The Mapping and Classification of Cave Geomorphic Processes within the United States

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Abstract

Terms utilized to describe caves are often based upon landscape morphological and/or anthropomorphic features. The emphasis is on form, not function. Since various processes can produce landscapes with similar appearances, this has led to a diverse, complex, haphazard, and sometimes confusing lexicon. Similarly, most cave classification systems focus upon management of caves as a recreational resource, or rank the hazards they pose to the visiting public. Many other scientific disciplines have taken a more scientific-based, process-oriented approach to classification. A similar approach for caves would aid analyses, cave assessments, the development of protection strategies and the development of protection and restoration priorities. Various researchers have produced national cave or karst distribution maps. However, these maps primarily depict the presence of carbonate rocks. The presence of suitable lithology is only one of five necessary criteria for solution cave development. These maps do not incorporate the other criteria, nor do they incorporate the processes necessary for cave development of the other seven cave types.There are 85 physiographic sections within the 48 contiguous United States. Section boundaries are based upon similar geology and geomorphic processes. Since these are critical components of cave-development, physiographic sections were found to form usable boundaries for mapping cave-forming processes. This national, regional, and landscape-scale approach proves useful in understanding local cave-forming processes and why caves occur where they do, assessing the dominant limiting factors in cave development, as well as providing a more analytical and systematic framework for karst researchers working on a regional or national scale.

Introduction

Terms utilized to describe caves are often based upon landscape morphologic and/or anthropomorphic features. The emphasis is on form, not function. Since various processes can produce landscapes with similar appearances, this has led to a diverse, complex, haphazard, and sometimes confusing lexicon. Similarly, most cave classification systems focus upon management of caves as a recreation resource, or rank the hazards they pose to the visiting public. Many other scientific disciplines have taken a more scientific-based, process-oriented approach to classification. A similar approach for caves would aid analyses, cave assessments, the development of protection strategies, and the development of protection and restoration priorities.

Various researchers have produced national cave or karst distribution maps. However, these maps primarily depict the presence of carbonate rocks. The presence of suitable lithology is only one of five necessary criteria for solution cave development. These maps do not incorporate the other criteria nor do they incorporate the processes necessary for cave development of the other seven cave types.

This paper is a summary of the on-going effort by the author in the development of a process-oriented classification system and national map of these processes. This goal is that one may better able to recognize and assess the active cave-forming processes within any given area within the United States.

Cave Types

A diverse array of names is in common usage to describe cave types. However, many of these names refer to morphologic features and not any speleogenetic process. There are times however, where similar processes can form widely divergent landscape features, especially under different environmental conditions (Daoxian and Zaihua, 1998). Conversely, widely divergent processes can form similar looking landscape features. As such, confusing terminology results. For instance, the term "pseudokarst" has been used to describe landscape features in situations where processes not even remotely similar or analogous to karst processes were involved in their formation. It is confusing and imprecise to use terminology that implies otherwise.

In pursuit of an understanding of current geomorphic processes affecting a cave's ecosystem, it is imperative that we understand the processes affecting the landscape during the initial creation of the cave. As in many other efforts, it is perhaps easier to understand complex and interrelated processes by breaking these parts into isolated components. In the case with caves, what were the processes that created the cave in the first place? Since a cave is in essence a hole, what created the hole? Was there something there originally? Many caves were formed after the original host material (rock, for example) was formed. Space that had once been occupied by solid matrix was changed or altered in a manner that locally and/or preferentially removed material leaving a void in its place. An important aspect of cave geomorphology is the assessment and evaluation of the processes that could have removed or altered this solid material. At the most basic level, caves may be formed either as primary features where the cave is formed at the time that the host rock is formed (for example a lava tube), or as a secondary features where a portion of the solid material was removed (Daoxian, 1991).

There are two types of primary caves: those formed by the cooling of molten rock, and those formed by the growth and crystallization of soluble rock that forms a roof over an existing void. The majority of primary caves are formed in and around molten lava, hot ash, and other material that originated from volcanic eruptions.

Many of the better-known caves, such as Mammoth Cave and Carlsbad Cavern, were formed long after the surrounding host substrate (limestone) was deposited. The removal of the solid material necessary to form secondary caves is by either: (1) mechanical separation; (2) solid material going into, and then being removed by, solution; (3) melting of solid matrix, or (4) by the physical excavation by erosion or other processes.

However, there is another form of secondary cave, which is formed by the unique juxtaposition of discreet solid material that is arranged in a manner that creates a void. An example is large blocks of stone that have fallen from a cliff and arranged themselves at the foot of the cliff in a manner that the spaces in between the boulders form a cave and provide an uniquely discreet microclimate from surface environments. These caves are typically called talus caves. However, since "talus" refers to a rock size smaller than boulders and since "talus caves" form more commonly in boulder fields, the term "spatial cave" is used to be more precise.

The countless variety and diversity of cave types are all variations of these seven basic cave-forming mechanisms. As in many other aspects of the natural world, cave-forming processes operate along a continuum, not in discreet units. Of the many and diverse factors that affect cave development, whether climate, geology, or the like, they operate within the context of these seven basic cave-forming mechanisms in tandem, which result in the creation of the many diverse caves known to exist.

Based upon these seven processes, the author has identified eight processes-oriented cave types. These eight cave types are as follows:

1. Caves that are formed by the recrystallization of soluble rock over an edge, much like a frozen waterfall, whereas there is airspace between the main cliff edge and the recrystallized roof. This type of cave is very rare, however they have been found in certain travertine deposits, therefore are called "Mineralization Caves." Mineralization Caves are likely quite small, being formed by the chance occurrence of an air space sufficiently large between a small cliff and travertine deposits that has cascaded over the cliff edge.

2. Caves that are formed during the process of molten material changing from liquid to solid form are called "Solidification Caves." The term Solidification Cave refers to all type of caves formed by the cooling of lava, such as lava tubes, blister caves, gas injection caves, pressure ridge (Larson and Larson, 1993) caves, and the like. The term "lava cave" is more precise than the term "lava tube." Many solution caves display more "tube" like morphology than do "lava tubes." Additionally, some caves are formed during the cooling/solidification process by means other than the crusting over process common in "lava tubes." The term "lava cave" is more precise due to not describing only one particular form. However, some caves formed by the cooling/solidification proc-

ess are formed in ash and other non-lava material, therefore, the awkward but more appropriate "solidification cave" is used.

3. Caves that are formed by chemical processes that dissolve and relocate by solution the surrounding substrate are called "Solution Caves." Solution processes are involved in both solution and mineralization caves, however one is a primary process and the other is a secondary process.

4. Caves that are formed by wind, water, wave, and other erosional excavation processes are called "Erosion Caves."

5. Caves formed by air and/or water melting of glacial ice, firn, or permanent snowfields are called "Phasic Caves." Caves formed in glacial ice and solidification (lava) caves are in some ways created by similar processes, since they both involve the melting of solid material. However, one is a primary process and one is a secondary process.

6. caves formed by the unique juxtaposition of discreet blocks, boulders, or talus are called "Spatial Caves."

7. Caves formed by geologic stress, pressure, gravity, or other physical force which displaces two or more sections of surrounding substrate are called "Tectonic Caves."

8. Caves formed by the actual excavation by biologic organisms are called "Biologic Caves." This is similar to erosion caves, however the erosion agent for one is physical, while the other is biological.

A schematic model representing these cave types and the processes leading up to them is depicted in Figure 1.

Cave Geomorphic Classification System

Classification systems are common for a variety of resources, even for more specific aspects pertaining to karst (Chilinger *et al.*, 1967a and b). In an effort to develop a more systematic and resource-based classification system for caves, much can be learned from these other classification systems. For example, the National Wetland Inventory developed by the United States Fish and Wildlife Service. The National Wetland Inventory breaks wetlands into a series of systems, subsystems, classes, and subclasses, as well up to four modifiers. For instance, "Riverine" is one of five wetland systems. "Intermittent" is one of five subclasses of Riverine wetlands. "Unconsolidated Bottom" is one of eight

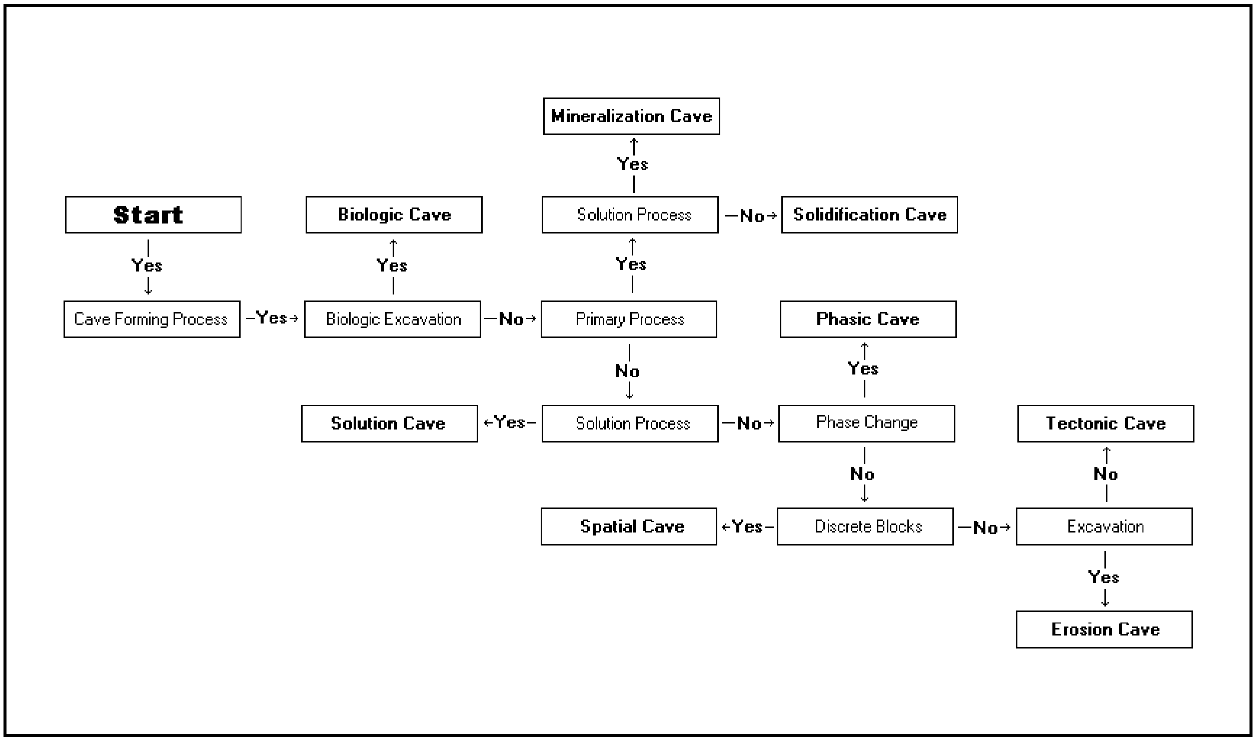

Figure 1. *Process-oriented cave types*

classes, and "mud" is one of four subclasses within the Unconsolidated Bottom class. Therefore, in this example, the wetland classification "R4UB3" wetland stands for:

System–Riverine (R)
  Subsystem–Intermittent (4)
    Class–Unconsolidated Bottom (UB)
Subclass–Mud (3).

As mentioned earlier, there are up to four modifiers that could be used: Water Regime, Water Chemistry, Soil, and Special Modifiers. An example of a Water Regime modifier is "C–Seasonally Flooded." An example of a Water Chemistry modifier is "7I–Hyperhaline, alkaline." An example of a Soil modifier is "g–Organic." Lastly, an example of a Special Modifier is "h–Diked/Impounded." Therefore, if a wetland was determined to be a diked/impounded, seasonally flooded, intermittent riverine wetland with a muddy, unconsolidated bottom, it would be coded as "R4UB3Ch." Therefore, no matter what part of the country one is in, or whatever habitat one encounters, the same logical hierarchical wetland classification system is in place. Therefore, useful comparisons may be made between wetlands containing similar processes. Conversely, one would also be able to differentiate two nearby wetlands that may look alike, but in actuality may be quite different. If different processes are occurring in these two nearby wetlands, conducting an analysis of these two wetlands with the assumption that they are within the same population set may lead to disparate results.

A classification such as this would be equally useful for caves, based upon similar physiographic and genetic characteristics. For example, Worthington (1991) found that combining water chemistry data from different spring types, such as overflow and underflow, brings disparate results. However, upon separate classification and analysis, appropriate comparisons could be made and relevant trends observed.

A proposed classification system is as follows:

SYSTEM	I. Primary Process
SUBSYSTEM	A. Solidification
CLASS	1. Solidification Caves
SUBCLASS	a) lava tubes
	b) casts
	c) pressure
	d) eruptive
	B. Recrystalization
	1. Mineralization Caves
	II. Secondary Processes
	A. Physical Movenent/Relocation of Matrix
	1. Spatial Caves
	2. Tectonic Caves
	a) gravity slip
	b) gravity joint
	c) fault
	d) expansion
	B. Excavation
	1. Erosion Caves
	a) littoral
	b) aeolian
	c) frost wedging
	d) crumbling
	e) suffosion
	2. Phasic Caves
	a) normal heat exchange
	b) external heat
	3. Solution Caves
	a. dissociation
	b. carbonic acid dissolution
	c. sulfuric acid dissolution
	d. other acid dissolution

Modifiers

A. Matrix
   1. Salt
   2. Gypsum/Anhydrate
   3. Limestone
   4. Dolostone
   5. Marble
   6. Coral Reef
   7. Other Solutional
   8. Sandstone
   9. Other Sedimentary
   10. Basalt
   11. Plutonic
   12. Other Igneous
   13. Other Metamorphic
B. Climate
   1. Arctic
   2. Alpine
   3. Arid
   4. Subarid
   5. Temperate
   6. Subtropical
   7. Tropical
C. Setting
   1. Terrestrial
   2. Carbonate Island/Sea Coast
   3. Marine
D. Water Temperature
   1. Natural/Environmental
   2. Thermal
E. Activity
   1. Speleogenesis Process Active
   2. Speleogenesis Process Relic
   3. Both Active and Relic components
F. Structure
   1. Bedding Plane Parting Dominated System
      a. strike dominated
      b. dip dominated
      c. complex/combination dominated
   2. Joint/Fracture Dominated System
      a. strike dominated
      b. dip dominated
      c. complex/combination dominated
   3. Intergranular Dominated System (Palmer, 1991)
   4. Complex/Combination/Other Dominated System
G. Hydraulics
   1. Vadose Dominated System
   2. Phreatic Dominated System
   3. Complex/Combination/Other Dominated System

Cave Geomorphic Mapping

The mapping of current cave-forming processes within the United States will not completely depict the distribution of all caves, since many caves are residual features of former and relic processes. However, to map even the current cave-forming processes, one must break these processes into individual components. For instance, five separate processes are required for solution caves to form: suitable lithology, solvent, gradient, structure, and time. Lithology refers to rocks such as limestone that are soluble enough in relatively weak acids to form caves, yet not too soluble that surface processes do not erode the entire rock away before the cave has time to develop. Solvent refers to a naturally-occurring acid such as carbonic acid that is strong enough to dissolve rocks, yet abundant enough to play a significant role in cave development. A gradient is necessary to carry saturated water away from freshly dissolved rock so that fresh acid may take its place for further dissolution. Structure—such as bedding plane partings, faults, joints, or fractures—are necessary to allow the solvent to penetrate and dissolve caves within the interior of a rock rather than just lower surface exposures (Jakucs, 1977). Structure is also important in the development of preferred flow paths that lead towards conduit/cave development (Sasowsky, 1999). Time is needed, since the majority of naturally occurring solvents are weak enough that they may take thousands or

Figure 2. The Components Necessary for Cave Development

Cave Requisites/ Cave Type	Solution	Erosional	Spatial	Phasic	Solidification	Tectonic
Lithology	✓	4	4	4	4	
Solvent	4			4		
Gradient	4	4	4	4	4	
Structure	4	4	4			4
Time	4	4	4	4		4
Erosive Agent		4	4			
Topography			4		4	
Temperature Gradient				4	4	
Heat					4	
Force						4

tens of thousands of years to form a cave (White, 1988; Daoxian and Zaihua, 1998).

There are four necessary components for the development of a solidification cave: suitable lithology, gradient, topography, and a heat source. The requirements for a suitable lithology are the proper chemical constituents of the molten rock, suitable temperature, and proper viscosity (Peterson and Tilling, 1980). For instance, lava tubes appear to form more commonly within lavas with the proper temperature, viscosity, and chemical composition, such as calc-alkaline basaltic lavas (Mertzman, 1977) with an alkali-lime index between 55 and 61 (Clynne, 1999; Anderson, 1941). These lavas need an elevation gradient so that they may flow down slope and they require a suitable environment that would enable them to lose temperature and degas, thus beginning the solidification process.

Each one of the eight cave types requires its own unique components for cave development. These various factors are summarized in Figure 2. If only one of these components stops, cave development will cease. For instance, why are there not many caves in southern Florida? Suitable rock, such as limestone, is abundant. Similarly, abundant rainfall and carbon dioxide exist to form a suitable solvent. There are enough bedding plane partings and joints to serve as suitable geologic structure. The combination of the limestone, carbon dioxide, rainfall, and structure have been around long enough (time) for caves to develop (Ford and Williams, 1989). Upon closer look, one notices that the flat and low-lying limestone surface shows solution features (Mylroie and Vacher, 1999). However, the limestone is being dissolved and recrystallized in nearly the same place, for the saturated water often has no place to go. In this situation, a suitable gradient is the critical missing factor. If there were to be a small uplift, or if the sea level dropped, there would become a point in which all the factors necessary for solution cave development would occur simultaneously, thereby solution cave development would commence. Attempting to figure out which are the active cave-forming processing going on in a particular area, and which critical factor(s) are missing, is fundamental in understanding cave geomorphology and for the proper management of cave ecosystems. Such a thought process could be termed the "Concept of Limiting Factors."

In order to map the current cave-forming processes it would be necessary to map the necessary components of cave development. Preferably, this mapping should be conducted in as quantifiable means as possible. Each area of the country could be assigned points for the suitability of its lithology, solvent, gradient, structure, and time. These points could be tabulated and the results mapped. Such a map would depict the relative abundance of active solution cave-forming processes within the United States. More accurately, the map would represent the relative probability and distribution of active solution cave-forming processes. Such a map could be used in research, land management, and hazard management. It could also be used by land managers to understand the processes occurring within areas they manage so that they may better ensure that activities that they permit or oversee do not unknowingly impact these natural physical and biological processes.

In order to produce a map such as this would require the selection of the proper map unit

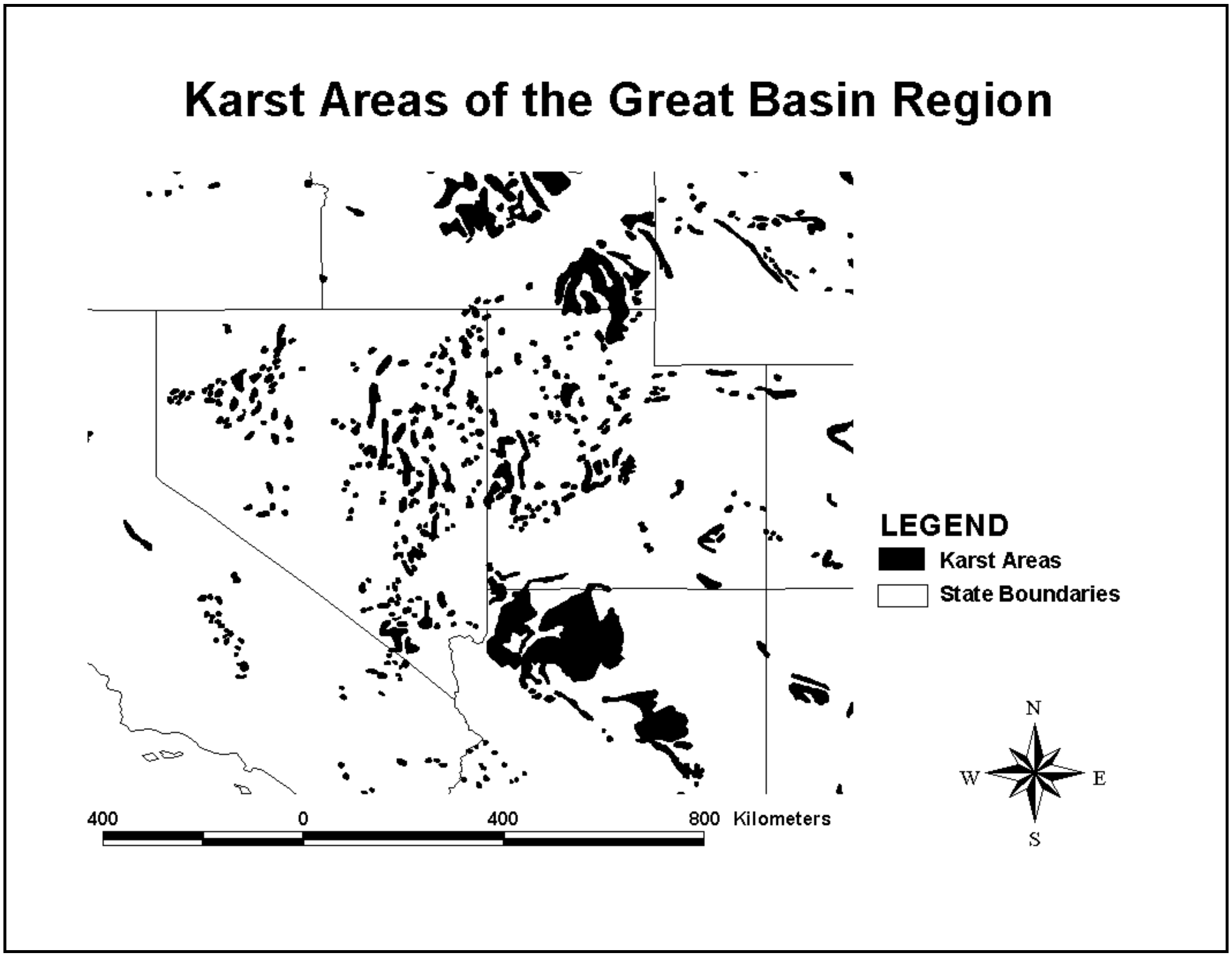

Figure 3

and scale. Units that are too large would not have sufficient detail to be useable. Conversely, units that are too small and detailed would be too cumbersome and one would lose within the detail the local and regional trends that would be necessary to understand important relationships.

To aid in this effort, the author digitized the soluble rocks depicted in the Engineering Atlas of Karst map (Davies *et al.*, 1984) included in the National Atlas. This map aided this effort, but was not utilized to represent the location of soluble rocks due to three limitations: accuracy, the loss of trends and commonalties, and differences in cave-bearing potential between individual rock units. As for accuracy, this map is useful, but it needs updating. The trends and commonalties issue is represented by the author's digitized version of the Great Basin Province portion of Davies' map (Figure 3). As shown in Figure 3, the cluster of the numerous carbonate rock units throughout eastern and northwestern Nevada shows a clear relationship between the individual rock units. This relationship between adjacent rock units indicates a grouping/clustering within the region that is not represented by showing only the individual components. Lastly, the connection between a large carbonate unit may physically exist, however differences in climate, elevation, soil cover, slope, and aspect, as well as numerous other factors may make one portion of the carbonate rock behave much differently than another portion of the same rock unit in regard to cave-forming potential. Due to these limitations, as well as needing a base map that transcends all the necessary components needed for all cave types, a different approach is needed to serve as the basemap.

There are 85 physiographic sections and 24 provinces (Figure 4) within the 48 contiguous United States (Fenneman, 1928a, 1928b, and 1931). Fenneman and McNab and Avers (1994), developed these 85 section boundaries based upon similar geology and geomorphic processes. Since cave development is also depended upon geology and geomorphic processes, it follows that these sections may be used

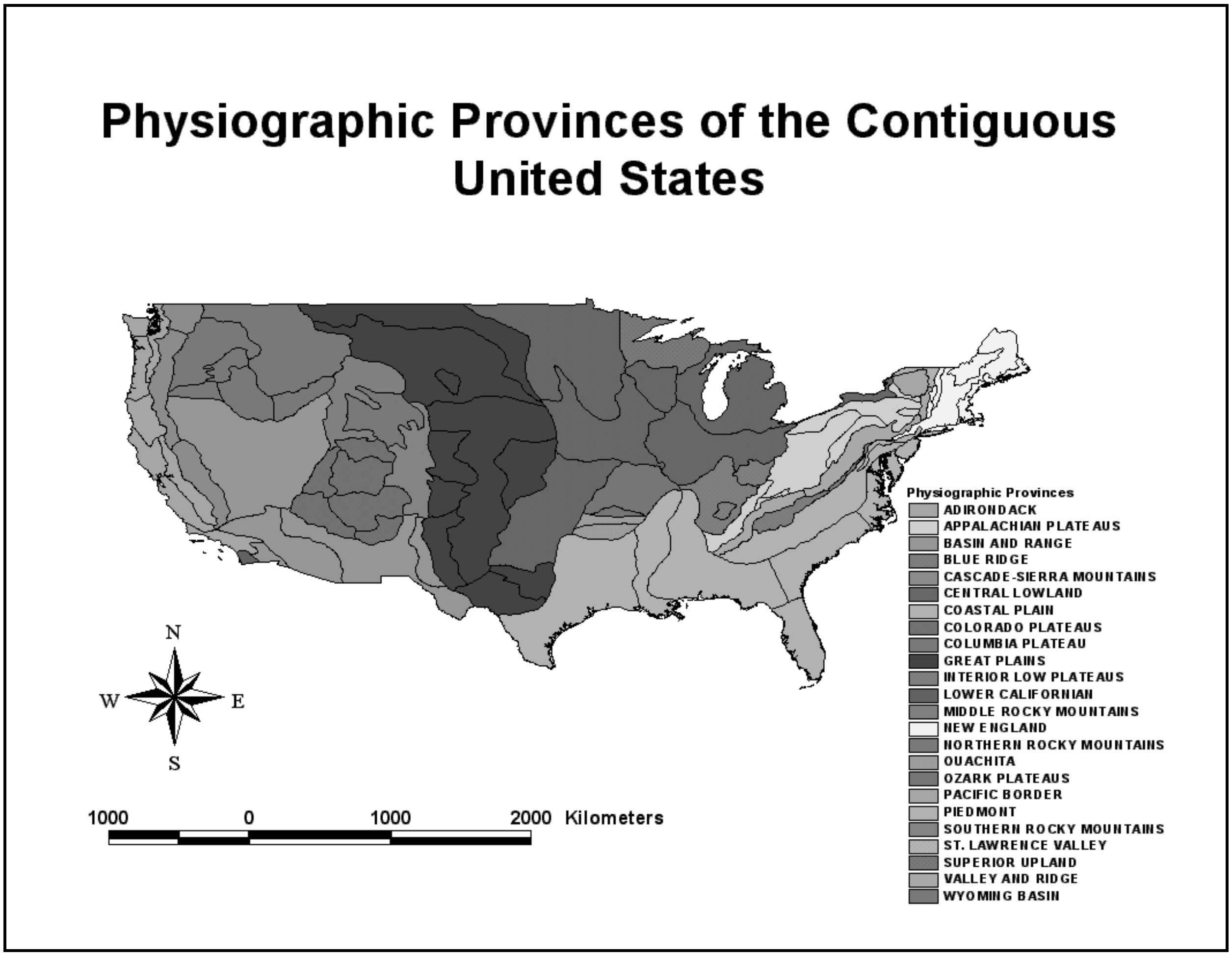

Figure 4

to describe and summarize current cave forming processes within the United States. If one could quantify the amount, degree, and distribution of cave-forming processes, then a map could be developed that would provide a good representation of the actual potential or likelihood of caves being formed within each particular section.

This national, regional, and landscape-scale approach proves useful in understanding local cave-forming processes and why caves occur where they do, in assessing the dominant limiting factors in cave development, as well as providing a more analytical and systematic framework for karst researchers working on a regional or national scale.

Therefore, to produce a solution cave "potential" map; it would be necessary to assign lithology, solvent, gradient, structure, and time values for every map unit within the United States. Ideally, these values would then be weighted depending upon the relative importance each value played in the development of solution caves. Based upon these combined attributes, a map could then be produced. For the lithology component, it is important to assess the regional trends and not just the exact occurrences of soluble rock types. For instance, if there were a small body of limestone in a given area, it would be relevant to know if this is a rare occurrence or is most of the region made up of hundreds of these scattered but widely distributed small soluble rock units. Each of the 85 sections were ranked "high," "medium," or "low" probability of containing suitable rocks for solution cave development. These values were assigned by investigating available literature for references of having exposed soluble rocks present.

Suitable solvent was mapped using national precipitation Geographic Information System maps.

Areas of known active cave systems were plotted along with mean precipitation data. This was conducted to assess where the threshold precipitation values are located, and where

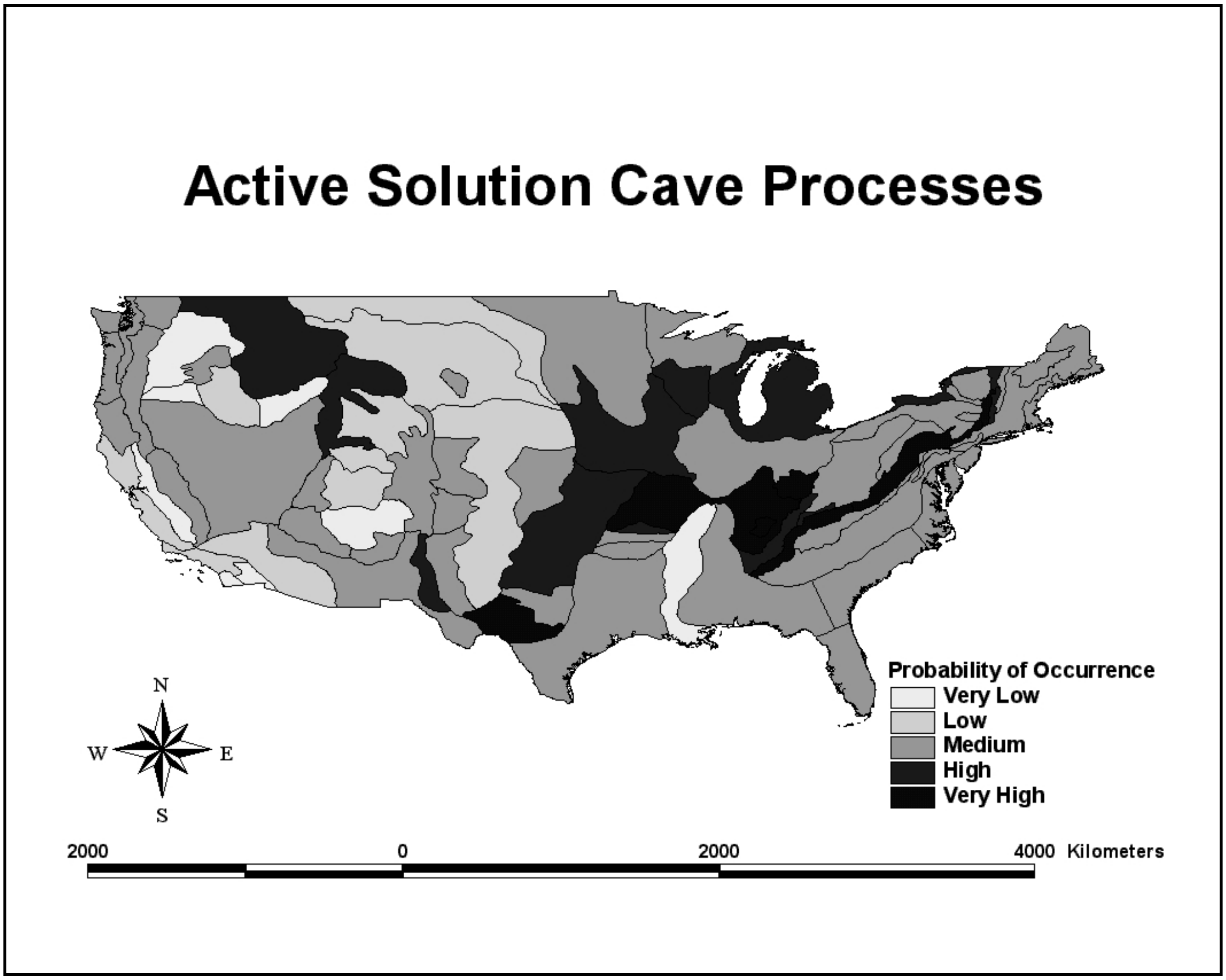

Figure 5

precipitation no longer becomes a limiting factor for solution cave development. Recognizing that it is highly variable, based upon allogenic versus autogenic recharge, form and duration of precipitation, size of basin, and the like, preliminary analysis has indicated that an upper threshold of total precipitation is approximately 0.5 meters (20 inches) per annum. Based upon these variables, the lower threshold appears to be approximately 0.4 meters (17 inches) per annum. Within the solution cave matrix, physiographic sections containing mostly 0.5 meters or more of precipitation were assigned a "High" value. Areas with 0.4 to 0.5 meters of precipitation were assigned a "Medium" value. Those areas with less than 0.4 meters of precipitation were assigned a "Low" value. Areas assigned a "Low" rating could still produce solution caves, however its potential is limited. Similarly, areas with a "Medium" rating could still produce solution caves; however, the conditions suitable for their development would typically be more scattered. Areas with a "High" rating were found not limited with regard to precipitation.

The completion of the matrix for gradient, structure and time was much more subjective and much less variable. Only five sections were given a rating that reflected limitations for gradient, three for structure, and four time. More refined, accurate, and quantifiable technique needs to be developed in the future for these elements.

Currently, no weights were applied to any of the factors in the matrix. This would be needed for future updates and refinements; however, not enough is currently known to appropriately assign weights. Which is more important, suitable structure or suitable gradient, and by how much? Until these questions can be answered, each factor was given equal weight. The totals were summed and these sums were mapped depicting the probability of active solution cave processes occurring within the 48 contiguous states (Figure 5).

Similarly, a map could be produced that is a combination of all the cave-forming processes occurring within each section. In essence, such a map would be a combination of the following:

- a carbonate distribution map;
- an evaporate distribution map;
- a spatial cave distribution map;
- a tectonic cave distribution map;
- an erosion cave distribution map;
- a phasic cave distribution map;
- a solidification cave distribution map;

This would then be a complete and summarized depiction of all current cave-forming processes operating within the United States.

Conclusion

Future improvements in this project could involve the following:

- Replace the 85 physiographic sections as the basemap with the more refined and numerous state-level physiographic sections or perhaps replace or combine this with cluster analysis or other similar spatial statistical analysis technique to more accurately identify regional trends and commonalties;
- update and refine a national map of soluble rocks to use to depict the presence of cave-forming soluble rocks. This would need to be carefully attributed to reflect the many geomorphic aspects affecting the rock's solubility;
- develop a reliable means of quantifying geologic structure, gradient, and time in regards to cave-forming potential.
- develop a reliable means of quantifying the various factors for all cave types;
- develop a reliable means of weighting factors within each cave type;
- develop a reliable means of weighting factors among cave types so that maps could be made that reflect the total combined cave potential within the United States for all cave types;
- and lastly, integrate the process-oriented cave classification system with the process-oriented cave map.

It is not only important to look at geomorphic processes from a landscape or regional scale, it is also important to assess them in relation to other processes operating in the same areas. Looking at a map of karst regions of the United States does little to explain the other processes operating in the same areas. Additionally, it does little to explain or describe the cave-forming processes operating within the blank areas on the map. The logical next step is a shift towards a more comprehensive and system-wide approach.

Another benefit of taking a comprehensive approach is it is perhaps easier to appreciate the wide diversity of cave-forming processes that are acting upon the landscape. Cave-forming processes are of course not disjunct from other processes operating upon the landscape. Processes that form a cave in one environment may form a mountain, rock spire, river, canyon, plateau, dune, or soil layer in another. Researchers must be aware of the similarities and dissimilarities of the processes within their study area. At the same time, managers must understand processes within their administrative unit in order to properly manage landscapes without unintended consequences. By classifying and mapping the processes one is better able to understand, study, and manage these processes.

References

Anderson, Charles A., 1941. Volcanoes of the Medicine Lake Highland, California. University of California, Publ. Bull. of the Dept. of Geological Sciences 25(7):347-422.

Chilingar, George V.; Harold J. Bissell; and Rhodes W. Fairbridge (eds.), 1967a. Carbonate rocks- origin, occurrence and classification. Developments in Sedimentology 9A, Elsevier Publ. Co., New York, NY, 471 pp.

Chilingar, George V.; Harold J. Bissell; and Rhodes W. Fairbridge (eds.), 1967b. Carbonate rocks- origin, occurrence and classification. Developments in Sedimentology 9B, Elsevier Publ. Co., New York, NY, 413 pp.

Clynne, Mike, 1999. Personal communication with USGS geologist, 4/1999.

Daoxian, Yuan, 1991. Karst of China. Geological Publishing House, Beijing, China, 232 pp.

Daoxian, Yuan and Liu Zaihua (eds.), 1998. Global karst correlation. International Geol. Correlation Program Project 299, Science Press, New York, 324 pp.

Davies, William E., *et al.*, 1984. Engineering aspects of karst. 1:7,500,000 scale map, map number 38077-AW-NA-07M-00, In: USGS's National Atlas.

Fenneman, Nevin M., 1931. Physiography of western United States. McGraw-Hill, New York, NY, 534 pp.

Fenneman, Nevin M., 1928a. Physiography of eastern United States. McGraw-Hill, New York, NY, 714 pp.

Fenneman, Nevin M., 1928b. Physiographic divisions of the contiguous United States. 3rd edition, Annals of the Association of American Geographers, 18(4):261-353.

Ford, Derek and Paul Williams, 1989. Karst geomorphology and hydrology.Chapman and Hall, London, 691 pp.

Grove, Timothy L; David C. Gerlach; and Thomas W. Sando, 1982. Origin of calc-alkaline series lavas at Medicine Lake Volcano by fractionation assimilation and mixing. Contrib. Mineral Petrol 80:160-182.

Jackucs, László, 1977. Morphogenetics of karst regions- variants of karst evolution. Halsted Press, New York, 284 pp.

Larson, Charlie and Jo, 1993. An illustrated glossary of lava tube features. Western Speleological Survey Bulletin No. 87, Vancouver, WA, 56 pp.

Leopold, Luna, B., 1992. Fluvial processes in geomorphology. Dover Publications, New York, 522 pp.

MacDonald, Gordon A., 1953. Pahoehoe, aa and block lava. American Journal of Science 251:169-191.

McNab, W. Henry and Peter E. Avers (compiled), 1994. Ecological subregions of the United States: section descriptions. Administrative Publication WO-WSA-5, Washington, D.C., United States Dept. Agriculture Forest Service 267 pp.

Mertzman, S.A., Jr., 1977. The petrology and geochemistry of the Medicine Lake Volcano, California. Contrib. Mineral. Petrol. 62:221-247.

Mylroie, J.E. and H.L. Vacher, 1999. A conceptual view of carbonate island karst. In: Karst Modeling, A.N. Palmer, M.V. Palmer and I.D. Sasowsky, Special Publication 5, Karst Waters Institute, Charles Town, WV, p. 48-57.

Palmer, Art N., 1991. Origin and morphology of limestone caves. Geological Society of American Bull.103:1-21.

Peterson, Donald W. and Robert I. Tilling, 1980. Transition of basaltic lava from pahoehoe to aa, Kilauea Volcano, Hawaii: field observations and key factors. Journal of Volcanology ad Geothermal Research 7:271-293.

Sasowsky, Ira, 1999.Structural effects on carbonate aquifers. In: Karst Modeling, A.N. Palmer, M.V. Palmer and I.D. Sasowsky, Special Publication 5, Karst Waters Institute, Charles Town, WV, p. 38-42

Sharp, Robert P., 1960. Glaciers. Condon Lectures, Oregon State University, Eugene, OR 78 pp.

Soller, David R. and Patricia H. Packard, 1998. Digital representation of a map showing thickness and character of Quaternary sediments in the glaciated Unites States east of the Rocky Mountains. USGS Survey Digital Series DDS-38, CD-ROM.

United States Fish and Wildlife Service, and National Wetland Inventory (NWI) map project.

United States Geological Survey, 1979a. The Mississippian and Pennsylvanian (Carboniferous) systems in the United States. Geol. Survey Prof. Paper 1110—A-L.

United States Geological Survey, 1979b. The Mississippian and Pennsylvanian (Carboniferous) systems in the United States. Geol. Survey Prof. Paper 1110—M-DD.

White, William B., 1988. Geomorphology and hydrology of karst terrains. Oxford University Press. New York, NY, 464 pp.

Worthington, S.R.H., 1991. Karst hydrogeology of the Canadian Rocky Mountains. Unpubl. Ph.D. thesis, McMasters University, Hamilton, Ontario, 227 pp.