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FIELD TESTING OF ROCK HARDNESS AND ITS RELATIONSHIP TO LIMESTONE DISSOLUTION IN GUILIN, SOUTHERN CHINA

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ABSTRACT: *This research investigates the relationship between rock hardness and limestone dissolution. Bedrocks at Guilin in subtropical southern China are mainly Devonian and Carboniferous limestone and dolostone. The overburden Triassic and Cretaceous mudstones and sandstones occur sporadically as a result of extensive weathering and dissection. Major surface landforms in Guilin are steep-sided karst towers. A type N Schmidt Hammer was used to test the rock hardness in the field. Purity and solubility of limestone and dolostone samples were tested using 3N hydrochloric acid (HCl) under laboratory conditions. The result of compressive strength test indicates that limestone is the hardest(R=40-50), dolostone is second (R=25-40), conglomerate is third (R=25-37), and the remnants of mudstone are the softest (R=21.8). The result of chemical dissolution test indicates that the limestones in Guilin are very pure (0.55% insoluble residue) and susceptible to chemical dissolution. The results suggest that the steep slopes of tower karst in Guilin are developed and maintained as a result of a combination of two outstanding properties of the limestones: their considerable mechanical strength and durability versus physical weathering and erosion, and their low susceptibility to chemical dissolution.*

INTRODUCTION

Geomorphologists have long attempted implicitly to associate compressive and shear strengths of bedrock with its susceptibility to weathering and erosion, although the relationship appears not to be straightforward. One of the major problems of this approach is that it is difficult to measure compressive strength and shear strength in the field. However, laboratory tests under controlled environments may not help to explain weathering and erosion in the real world. Day and Goudie (1977) introduced a method of *in situ* testing of rock hardness or compressive strength using the Schmidt Concrete Test Hammer. Day (1978; 1980; 1981; and 1982) examined the role of rock hardness in the weathering of carbonate rocks in humid tropical and subtropical regions of the Central America and Southeast Asia. The objectives of the present research are:

(1) to test the rock hardness of limestone as well as other bedrocks in the study region (Guilin, China);
(2) to test the solubility of limestone and dolostone of the region, and
(3) to relate the results of rock hardness to the susceptibility of physical weathering and chemical dissolution of the bedrocks in the region.

Guilin is located in the northeastern part of the Guangxi Zhuang Autonomous Region of southern China (Figure 1). It experiences a subtropical monsoonal climate (Huang et al., 1988). The annual average precipitation in Guilin is 1873.6 mm and the annual average temperature is 18.8°C (Yuan, 1992). There are well-defined wet and dry seasons. The rainy season begins in May and ends in October, accounting for 60 to 80 percent of the total annual precipitation (Zhao, 1986).

Stratigraphically, the outcrops of carbonate rock (limestone and dolostone) in Guilin are mainly of upper Paleozoic, Mesozoic, and

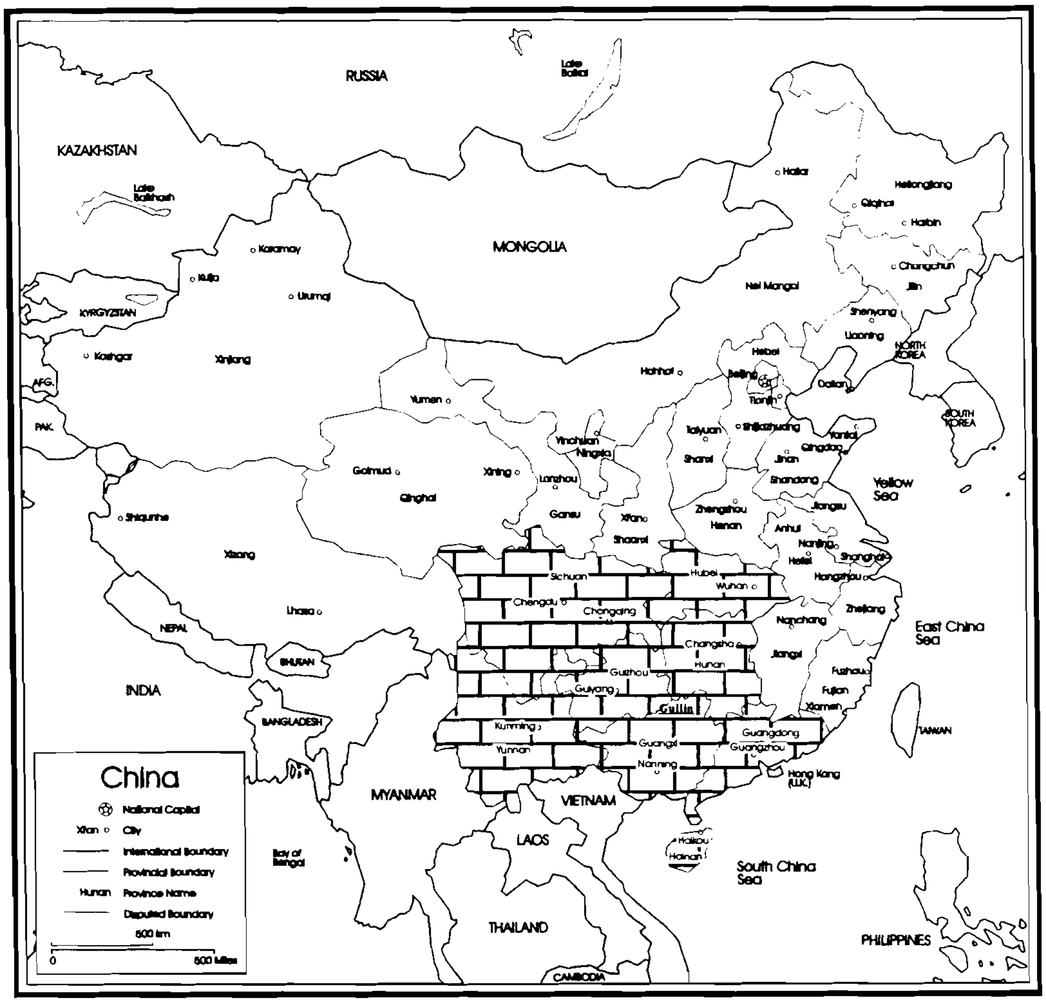

Figure 1: Location of Guilin in Karst Area of Southern China

Cenozoic in age. Of these, the strata from the middle Devonian Donggangling Formation to the Lower Carboniferous Datang Formation comprise the major carbonate rocks, with a thickness of 2600-3000 m. Triassic and Cretaceous silty reddish mudstones and sandstones unconformably overlay the carbonate strata, occurring sporadically as a result of extensive weathering and dissection. The limestones and dolostones are thick to massively bedded and occasionally interlayered with sandstones and shales.

The major geological structure of the Guilin district is a NNE-SSW trending synclinorium on which are superimposed N-S trending thrust fault systems. The rock strata have also been dissected by WNW-ESE trending transverse and shear fault systems (Deng et al., 1988). It is probable that the major folding and faulting structures of the region were formed during the Caledonian movement of the Paleozoic and the Indo-Sinian and Yanshanian movements of the Mesozoic. These movements in turn possibly originated through the collision and subduction of the Eurasian Plate, the Pacific Plate, and the Indian Plate.

Topographically, the Guilin Basin developed in tandem with the geologic syncline (Sweeting, 1990). A variety of karst features are developed in the area, but the major surface landforms are steep-sided karst towers. In the context of this research, "tower karst" is regarded as a general term of karst landform that includes both isolated towers ("peak forests") and towers emerging from a common bedrock base ("peak clusters"). In general, peak forest karst mainly occurs in the central part of the syncline, and peak cluster karst occurs on the two limbs of the syncline. The average summit elevations in peak forests are 250-350 m and the height above the flood plain ranges from tens of meters to 200 m. The average summit elevations in peak clusters are up to 600-800 m and the height above the flood plain reaches up to 600 m.

METHODS AND APPROACH

Sampling Sites and Field Testing of Rock Hardness

Three sampling areas were selected for detailed field survey and measurement. These are: (1) the Experimental Station of the Institute of Karst Geology (EXS), which is representative of peak clusters and is located in the northeast part of the region; (2) the Putao Township (GPT), which is a representative of peak forests and is located in the central part of the region; and (3) Yangshuo (YS), which is an area of mixed peak clusters and peak forests and is located in the town of Yangshuo, in the southern part of the region (Figure 2). Owing to instrument malfunction in the latter period of the fieldwork, no test results of compressive strength were obtained from the YS area.

A type N Schmidt Hammer was used to evaluate the rock hardness in the field. This instrument measures the distance of rebound of a controlled impact on a rock surface. Because the recovery distance depends on the hardness of surface, and hardness is related to compressive strength, the distance of rebound (R value) gives a relative measure of surface hardness or compressive strength. The R value ranges from 10 to 100 and is recorded from a scale on the side of the instrument.

Limestone hardness was tested at two sampling areas (EXS and GPT) and correspond to the tower karst slope profiles surveyed (slope survey results will be published later). Two different types of limestone surfaces on the towers were tested at each of the locations: fresh broken surfaces and weathered surfaces. A fresh broken surface is one that was purposely exposed in order to obtain a measure of the original compressive strength of the limestone. A weathered surface is a natural surface on a slope which had been weathered but which otherwise appeared intact. There is no evidence of formation of hard weathering crusts (case-hardening) on the limestones in Guilin. Obvious weathering effects on the slopes of towers are very limited in depth and generally do not exceed three millimeters depth from the surface. Biological weathering of limestone by lichens is also limited to the upper layer beneath the surface with a range of less than five millimeters.

Six impacts of the Schmidt Hammer were conducted for each of the two types of rock surface at each of the sites tested. A total of twelve readings were collected for each site. Readings of each of the impacts were recorded in the field and the mean R (rebound) values at the locations (sites) were calculated.

Laboratory Dissolution Tests of Limestone and Dolostone

Chemical purity is one of the major properties of limestone and dolostone which may be directly related to dissolution processes and landform morphology. Generally speaking, if all other conditions remain constant, the purer the limestone, the higher the solubility and the more susceptible it is to dissolution (Ford and

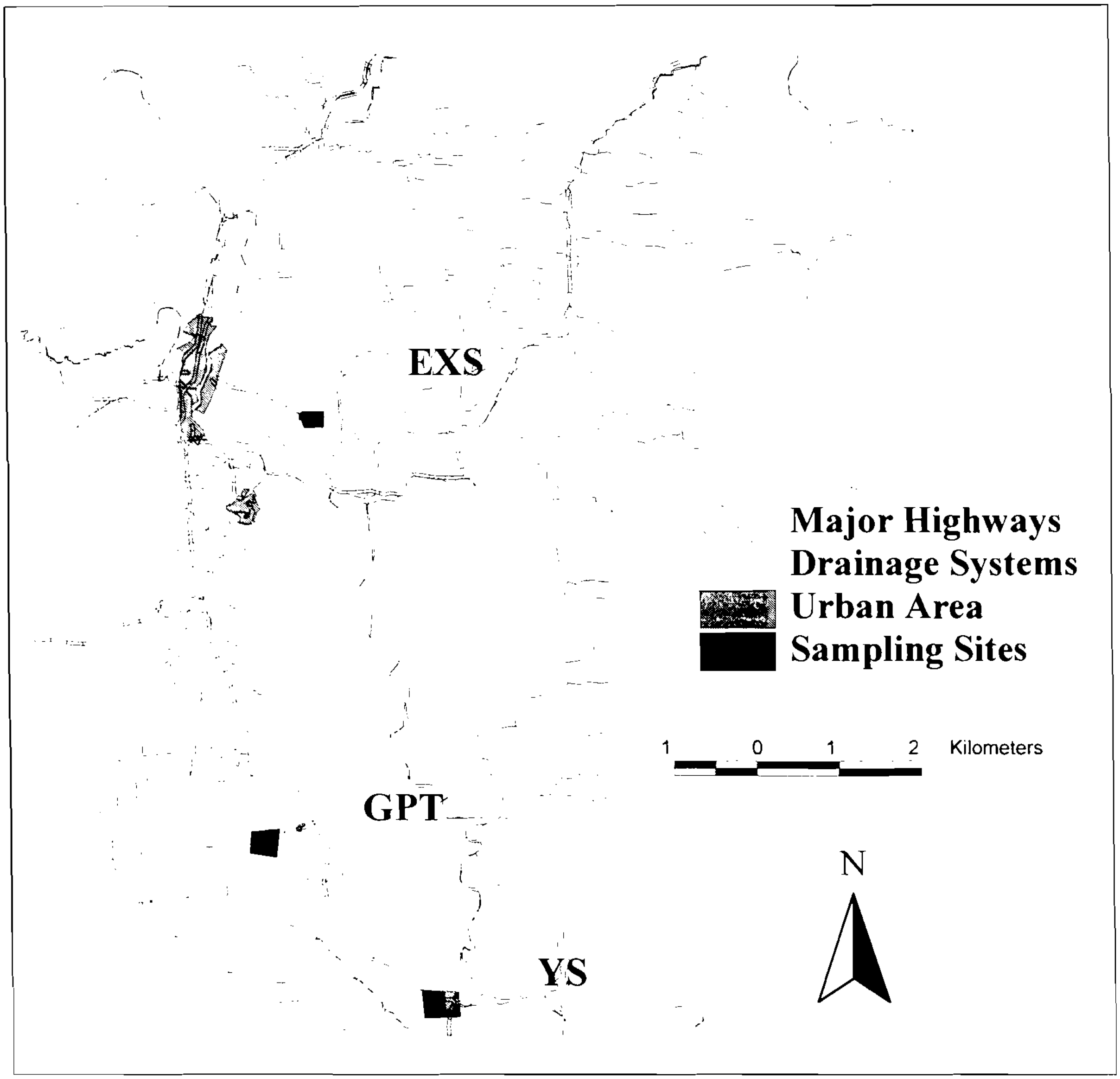

Figure 2: The Sampling Areas in Guilin Region

Williams, 1989). Purity and solubility of limestone and dolostone samples were tested in this study by determining the percentage content by weight of their insoluble residues.

The purposes of this part of the investigation are: (1) to gain a preliminary understanding of the purity of the limestone on which the tower karst of the region is developed; (2) to make comparisons of soluble and insoluble compositions of limestone with those of dolostones and mudstones in the region; (3) to contrast the solubility of limestone, dolostone, and mudstone of the region to their physical strength. It is not an exhaustive study of the purities of the different carbonate formations. All the tests were carried out using 3N hydrochloric acid (HCl) under laboratory conditions. The process of laboratory dissolution of limestone and dolostone took 12 hours for each sample. The solutions were stirred in one-hour interval in order to simulate the water flowing environment in the real world. The detailed procedure of laboratory dissolution experiment is as follows: (1) weigh the carbonate rock sample; (2) put the sample in a large beaker and pour HCl into the beaker; (3) stir the solution in one-hour interval until the sample is fully dissolved; (4) drain HCl from the beaker, dry the residue in the beaker, and weigh the residue for calculation.

RESULTS

Compressive Strength of Bedrocks

Mean R values of limestone surfaces at different locations in the sampling areas are shown in Table 1. Tests of limestone hardness were conducted in two of the three sampling areas, EXS (peak clusters) and GPT (peak forests). A total of 26 sites were selected to conduct the testing, 18 in EXS area and eight in GPT area. The mean R value of fresh broken surfaces in the EXS area was 46.3 and the range was from 39.1 to 61.3. In the GPT area, the mean was 47.7 and the range was from 40.9 to 57.3. By contrast, weathered surfaces had a mean R value of 35.5 with a range from 30.0 to 43.4 in the EXS area and a mean of 36.7 in the GPT area with a range from 34.3 to 39.8. The lichen-covered surfaces in both areas have even lower R values with means of 18.8 and 24.9.

The T test was applied in this research to test statistically the significance of similarities or differences of compressive strength between limestones of the two sampling areas and between the limestone and dolostone of the region. The null hypothesis is that there is no difference in rock hardness between two sampling areas or between two types of rocks (H_o: $m_1=m_2$). The alternative hypothesis is that there is a significant difference between them. The confidence interval of significance testing is 95% ($\alpha = 0.05$).

The tests were performed according to the procedures outlined by Swan and Sandilands (1995) and using Microsoft-Excel statistical module. The results of T tests of limestone between the sampling areas of EXS and GPT indicated that the null hypothesis can not be rejected (P=0.61 for fresh broken surface, and P=0.22 for weathered surface). Hence there is no significant statistical difference of compressive strength between the peak clusters area of EXS and the peak forests area of GPT. However, the results also indicated that there are significant differences between the limestone and the dolostone of the region (P=8.15E-09 for fresh broken surface, and P=1.43E-16 for weathered surface). Therefore, the results indicate: (1) there is no significant difference between R values in the peak clusters (EXS) and peak forests (GPT); the limestone of the two sites belongs to the same formation, the Rong County Formation of the Devonian; (2) the mean R values are lower than those in the Gunong Mulu National Park, Sarawak, Malaysia (Day, 1981) where pinnacle karst has developed, but significantly higher than those of limestones in the Caribbean and Central America (Day, 1979; 1982); (3) the mean R values decrease from fresh broken surfaces to weathered surfaces, which indicates that the higher the physical and biological weathering the lower the compressive strength. The pattern of the weathering influence on compressive strength is similar to that found in the Gunong Mulu National Park, Malaysia, but it differs from those reported in the Caribbean and Central America due to the lack of surface dissolution and case-hardening (Day, 1981; 1982); (4) although weathering on the slopes of towers decreases the surface hardness, it was found through field observation that the weathering penetration by the atmosphere and growing lichen is limited and reaches a maximum of up to 5 mm below the surface; (5) very few talus accumulations and break-down deposits were observed at the bases of the towers. This suggests that neither landslides nor mechanical breakdown are major processes on the tower karst in the region.

Schmidt Hammer hardnesses of the Carboniferous dolostones, the Jurassic conglomerates, and the Cretaceous mudstones of the region are presented in Table 1. These tests were conducted in the LinGui County and Guilin Airport at the suburban area of the Guilin City (about 50 km away from the sampling areas) because the sampling areas are all covered by

Table 1 R Values of Compressive Strength of Limestone, Dolostone, Mudstone, and Conglomerate in Guilin

Rock Type and Sampling Area			Fresh Broken Surface	Weathered Surface
Limestone:				
	EXS:			
		Mean	46.3	35.5
		Maximum	61.3	43.4
		Minimum	39.1	30
	GPT:			
		Mean	47.7	36.7
		Maximum	57.3	39.8
		Minimum	40.9	34.3
Dolostone:				
	LinGui County:			
		Mean	29.2	15.95
		Maximum	39.7	21.9
		Minimum	25	14
Cretaceous Mudstone (Redbed):				
	Guilin Airport:			
		Mean	21.8	
Jurassic Conglomerate:				
		Mean	31.2	
		Maximum	36.8	
		Minimum	25.3	

limestone. The mean R value of dolostone fresh broken surfaces is 29.2 with a range from 25.0 to 39.7. By contrast, the mean R value of dolostone weathered surfaces is 16.0 with a range from 14.0 to 21.9. It is evident that the compressive strength of the dolostone in the region is significantly lower than that of the limestone (Table 1).

Solubility of Bedrocks

Table 2 summarizes the results of the insoluble residue determinations of limestones and dolostones in Guilin. According to the dissolution test results, the limestones in Guilin are very pure and contain a mean of only 0.55% insoluble residue. These results are coincident with those of previous studies in the Guilin area as well as elsewhere in southwest China (Yuan et al., 1991). The purity of the limestones is comparable to that of limestones in Jamaica where cockpit karst is developed (Day, 1982), but much purer than limestones in other locations in the Caribbean and Central America. There is no significant difference in purity between the two major limestone formations in the region, namely the Rong County Formation of the upper Devonian (insoluble residue: 0.56%) and the Dongangling Formation of the middle Devonian (insoluble residue: 0.53%). However, there is a significant difference when the purity of the limestone is compared with that of the dolostone, which is less pure than the limestone with an insoluble residue content of 1.86%.

Table 2 Summary of Insoluble Contents of Carbonate Rocks in Guilin

Sample Number	Lithology	Location	Total Weight (g)	Residue Weight (g)	Percent of Residue Content (by weight)
R#1	Limstone (D2d)	YS	100.00	0.53	0.53%
R#2	Limstone (D3r)	EXS	100.00	0.64	0.64%
R#3	Limstone (D3r)	EXS	100.00	0.62	0.62%
R#4	Limstone (D3r)	GPT	100.01	0.42	0.42%
R#6	Dolomite (C2)	LinGui County	104.61	1.95	1.86%

DISCUSSION AND CONCLUSION

Ranking the different lithologies of the region by compressive strength (Table 1), limestone is the hardest (R=40-50), dolostone is second (R=25-40), conglomerate is third (R=25-37), and the remnants of mudstone are the softest (R=21.8). Combining compressive strength data with previous studies and the results from laboratory dissolution testing of limestone and dolostone, it is suggested that: (1) there is a direct relationship between R value and resistance of rock to mechanical weathering and erosion. For instance, limestones in the region with the highest R value are those least susceptible to mechanical weathering and breakdown. By contrast, mudstones in the region with the lowest R value are those most susceptible to mechanical weathering. (2) R value is inversely related to the susceptibility of rock to chemical dissolution. The limestones with the highest R value are those most susceptible to chemical dissolution.

In summary, there is evidence to suggest that the mechanical strength of limestones is as important as the pattern of chemical dissolution in controlling the development of karst landforms in tropical areas such as Guilin. The results of compressive strength tests of limestones in the field and chemical dissolution in the laboratory suggest that the steep slopes of tower karst in Guilin are developed and maintained as a result of a combination of two outstanding properties of the limestones: their considerable mechanical strength and durability against physical weathering and erosion, and their low susceptibility to chemical dissolution.

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