more convex, producing rounded hills, or the *sinoid karst* of Flathe and Pfeiffer (1965), resembling the “egg-box” terrane described elsewhere (Ford & Williams 1989). Structural control is also evident in the 9.6 km² polygonal karst study area (Figure 5), where lineations in the 31–40°, 41–50°, 51–60° and 311–320° classes are statistically significant at the 0.001 level. Depression slope steepness and morphology are influenced by the spacing of lineaments, and by the relative rates of vertical and lateral corrosion (Tjia 1969). In the field study area in the western Gunung Kidul

Figure 4. Labyrinth-cone karst: ground photograph.

Figure 6. Polygonal karst: ground photograph.

Figure 8. Residual cone karst: ground photograph.

bedding is less massive, commonly on the order of 2 m, with riser heights reflecting those dimensions. There is also a lithological influence, with steeper slopes (mean 31°) developed on the harder rudstones and framestones (Schmidt Hammer mean hardness 43.0 weathered, 22.7 fresh, n=15 in both cases) and gentler slopes (mean 15°) on softer, impure, marly limestones further north (SH mean hardness 32.6, 19.8, n=10 in both cases). Porosities of the polygonal karst limestones range from 1.1 to 14.0% (n=3). Relative relief ranges considerably, from about 30 m to over 100 m, and enclosed depressions are generally rather smaller than in the labyrinth-cone area and less elongated (Table 2).

Residual Cone Karst

Tower karst consists of residual carbonate hills set in a plain; the residuals may or may not be steep-sided (Ford & Williams 1989). Here we use the term residual cone karst to describe the karst of Gunung Kidul that is characterized by conical isolated hills scattered on a corrosional plain (Figures 7 and 8).

Residual cone karst has developed primarily in the northeast of the study area and locally near the south coast where corrosion plains are close to sea level. The main factor governing the development of residual cone karst in the Gunung Kidul karst appears to be lithology. In the 21.5 km² study area, bedding generally is not obvious, the limestones being massive, but most of this karst is formed in *wackstones*, which here are relatively soft limestones containing a high percentage of *micrite* and perhaps best characterized as chalks. In a wet condition, fresh wackstone is easily broken by hand. Mean Schmidt Hammer hardness is 35.0 weathered (n=35), 19.8 fresh (n=20) and porosities are high, ranging from 23.1 to 48.1% (n=3).

Closed depressions are not numerous in the residual cone karst, having generally been degraded and coalesced within the larger plain, but such as do occur are broad and shallow, with mean lengths of 1230 m and mean widths of 810 m. Lineations are less conspicuous than in the other landscape types (Figure 7), with only the 31–40° class statistically significant at the 0.001 level in the field study area. Hillslope angles vary from 30° to 40° with a mean height of 90 m (Table 3).

DISCUSSION

Although the overall karst assemblage in the Gunung Kidul can be described as cone- or kegelkarst, a more detailed investigation reveals three subtypes: labyrinth-cone, polygonal, and residual cone karst. These are not randomly distributed throughout the Gunung Kidul area, but are spatially distinct and, on the basis of this preliminary investigation, appear to show a close association with structural and lithological variations in the limestones.

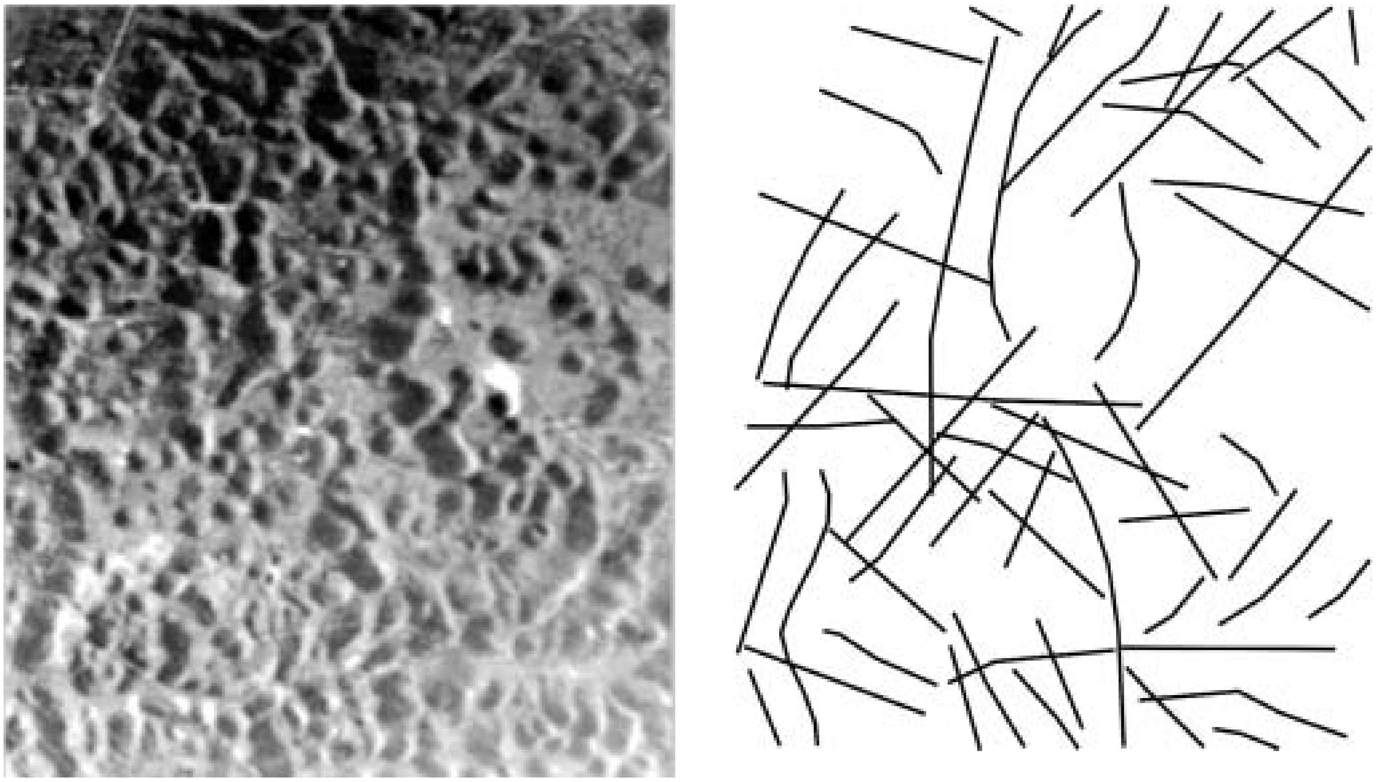

Figure 7. Residual cone karst: air photograph (left) and lineaments (right).

Table 2. Enclosed depression measurements in polygonal karst of Gunung Kidul (m).

Doline Order	Length Range	Mean Length	Width Range	Mean Width	N
0	100–225	160	75–225	145	35
1	275–750	539	200–375	326	6
2	500–1000	713	200–550	459	14
3	980–1450	1215	350–1150	747	3

Table 3. Enclosed depression measurements in residual cone karst of Gunung Kidul (m).

Doline Order	Length Range	Mean Length	Width Range	Mean Width	N
0	900–225	1090	775–1025	887	6
1	…	…	…	…	0
2	…	…	…	…	0
3	975–1800	1230	450–1020	810	4

The labyrinth-cone subtype occurs in the central part of the Gunung Kidul karst, where hard thick limestones have undergone intensive deformation. This karst sub-type conforms to what Lehmann (1936) termed directed, oriented or *gerichteter* karst, and it reflects the significance of faulting in the delineation of tropical karst landscapes, as was suggested earlier by Pannekoek (1948). The general north-south alignment mirrors the distribution of depression long axes measured by Quinif and Dupuis (1985). Although the residual hills do not attain the same dimensions or steepness as in the Chinese karst, this landscape resembles Fencong Valley landscape (Lu 1986; Yuan 1991; Smart *et al*. 1986).

Polygonal karst develops in the western area on similarly hard but thinner limestone beds. Although the polygonal karst resembles that described elsewhere, many of the residual hills retain their distinctly rounded shape, particularly resembling the Chocolate Hills area of Bohol, in the Philippines (Voss 1970). Overall, this sub-type approximates Karst Hill Depression landscape (Lu, 1986; Yuan, 1991; Smart *et al*. 1986).

The residual cone subtype occurs in weaker limestones (wackstone) with high porosities but relatively thick beds in the northeast of the study area. The influence of thicker beds on residual cone formation echoes the ideas of Tjia (1969), but the overriding control appears to be the softness and the high porosity of the chalks. Again bearing a striking resemblance to the karst on the periphery of the Chocolate Hills in Bohol, this sub-type resembles a subdued version of the Fenglin Valley landscape of China (Lu 1986; Yuan 1991; Smart *et al*. 1986).

It is as yet unclear whether these three different subtypes represent a definite zonation of the overall karst landscape that is related to former surface drainage systems (cp. Smart *et al*. 1986), although this seems quite possible given the existence of obvious valley systems in the contemporary terrain and evidence of previous valley systems (Lehmann 1936; Waltham *et al*. 1983; Quinif & Dupuis 1985). Waltham *et al*. (1983) raised the possibility of the landscape developing by dissection of an anticline, and Quinif and Dupuis (1985) postulated preliminary fluvial development on a Pliocene erosion surface. More recently, Urushibara-Yoshino (1995) and Urushibara-Yoshino and Yoshino (1997) have postulated that the valley systems, and subsequently the cone karst, developed on marine terraces, with the valley systems developed under drier conditions with lower sea levels during the last glacial stage of the Pleistocene, and with karstification more prevalent during wetter interglacial periods.

CONCLUSIONS

General variation in the landscape morphology, and in the form of individual residual hills, has been observed previously (Tjia 1969; Balazs 1971), although the lithological, structural and hydrologic influences have not been examined in detail before. The evident role of lithology in influencing the karst landscape morphology echoes the results of other studies in tropical karst (e.g. Day 1982; Smart *et al*. 1986), in that the greatest local relief is developed on the limestones with the greatest bed thickness and hardness. The lithological heterogeneity is in contrast to earlier accounts of the carbonate geology, which suggested that homogeneity was the rule (Lehmann 1936), and the landform differentiation also reveals greater geological influence than recognized previously (Waltham *et al*. 1983). Structural variability is also greater than was previously acknowledged, although broadly it is the northeast-southwest and northwest-southeast lineations that are statistically significant.

In addition to lithology and geological structure, regional slope also plays a role in influencing karst landscape development and individual karst landforms. The southerly regional 2% slope controls karst development indirectly through promoting slope-directed runoff, which results in linear depressions or valleys being more numerous than enclosed depressions. This is particularly notable in the southern part of the Gunung Kidul. In this context, Lehman's (1936) model of karst development progressing from an initial stage dominated by surface runoff and surface valleys to a later stage in which the valleys become increasingly underdrained and dismembered by the development of enclosed depressions seems not inappropriate, particularly given the empirical evidence (Quinif & Dupuis 1985) and the supporting theory put forward since (Smith 1975; White 1988).

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