PRELIMINARY DEVELOPMENT OF A STATISTICALLY-BASED KARST CLASSIFICATIO SYSTEM, PHORMS

Daniel H. Doctor[1], Benjamin F. Schwartz[2], Marcus O. Gary[3]
[1]United States Geological Survey, 12201 Sunrise Valley Drive, Reston, VA, 20192 USA
[2] Department of Biology, Texas State University, San Marcos, TX 78666, USA
[3] Zara Environmental, LLC, 118 West Goforth Dr., Buda, TX 78610, USA

A karst classification system is necessary in order to identify common processes of karstification in disparate regions. A robust classification scheme for karst terrains and aquifers should be grounded in 1) a well-constructed geologic framework and 2) the hydrogeologic processes of karst development taking place within that framework. Prior classifications of karst have been largely descriptive, lacking a foundation in quantifiable parameters. A classification of karst should avoid being based solely upon morphologic descriptions of the numerous geomorphic features recognized within karst terrains, and instead be linked to the processes and geologic attributes that give rise to karst features. Ranking such processes and attributes according to their importance for karstification allows for a statistical comparison of different karst regions, and ultimately a more quantitative classification of karst terrains.

Here, we introduce the PHORMS karst classification method. PHORMS is an acronym for the six factors considered in the classification: Physiography and climate, Hydrology, Other conditioning attributes, Rock properties, Morphology of karst features, and geologic Structure. The method is designed to be as quantitative as possible. Each factor comprises several attributes that are numerically scaled with regard to their relative importance for karstification processes then summed. A 6 x *n* matrix results: 6 numerical PHORMS factor values for each of the *n* karst regions being compared. The karst regions are then classified through the statistical techniques of Hierarchical Cluster Analysis (HCA), and the importance of each of the PHORMS factors within the classification is assessed through Principal Components Analysis (PCA).

The approach presented here is preliminary and subject to refinement. Our goal is to provide a classification system based upon quantitative parameters that can be used to efficiently compare karst terrains around the world. The PHORMS classification method is sufficiently flexible to be used as an exploratory tool as well as a means of comparison among factors responsible for karstification in a wide range of environments.

1. Introduction

Attempts to classify karst extend as far back as the history of karst science. Early work by Cvijić and Grund classified karst terrain according to the degree of development of morphometric and hydrologic features, resulting in the broad classifications of *holokarst* (complete or true karst), *merokarst* (partial karst) and *transitional karst* (SWEETING, 1973). QUINLAN (1967) and SWEETING (1973) expanded upon this approach and attempted to classify karst based upon a range of geomorphologic factors. More terms were added to the list of karst types, including designations such as fluviokarst, glacio-karst (also known as nival-karst or cryo-karst), cone and cockpit karst (*kegelkarst*), tower karst, interstratal karst, naked karst (*nacktkarst*), denuded karst, exhumed karst, covered karst (including variants within), relict or fossil karst, paleokarst, syngenetic karst, thermal karst and pseudokarst. In spite of these various designations of karst types, several universal criteria were recognized to be important for karst development: rock properties, geologic structure, climate, type of unconsolidated cover, physiography, and past and present hydrologic conditions.

Recently, greater focus has been placed upon the processes of karstification as a means of classifying karst. Debate has turned from questions such as "what is epikarst?", "what is paleokarst?", or "what is pseudokarst?" to "what are the criteria for epigenic and hypogenic karst development?" The three former questions arise when comparing karst terrains on the basis of their geomorphic features;however, due to varying interpretations of processes that give rise to observable morphologic features, clear consensus is hardly possible. The latter question, on the other hand, grounds the discussion in the processes of karstification and landscape evolution that give rise to the features we observe, many of which are common in seemingly disparate regions.

Quantitative approaches to classification of karst have been based largely upon aquifer characteristics (see, for example, BAKALOWICZ AND MANGIN, 1980; SMART AND HOBBS, 1986; EL-HAKIM AND BAKALOWICZ, 2007). In spite of the potential success of such an approach, its application thus far has been largely conceptual rather than practical. A more comprehensive approach would incorporate the geologic and geomorphologic aspects of karst development (WHITE, 1999), but this, too, has yet to be formulated in a practical manner.

2. The PHORMS Classification System

Here, we present a preliminary classification system designed to include both the geomorphologic and hydrologic aspects of karst in a quantifiable manner that can be applied globally to any karst region where the requisite data exist. We call this the PHORMS classification. PHORMS is an acronym for the six

ATTRIBUTES OF KARST		KARST REGIONS COMPARED																
Values listed from none, low, med, high (0,1,2,3) to indicate relative importance to karstification	WEIGHT	Mammoth Cave, Kentucky	Ozarks, Missouri	Edwards Plateau, Texas	Shenandoah Valley, Virginia	Classical Karst, Slovenia	Lilburn Cave, California	Omega System, Virginia	Burnsville Cove, Virginia	Sistema Zacaton, Mexico	Bahama Flank Margin Karst	Alpine Karst	Idealized Carbonate Island	English Chalk	Biscayne Aquifer, Florida	Basin and Range, Nevada	Puerto Rico Cockpit Karst	Tropical Mts., Mexico
P - Physiography & Climate		5	4	5	6	8	6	8	7	7	7	8	7	4	7	6	8	8
Relief of soluble terrain (<50m=1, 50-300m=2, >300m=3) (*degree of gradient*)	1	1	1	2	2	3	3	3	2	1	1	3	1	1	1	3	2	3
Unconsolidated overburden thickness (>10m=1, 3-10m=2, <3m=3) (*degree of mantling*)	1	2	1	2	2	3	2	3	3	3	3	3	3	1	3	3	3	2
Climate (Arid=0, Semi-arid=1, Temperate=2, Tropical=3)	1	2	2	1	2	2	1	2	2	3	3	2	3	2	3	0	3	3
H - Hydrology		9	8	7	5	6	9	9	9	4	4	9	3	3	3	3	9	9
Q freq. dist. (unimodal=1, bimodal=2, multi-modal=3) (*degree of discharge variation*)	1	3	3	3	2	2	3	3	3	2	1	3	1	1	1	1	3	3
% Allogenic recharge (none=0, <10%=1, 10-30%=2, >30%=3)	1	3	3	2	1	2	3	3	3	1	2	3	1	1	1	1	3	3
Baseflow depletion coeff. a (<0.01=1, 0.01-0.02=2, >0.02=3) (*degree of aquifer storage*)	1	3	2	2	2	2	3	3	3	1	1	3	1	1	1	1	3	3
O - Other Conditioning Factors		0	4	4	7	0	2	1	1	7	3	0	3	0	0	7	0	2
Pre-exisiting karst (none=0, low=1, med=2, high=3) (*degree of invasion/overprinting*)	1	0	1	2	3	0	0	0	0	1	0	0	0	0	0	2	0	0
Hydrothermal influence (none=0, low=1, med=2, high=3)	1	0	2	0	2	0	2	1	1	3	0	0	0	0	0	3	0	1
Enhanced geochemical corrosion (none=0, low=1, med=2, high=3)	1	0	1	2	2	0	0	0	0	3	3	0	3	0	0	2	0	1
R - Rock Properties		7	7	8	6	9	7	6	6	6	7	8	5	5	6	7	8	9
Primary Porosity (>15%=1, 5-15%=2, <5%=3) (*higher porosity = less karstification*)	1	3	3	2	3	3	3	3	3	1	2	3	1	1	1	3	2	3
Impurities (>50%=1, 10-50%=2, <10%=3)	1	2	2	3	2	3	3	2	2	2	3	2	3	3	3	2	3	3
Bedding thickness (<1m=1, 1-3m=2, >3m=3)	1	2	2	3	1	3	1	1	1	3	2	3	1	1	2	2	3	3
M - Morphology		8	6	3	6	8	7	7	6	6	5	8	5	4	5	5	6	9
Median cave length (<300m=1, 300-1000m=2, >1000m=3) (*degree of flow integration*)	1	3	2	1	1	2	3	3	2	2	2	3	1	1	1	1	2	3
Dolines per sq. km (none=0, low=1, med=2, high=3) (*degree of surficial karstification*)	1	3	2	1	2	3	2	1	2	1	2	2	3	2	3	1	3	3
Cave depth (<30m=1, 30-100m=2, >100m=3) (*degree of deep karstification*)	1	2	2	1	3	3	2	3	2	3	1	3	1	1	1	3	1	3
S - Structure		3	3	6	9	9	8	6	9	3	1	9	1	2	3	9	2	9
Inclination of strata (<5º=1, 5-30º=2, >30º=3)	1	1	1	1	3	3	3	2	3	2	1	3	1	1	1	3	1	3
Sub-vertical fracture frequency (low=1, med=2, high=3) (*degree of vertical permeability*)	1	1	1	3	3	3	2	2	3	1	0	3	0	1	1	3	1	3
Faulting and folding (none=0, low=1, med=2, high=3) (*degree of rock deformation*)	1	1	1	2	3	3	3	2	3	0	0	3	0	0	1	3	0	3

***Table 1**. Attributes included in the PHORMS classification and the values assigned to the karst regions being compared. Values include relative scales for some attributes and quantitative scales for others.*

factors considered in the classification: Physiography and climate, Hydrology, Other conditioning attributes, Rock properties, karst Morphology, and geologic Structure. Each factor comprises several attributes that are ranked with regard to their relative importance for karstification processes (Table 1). The physiography and climate (P) factor includes topographic relief, prevailing climate, and thickness of insoluble, unconsolidated overburden. The hydrology (H) factor includes the modality of discharge frequency distribution for an index spring, the percentage of allogenic recharge, and the baseflow depletion coefficient of the spring as a measure of storage within the aquifer of interest. A factor termed other conditioning factors (O) accounts for hydrogeologic processes that may influence current karstification processes, such as paleokarst, hydrothermal flow, or strong geochemical drivers toward karstification such as mixing corrosion or the influence of sulfuric acid on speleogenesis. The factor that describes morphology of karst features (M) includes estimates on the spatial density of dolines, length of caves, and depth of caves. Rock properties (R) include matrix porosity, purity, and thickness of bedding. Finally, the geologic structure (S) factor includes inclination of strata, fracture frequency, and degree of deformation as expressed by faults and folds. This preliminary classification system only considers karst in carbonate rocks; classification for karst within other rock types and for pseudokarst will be developed separately.

This system is designed to be as quantitative as possible, but necessitates some degree of subjectivity and simplification to include as many relevant factors as required to generate a useful classification. We have followed a method of attribute ranking and weighting as is done in karst groundwater and fractured aquifer vulnerability assessments (DOERFLIGER ET AL, 1999; DENNY ET AL, 2003). The approach ranks each factor attribute in terms of its perceived significance to karst development, as well as permits relative weighting (integer multipliers) of the attributes of each factor. The weighted ranks of the attributes within a factor are then summed, and the resulting values of a particular factor are normalized among all karst regions being compared for statistical and graphical purposes.

For example, doline density is an attribute of the Morphology factor. As with all attributes, we use a simple tiered ranking, with 0=none, 1=low, 2=medium, 3=high. A more quantitative ranking could be based on an actual value of dolines per square kilometer where data are available. The higher rank indicates a higher significance for karstification. The other Morphology factor attributes are mean cave depth and mean cave length. The attributes values are then summed to provide a single numerical value for the factor. This factor value is then standardized by subtracting the mean and dividing by the standard deviation among all of the other M values assigned to the karst regions being compared. Standardization is necessary to place all of the factor values within the same numerical scale. The standardized values of all PHORMS factors are a matrix of $6 \times n$, with n being the number of karst regions compared.

Two multivariate statistical methods (DAVIS, 2002) were employed to explore the data: Hierarchical Cluster Analysis (HCA) and Principal Components Analysis (PCA). HCA classifies the different karst regions according to hierarchical correlations among the values in the PHORMS matrix. PCA identifies the components of the matrix that account for the greatest amount of variance in the dataset. Although PCA is not a technique that can be directly used for classification, it permits an examination of those aspects of the dataset that are most likely exerting strong control over the classification borne out by the HCA.

3. Results

The example data shown in Table 1 are preliminary and are used to demonstrate "proof of concept" only. For this example, we chose to weight all of the attributes equally. Addition or modification of attributes, including weighting, within each of the six PHORMS factors is expected as the method is refined.

The HCA was performed twice: first using only the values of the six PHORMS factors as variables, and a second time using all of the attributes included in the classification as variables (Fig. 1). This served to test the method of summing the attribute values into single PHORMS factors. The HCA results of the PHORMS factors (Fig. 1A) fall into two major groupings separated to the first-order on the basis of hydrologic condition: those having deep or significant phreatic storage, and those generally lacking such storage. To a second-order, the classification seems to further divide the first-order groups on the basis of structural deformation or lack thereof. At the third-order, differentiation among karst regions occurs more rapidly as other conditioning attributes, such as pre-existing paleokarst, strong acids, or hydrothermal activity come into play. In contrast, the results of the HCA performed on a matrix of all attributes as individual variables showed a different discrimination within the first-order, placing those regions having high structural deformation as well as significant phreatic storage into the same grouping as those with little phreatic storage (Fig. 1B). As before, the first-order discrimination among the three groups appears to be largely based on the degree of

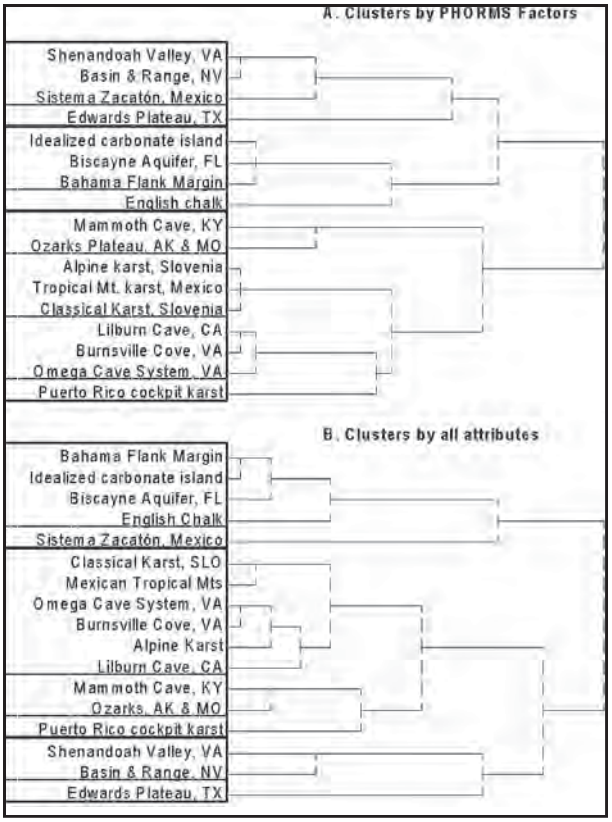

Figure 1. Hierarchical Cluster Analysis (HCA) results. A) HCA results using the six PHORMS factors (summed attribute values) as variables. B) HCA results when all of the attributes were used as individual variables in the HCA classification.

phreatic storage; however, the discrimination is stronger.

Although there is some similarity between the two HCA results, the discrepancies are interesting. For example, the Shenandoah Valley, Basin and Range, and Edwards Plateau regions were shifted out of the first-order grouping reflective of high phreatic storage when the analysis was performed on all attributes. In order to explain this, the results of the Principal Components Analysis (PCA) can be used to provide additional insight into the HCA classification. In the case of the Shenandoah Valley and Basin and Range, the shift in categorization might be explained by the lack of primary porosity in the indurated Paleozoic carbonate rocks of these regions, since this attribute has the highest factor loading within the first component of the PCA (Table 2). For the Edwards Plateau, the explanation is likely a more complex combination of attributes.

As with the HCA, the PCA was performed first using only the six PHORMS factors. The first two components account for 66% of the variance of the data. The projection of the 6-dimensional data cloud into 2-dimensional space may be visually misleading due to the collapse of some points near to one another that may, in fact, be separated in a space of greater dimensions (Fig. 2). For example, the vectors for physiography (P), hydrology (H), rock type (R), and morphology (M) all fall within a cluster. These four factors would be more separated in a space of greater dimension, as indicated by the factor loadings provided in the full component matrix (Table 2A). The first component accounts for 47% of the variance of the data, and the factor loadings show that the greatest influence on this component is exerted by the morphology (M=0.85) hydrology (H=0.78) and rock type (R=0.75) factors. The second component accounts for an additional 19% of the variance in the data matrix, and its loading factors are most strongly weighted on other conditioning attributes (O = 0.82) and geologic structure (S = 0.65). The third component is most weighted on the physiography factor (P=0.77).

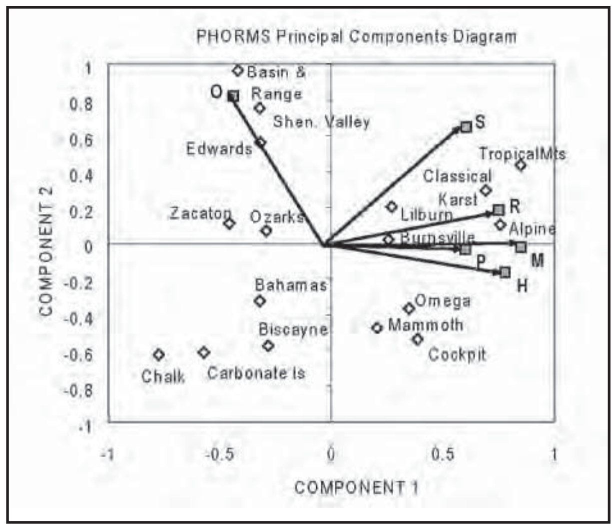

Figure 2. Principal Components Analysis results of the PHORMS factors. The arrows are vectors of the factor loadings, indicating relative importance for position of points within the 2-component space.

The PCA using all of the karst attributes as variables required three principal components to explain the same amount of variance (69%) that two components explained using only the six PHORMS factors as variables. High factor loadings (>0.70) within the first component were on structural attributes (dip of strata, fracture frequency, and degree of faulting and folding) and hydrologic attributes (discharge frequency distribution and baseflow storage); however, the highest loading (0.89) was on rock porosity (Table 2B). Other attributes with high loadings within the first component (in decreasing order) were topographic relief (0.83) and cave depth (0.75). Attributes of the first principal component with moderate loadings (between 0.70

and 0.50) were the percentage of allogenic recharge and cave length. The second principal component was most heavily weighted on other conditioning factors such as the presence of paleokarst (-0.82) and hydrothermal activity (-0.69). The negative loadings on these attributes indicate an inverse relation between these attributes and others with moderate loadings within the second component such as allogenic recharge (0.68) and doline density (0.66), possibly reflecting the different expressions of deep and shallow karstification.

A. PHORMS Factors	COMPONENT FACTOR LOADINGS					
	1	2	3	4	5	6
P	0.60	-0.04	0.77	0.02	0.00	0.21
H	0.78	-0.16	-0.45	-0.14	0.14	0.35
O	-0.44	0.82	0.03	0.01	0.35	0.11
R	0.75	0.18	-0.14	0.62	0.01	-0.08
M	0.85	-0.02	0.06	-0.26	0.32	-0.32
S	0.60	0.65	-0.08	-0.23	-0.40	-0.03
Cumulative % Variance Explained:	47%	66%	80%	88%	95%	100%
B. All attributes	COMPONENT FACTOR LOADINGS					
	1	2	3	4	5	6
Relief	0.83	-0.05	0.40	-0.13	0.01	-0.18
Cover	0.02	-0.01	0.65	0.49	-0.17	-0.43
Climate	-0.49	0.50	0.17	0.48	-0.04	0.34
Q-freq. dist.	0.70	0.44	-0.36	0.09	0.31	-0.03
Allogenic rech.	0.61	0.68	-0.28	0.08	0.10	-0.13
Baseflow Storage (α)	0.76	0.56	-0.17	-0.02	0.04	-0.02
Paleokarst	0.11	-0.82	-0.18	-0.12	0.35	0.17
Hydrothermal	0.32	-0.69	-0.27	0.31	-0.12	0.13
Enhanced Acidity	-0.43	-0.58	0.03	0.38	0.22	0.03
Porosity	0.89	0.04	-0.13	-0.07	-0.04	0.10
Rock purity	-0.45	0.36	0.45	-0.43	0.21	-0.02
Bedding	0.11	0.17	0.35	0.34	0.79	0.06
Cave length	0.61	0.58	-0.14	0.38	-0.10	-0.04
Doline density	-0.20	0.66	0.33	-0.15	-0.12	0.54
Cave depth	0.75	-0.34	0.13	0.39	-0.12	0.25
Dip	0.79	-0.30	0.38	0.04	-0.23	0.16
Fracture freq.	0.81	-0.29	0.28	-0.26	0.20	0.04
Faults and folds	0.87	-0.22	0.26	-0.27	-0.05	0.08
Cumulative % Variance Explained:	37%	59%	69%	77%	84%	88%

Table 2. *Component matrices of the PCA results. Higher absolute value of a factor loading indicates a greater contribution of that variable to the overall component. Factor loading values with absolute value greater than 0.70 are highlighted in gray; absolute values greater than 0.50 are in bold. A) PCA results using only the values of the six PHORMS factors as variables. B) PCA results using rank values of each individual karst attribute as variables; only the first six principal components are shown for clarity.*

4. Discussion

There are several advantages to the PHORMS classification system. The first is that quantifiable information common among many karst regions is used in order to provide as objective a classification as possible. Databases on karst are growing rapidly in different regions; however, these databases lack a standard structure or guidance as to the key parameters needed for karst classification. The PHORMS system may serve as a guide to summarizing data collected within a particular karst setting in order to place the karst region within the classification. Admittedly, the values shown in Table 1 are based partly on objective data from the literature and partly upon "educated guesses" of the authors; thus, the analysis presented here should only be considered as preliminary. Nevertheless, the exercise provides a framework for further refinement.

The second advantage is that it permits direct comparison of different karst regions as well as a structure for statistically exploring the empirical connections among index parameters. Finally, the matrix structure also allows one to explore 'predictions' of karst attributes. For example, one might create a multiple regression model in which doline density is set as the dependent variable in order to assess the relative importance of the other attributes on the surface expression of karst. Although empirical, the exercise may provide useful insight and help steer new research directions concerning the underlying processes and controls on karstification.

5. Conclusion

The preliminary PHORMS classification system reflects an initial step toward a comprehensive classification of karst. Whatever classification scheme is applied to karst, it should enable theoretical models of karst processes to be placed within the classification alongside well-characterized regions. The ability to compile quantifiable aspects of karst regions around the world is increasing with increasing research. The PHORMS classification system attempts to take advantage of these data for practical application in karst research and possible inclusion into developing databases such as the Karst Information Portal (KIP) or other future and existing systems of karst information organization.

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