THE EXTREME KARSTIFICATION OF THE KINTA VALLEY, WEST MALAYSIA

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Abstract
Surface limestone makes up only about 7% of the whole karst area; the greater subsurface area lies beneath thick alluvial sediments. The depth of the subsurface varies from 9 m to more than 60 m, and shows various topographies from platforms with flat concordant tops to jagged sharp pinnacles with rounded tops. The ratio of surface to subsurface karst can be used as an indication of the intensity of dissolution that occurs and of advanced degradation. Based on its association with tin-rich alluvium, it is believed that the karst in this area developed mostly under a pluvial environment and the humid tropical conditions since the Tertiary.

Introduction
The Kinta Valley in Perak, Peninsular Malaysia is important historically; the richest tin mine in the world was located here. A tin-rich placer sourced from two granitic highlands has been deposited across the wide valley. Tin-bearing alluvium elsewhere has been dated to as much as 700,000 years old based on the presence of tektites, e.g., in Gambang, Pahang (Gangadharam and Stauffer, 1978; Gangadharam, 1984). It is believed that the unique subsurface feature of planation with jagged surface formed by limestone pinnacles has trapped the alluvial sediments and prevented them from being washed away. Topography further has an effect on weathering; it has been suggested that the lowlands and extreme highlands of Southeast Asia were influenced by the Quaternary pluvial and inter-pluvial periods (Ashton and Ashton, 1972). Streams from these highlands flow into major rivers in the valley, fed by the high rainfall throughout the year. This has provided a constant allogeneic water source to the plain and transported the placer to the vast lowland. The north to south variation of bedrock depths indicates the slope of the bedrock is on the order of 1.9 m per km, also suggesting a fluvial origin for the valley and that stream activity has been very widespread (Newell, 1971). Many ponds are scattered throughout the valley, most of which are ex-tin mines that have been left after mining ceased in the 1990s.

Parts of lowland equatorial Southeast Asia are amongst the few areas of the world where possibly little or no climatic change has taken place during the Quaternary (Ashton, 1972; Gale, 1986; CLIMAP, 1976; Prell et al., 1980). Paramananthan (1982) considers lateritic soils formed during the Tertiary (Batchelor, 1979; Law and Leamy, 1966; Eyles, 1970 after Raj, 1982) to have developed during the Pleistocene through the deposition of iron-coated materials that were derived by erosion from weathering profiles formed by intensive tropical weathering. Some evidence for this Tertiary humid tropical climate is seen in Mueller (1972), whose palynological analysis led to the conclusion that there was a uniformly humid climate throughout the Tertiary.

However, it has been suggested that this study area was subject to repeated climatic variations and changes in erosional base levels in the late Pleistocene to Holocene, based on characteristics of the Young Alluvium (of Walker, 1956) or Alluvial Complex that blanket the subsurface karst. The Pliocene to early Pleistocene probably experienced more arid, seasonal climatic conditions during periods of low sea levels. The palynological record from Kuala Lumpur, which is about 180 km from the valley, indicates a cooler climate around 41–36 ka (Haile & Mohammad, 1968), while guano from nearby Batu Caves indicates an open-savanna type environment 35–60 ka ago (Wurster et al., 2010).

The surface dissolution rate of the limestone in the study area, obtained using a micro-erosion meter, was found to range from 224 mm/ka and 369 mm/ka for calm pond water, and running water environments, respectively (Muhammad, 2003). These dissolution rates are rather high when compared to the rates in other karst areas around the world, including in other tropical areas; their rates range from 15 to 99 mm/ka (Kukal, 1990), as shown in Table 1. The dissolution rate in the Kinta Valley, coupled with its topographic setting, provided a suitable environment for a high rate of karstification.
The objective of this study is to describe the karst topography in Kinta Valley based on the morphological features on the surface and subsurface karst and its relationship to the overlying tin-bearing placer deposit.

Tower karst refers to a landscape of residual carbonate hills scattered across a plain, although the tower may not be necessarily be steep (Ford and Williams, 1989). The karst in this study was divided into two simply based on its expression relative to the ground level. The term surface karst is used to refer to topography that is present above the ground, while subsurface karst refers to topography below the ground. The topography of Kinta Valley is characterized by tower karst terrain comprising isolated limestone hills separated by alluvium and detrital sands, with subsurface karst dominating the rest of the area. Due to its setting on a plain, the term “residual hills” (Ford and Williams, 1989) applies here. However, unlike the Gunung Kidul area that features conical hills (Eko and Day, 2004), the residual hills in Kinta Valley are mostly steep-sided. Schist and shale outcrop as undulating hills throughout the plain, and dolines, described as small- to medium-sized closed depressions, range from metres to tens of metres in both diameter and depth (Ford and Williams, 1989). Beneath the alluvium, the limestone takes the form of limestone pavement with highly irregular surfaces and can be termed buried karst (Jennings, 1982).

### The Study Area

The Kinta Valley is a triangular-shaped, low-lying valley in the Western Belt of Peninsular Malaysia (Figure 2) bounded by two prominent granitic ranges: the Main Range in the east, which rises to about 1464 m above mean sea level, and Kledang Range in the west, which rises to about 752 m (Figure 3). The valley widens from about 7 km in the north to 20 km in the south over a distance of about 45 km. The surface area of the valley is estimated at about 450 sq km. From north to south, the first tower karst observed in this area is Gunung Kanthan, and the last is Gunung Tempurung. The alluvial plain is located from 40 m to 80 m above mean sea level.

The karst in the study area was formed from Kinta Limestone of the Silurian to Lower Permian age. The hills are made up of pure crystalline limestone and are invariably marmorised due granitic intrusions; they mostly lack fossils (Ingham & Bradford, 1960). Farther away from the granite, the subsurface limestone at the

### Table 1. Rates of dissolution of karst in other parts of the world including in other tropical areas (Kukal, 1990).

<table>
<thead>
<tr>
<th>Climatic zone and area</th>
<th>Rate of erosion (m³.km⁻².a⁻¹) or (mm.ka⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Derbyshire, Great Britain</td>
<td>60–193</td>
<td>Smith and Atkinson, 1976</td>
</tr>
<tr>
<td>South Wales</td>
<td>16</td>
<td>Groom and Williams, 1965</td>
</tr>
<tr>
<td>North-West Scotland</td>
<td>88–100</td>
<td>Groom and Williams, 1965</td>
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<tr>
<td>Ireland</td>
<td>51</td>
<td>Groom and Williams, 1965</td>
</tr>
<tr>
<td>Yugoslavia</td>
<td>9–126</td>
<td>Corbel, 1965</td>
</tr>
<tr>
<td>Swabish Jura</td>
<td>98</td>
<td>Aubert, 1969</td>
</tr>
<tr>
<td>Krakow Platform</td>
<td>20</td>
<td>Corbel, 1965</td>
</tr>
<tr>
<td>Poland, average for karst</td>
<td>10–32</td>
<td>Oleksynowma and Oleksynowma, 1971</td>
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<tr>
<td>Tatra Mts, Polish part</td>
<td>86–95</td>
<td>Kotarba, 1971</td>
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<tr>
<td>Moravian Karst, Czechoslovakia</td>
<td>25</td>
<td>Stelcl et al., 1969</td>
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<tr>
<td>Aggletek, Hungary</td>
<td>20</td>
<td>Balasz, 1971</td>
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<tr>
<td>San Antonio, Texas</td>
<td>4</td>
<td>Corbel, 1971</td>
</tr>
<tr>
<td>Eastern Siberia, USSR</td>
<td>1–32</td>
<td>Pulina, 1968</td>
</tr>
<tr>
<td>Southern England</td>
<td>40</td>
<td>Sweeting 1966</td>
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<tr>
<td>Tropical zone</td>
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<tr>
<td>Indonesia</td>
<td>63–99</td>
<td>Balasz, 1971</td>
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<tr>
<td>Florida</td>
<td>15</td>
<td>Runnels, 1971</td>
</tr>
<tr>
<td>Jamaica</td>
<td>39–96</td>
<td>Smith, 1972</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>42</td>
<td>Corbel, 1971</td>
</tr>
<tr>
<td>Arctic and Alpine zone</td>
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<td></td>
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<tr>
<td>Alaska</td>
<td>8–530</td>
<td>Corbel, 1959</td>
</tr>
<tr>
<td>Canada</td>
<td>2</td>
<td>Smith, 1972</td>
</tr>
<tr>
<td>Spitzbergen Is.</td>
<td>16–30</td>
<td>Corbel, 1965</td>
</tr>
<tr>
<td>Tatra Mts, Polish part</td>
<td>96</td>
<td>Corbel, 1965</td>
</tr>
<tr>
<td>Tatra Mys, Polish part</td>
<td>36–38</td>
<td>Kotarba, 1971</td>
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<tr>
<td>Tropical desert zone</td>
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<td>Sahara</td>
<td>3</td>
<td>Corbel, 1971</td>
</tr>
</tbody>
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south of the study area is less recrystallized and contains Palaeozoic fossils. The granitic highlands are mostly made up of coarse-grained porphyritic biotite granite. Other common rocks include several relatively thin argillaceous beds, which exceed 3000 m in stratigraphic thickness (Ingham and Bradford, 1960; Suntharalingam, 1968); these were folded and recrystallised by regional metamorphism in the Late Triassic.

**Methodology**

The occurrence of carbonaceous rocks is documented in Ingham and Bradford (1973), the Mineral Distribution Map of Peninsular Malaysia (Yin, 1988), and the Geological Map of Peninsular Malaysia (Malaysia Mineral and Geoscience Department, 2014). The topography of the surface karst is indicated as limestone hills, while subsurface limestone is expressed as a topography underlain by alluvial cover (Yin, 1988). Hills were identified by observing 1:50000 topography maps produced by the Department of National Mapping Malaysia, including Series L 7010, Sheet 3562, 3563, 3463, and 3564; aerial photos from Colombo Plan 1960 were also used. Map data were compared to recent Google Earth and satellite images, and numerous observations were carried out in the field to verify the results obtained in lab. Available data were combined using the Freehand software to reproduce the geological map with details of the outlines of the limestone hills (Figure 3). Each area of surface limestone was drawn and numbered, and the exposed subsurface karst and overlying alluvium material were also observed. The approximate ratio of surface to subsurface karst was measured by comparing subsurface limestone against surface limestone. In addition, solutional features on hill cliffs were observed and measured using a laser range finder, and selected profiles of these features were drawn. Due to the ready accessibility of Gunung Rapat, more detailed observation was carried out there compared to other hills; therefore, it was chosen as a representative limestone hill.

![Figure 1. Engineering classification of subsurface karst development by Waltham and Fookes, 2005. Class kV is labelled “Malaya”, without further elaboration, and resembles karst in the study area.](image-url)
The Karst of Kinta Valley

Surface Karst

There were a total of 34 towers in the study area, as shown in Figure 3. Studies on the morphostructure of these hills showed that pock marks and the alignment of dolines are controlled by the fault and major joints that can be seen extending from the granitic highland; most of these structural directions are in excellent agreement with the stress system on the Main Range side of the valley (Muhammad & Tjia, 2011). This feature is explained by the “Aligned or Intersecting corridor topographies” description of Ford and Williams (1989). The bases of the hills are connected to each other by lower connecting ridges and wind gaps. The hilltops and slopes are covered by vegetation or consist of bare slopes marked by a distinctively minimal terra rossa soil and organic hummus, while closed depressions are further deeply degraded to form dolines with concave floors covered by variable amounts of alluvial material, rock rubble, and soil. A number of hills showed more extensive vertical dissolution down to the base levels, and subsurface karst was present in certain doline platforms. Many of these platforms were blanketed by placer deposits, usually.

Figure 2. Map of Peninsular Malaysia showing the locations of limestone hills. The study area is indicated in the box.

Figure 3. Geological map of the floodplain of the Kinta Valley in Perak, West Malaysia. 34 limestone hills (in blue) represent karst on the surface, while large areas of karst are buried under the alluvial cover (in yellow). Granites (in red) form two highlands on the east and west sides of the Valley, while grey areas represent metasedimentary rocks (mainly schist) and white areas are ponds that occupy most of ex-mining land. Gunung Rapat is located in the black box and the study location for the geophysical survey in the red box. This map is based on topography maps, Geology of Peninsular Malaysia Map (JMG, 2014) and Mineral Distribution Map of Peninsular Malaysia (Yin, 1988).
stripped for mining and later filled with water either naturally or by quarry operators (Figure 4).

Another important feature thought to play an important role in tower karst development is notching or indentation formed by normally horizontal dissolution aided by the presence of numerous ponds at the foot of the hills and throughout the valley. This feature has been reported in Peninsular Malaysia by various researchers (Walker, 1955; Paton, 1964; Jennings, 1976; McDonald, 1976). Notches that are more extensive and create a flat roof regardless of geologic structure are termed corrosion bevels (Ford and Williams, 1989) or German ‘laugdecke’ (Kempe et al. 1975 after Ford and Williams, 1989).

The occurrence of swamp slots and notches is often cited as field evidence of the effectiveness of lateral corrosion (Ford and Williams, 1989). Based on observations of tropical tower karst in many areas, including the Kinta Valley, Sweetings (1972) and Roglic (1972) have suggested that marginal corrosion had progressed at a very fast rate due to a swampy solution or corrosion at the foot of the limestone hills. Sweetings (1972) additionally suggested that deep horizontal swamp notches intersected by vertical solutions resulted in the collapse or slicing off of vertical blocks of limestone, which fell into the swamp and were then quickly dissolved. Dolines were thus further enlarged, and the hills reduced in size. Thus, according to this hypothesis, notches play a very important role in the formation of steep-sided limestone hills in the humid tropics and in hastening the degradation process.

Many notches in the Kinta Valley were found to be preserved on cliffs in enclosed dolines within the limestone hills. Due to the collapse of limestone blocks, these notches can unfortunately no longer be seen on most of hill cliffs, only scars of collapse. Figure 5 shows a profile of these features. The notches can be as high as 20 m above ground, and show variable depths and shapes (Figure 5). Most higher-level indentations showed scalloped roofs, while lower-level ones had flat roofs. It is postulated that scalloped roofs form when pond water levels fluctuate rapidly, while stagnant ponds lead to the formation of flat roofs. These notches can be regarded as records of the climate during their formation. Detailed mapping is being carried out using terrestrial Light Detection and Ranging.

**Subsurface Karst**

The ratio of the surface to subsurface karst was calculated to be around 7%. While most of the subsurface topography is either covered by development or flooded after the cessation of mining, the various degree of degradation shown is important as evidence of the extent of karstification in this area. Some parts are prone to sinkhole occurrences and depression, and in certain areas the subsurface limestone is riddled with water conduits and cavities.

![Figure 4. GoogleEarth image of Gunung Rapat. The outline of the surface morphology of the limestone hill can be observed in Figure 3. Extensive vertical dissolution coupled with the slicing off of vertical blocks are thought to be responsible for the advanced karstification of the hill. The red dot shows the location of multilevel notches and yellow dot shows the location of a subsurface platform. This image was captured after the doline was filled with water. The author has received permission from Google to use this image.](image)

![Figure 5. Profiles of multi-level karst notches in the study area.](image)
A few locations show limestone in the pavement form with a very jagged surface created by subsoil downward dissolution; in some locations, further dissolution has produced pinnacles with flat, rounded, or sharp tops (Figure 6). An iron mine in a doline in Gunung Rapat has exposed part of the buried subsurface karst, extending up to 9 m below the ground. This subsurface karst is in the form of an almost concordant platform surface, but downward dissolution has further developed the pinnacles with flat to rounded tops. The platform was previously buried under iron-rich alluvium, of which a remnant can be seen up to 7 m above the ground. It was reported by Ford and Williams (1989) that the corrosion plain is commonly veneered with alluvium and, when uplifted, glaciated, or strip mined for placer deposits, removal of the clastic veneer reveals an impressively planar rock floor; particularly in the tropics, this floor can sometimes be rugged in detail because of etching down joints. Jennings (1972) commented on sections by Ingham & Bradford (1956) showing the floor of the Kinta Valley as corrosional karst plain, stating that in detail there is elaborate solutional sculpture but overall the steeply dipping limestone beds are horizontally truncated.

Further away from the subsurface karst found in doline floors, geophysical studies showed uneven topography of the subsurface karst at various depths. The bedrock depths were observed to range from about 20 m to more than 60 m, exceeding the depth allowed by resistivity studies (Riyadh et al., 2014). One example of such a survey was carried out in the north of the study area (shown in Figure 3).

The basal limestone bedrock is covered by soil or sandy clay, and in some places by friable sand; it is dissected by cavities that are believed to be produced by further dissolution of solution-widened joints. Sinkholes and cavities found at this site are of tubular and cylindrical shapes, and most of the cavities appear to be channels for transmission of water and material from the surface (Figure 7). These observations may indicate that these sinkholes and cavities are newly formed.

Figure 6. Right: Flooded subsurface limestone in a doline in Gunung Rapat, previously overlain by alluvial cover that has since been stripped off due to mining. This platform is 9 m below ground level. Left: Multilevel notches on the western flank of Gunung Rapat. Similar feature can be found throughout the valley.
Figure 7. Satellite image of the area of resistivity traverses at the north of Kinta Valley (shown in Figure 3) and inverse models of the resistivity sections, showing highly irregular topography of the subsurface. Values ranging from 400 Ω-m to > 3000 Ω (purple) are interpreted as massive limestone. Circular features with lower resistivity are interpreted as conduits filled with sand and clay (modified from Riyadh et al., 2014).
developed from the collapse of features. This supports the thought that all these cavities originated from pre-existing joints and likely widened due to subsidence/collapse movements in the area that had rapidly filled with clay.

Conclusion
Overall, Kinta Valley karst shows advanced stage tropical karst maturity with a low surface to subsurface area ratio. This is due to the rapid degradation caused by wet conditions in the fluvial and floodplain environment, which continues to exhaust the surface karst and leaves behind a jagged, pinnacled subsurface platform under alluvial cover. The ratio of surface to subsurface karst shows that most of the surface karst in the study area has been extensively degraded. The local setting of the area includes a pluvial environment with constant allogenic water supplied by rivers that flow from the granitic highlands. Degradation is further fasten by the rock collapsing in blocks. The advanced stage of karstification in Kinta Valley could on the surface possibly represent almost the end of the karstification process, with continuous dissolution of the subsurface ongoing from the Tertiary to the present.

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