

REVISING THE KARST MAP OF THE UNITED STATES

GEORGE VENI

George Veni & Associates, 11304 Candle Park, San Antonio, Texas 78249-4412 USA, gveni@satx.rr.com

The production of the recently published Living with karst: A fragile foundation required a map showing the distribution of karst in the United States. William Davies et al. (1984) produced the last such map. I used their work as the basis in developing a revised US karst map, but delineated karst primarily on lithology rather than cave lengths. The categories are: exposed and buried carbonate and evaporite karst, and volcanic and unconsolidated pseudokarst. The new US karst map updates the previous map with data from more detailed regional karst maps. Scale and information availability limited the accuracy of the new map. Buried evaporites and unconsolidated pseudokarst are underrepresented due to insufficient delineation. I had to interpolate from available information to adjust for discrepancies due to different map projections and differences between maps. The new US karst map improves on earlier versions but is still incomplete and of low precision in some areas. Production of detailed karst maps with drainage basins and other land management factors is best left to state agencies. The US Geological Survey is developing a new US karst map and the NSS Section of Cave Geology and Geography is assisting with that effort. Uniform standards need to be established for definitions, scale, and map projections. Section members include the country's most knowledgeable karst geoscientists and they play key roles in developing an accurate and definitive US karst map.

This report describes the process and rationale for the development of the United States (US) karst areas map recently published by the American Geological Institute (AGI) in *Living with karst: A fragile foundation* (Veni *et al.* 2001). Also discussed are the applications and limitations of the map and recommended directions for future refinements in delineating US karst.

Well before most people who were interested in caves knew the term "karst," maps were drawn showing the location of caves and occasionally their underlying geology. Some of the earliest examples were published in *Caverns of Virginia* (McGill 1933). Initially, these maps were meant to illustrate cave locations to facilitate further visitation and study. As time went on, the intent of the maps began to focus on spatial relationships between caves, typically to support exploration and hydrogeologic analysis. Maps of karst were not produced until late in the 20th Century because detailed, regional geologic maps were not broadly available until that time.

Most "karst" mapping has been the illustration of cave locations or the density of known caves and sinkholes within given areas. This was done for various karst regions, but Moore and Sullivan (1978) produced the first cave density map that covered the entire country. The first attempts to geologically delineate US karst were produced for county, state, and geographic regions by outlining areas of carbonate and evaporite rocks (e.g. Smith 1971).

Davies *et al.* (1984) produced the first map showing the karst areas of the United States. The karst was color-coded into four main areas based on the following characteristics:

- many caves over 300 m long and 75 m deep;
- caves generally less than 300 m long and 15 m deep;
- caves generally absent but where present, usually less than 15 m long and 3 m deep; and

-pseudokarst features in unconsolidated sediment and volcanic rocks.

Patterns drawn within each colored area identified if the karstic rocks were dipping, folded, carbonates, evaporites, metamorphosed, and/or buried. The map was published as one large sheet by the U.S. Geological Survey (USGS) with an explanation printed on one side and has since served as the standard reference that defines US karst.

The map by Davies *et al.* (1984) is generally correct but has limitations. The one most noticed is that some small but important karst areas are excluded. For example, the lower member of the Glen Rose Formation in central Texas is excluded even though it contains two show caves that have operated since the 1930s plus Honey Creek Cave, the state's longest, with over 32 km of surveyed passages (Elliott & Veni 1994). Another drawback is that the shapes of the karst areas are smoothed and generalized so that they are not as accurate or precise as they could be at that scale. Accessibility is also a problem. The map is known primarily to karst scientists, but is poorly accessible and not well known to land managers, educators, and other people who make critical decisions about karst. In fact, it may not be easily accessible to karst researchers either, since I could not find it cited in any major text on karst or in any of four karst bibliographic publication series.

In 1991, White (2001) initiated discussion to examine the need and means of developing a more complete and accurate karst map of the US. Project KarstMap was formally organized under the National Speleological Society's (NSS) Section of Cave Geology and Geography in 1995. Little progress was made except to review the status of karst mapping throughout the country and the rapidly changing technology for performing the job. Detailed state-funded karst maps were found completed or in production for some states and regions, but producing maps of this type was beyond the level of effort that

could be met by the NSS project. Consequently, the KarstMap project languished and its viability was in doubt in 2000.

DEVELOPING THE AGI KARST MAP

Near the end of 2000, I was completing work on the *Living with karst* booklet, which the NSS Section of Cave Geology and Geography wrote for publication by AGI. The booklet is part of AGI's "Environmental Awareness Series," aimed at educators, decision-makers, and the general public to teach important principles about geologic resources. The karst booklet was the fourth in the series, and AGI and I decided that a map showing the karst areas of the US was important for the public to realize that karst is not a rare phenomenon and it directly affects many people. We initially planned to use the Davies *et al.* (1984) map but couldn't locate a high quality digital version. Other problems arose after scanning the map, such as showing the fine geologic details when reduced in size for the booklet, so I offered to redraw the map digitally.

Rather than simply trace the existing map, I sought to make as many improvements as feasible given the intended audience for the booklet and the limited time and resources available. Discussing the issue with my co-editor Harvey DuChene and AGI editor Julie Jackson, we set five goals for the new map:

1. Base the map on lithology, not cave length. Cave length is an imperfect means of measuring karst. It falsely assumes uniform levels of exploration and knowledge of cave systems, and arbitrarily gives significance only to the humanly enterable portion of the conduit system. More fundamentally, caves have been used as a surrogate for the maturity of karst landscapes when in fact, karst can be hydrologically mature and have advanced troglobitic ecosystems even where caves are small relative to human access. Mapping based on lithology allows convenient grouping of areas with similar hydrologies, chemistries, morphologies, and land management issues.

2. Include missing karst and pseudokarst areas. Davies *et al.* (1984) did not include some karst and pseudokarst areas by mistake, oversight, or because those areas had not yet been identified. As many of these areas as possible would be included.

3. Improve the illustration of exposed versus buried karst. Non-karstic strata cover much of the US karst. Mapping of additional buried karst, along with a more easily recognizable means of representing these areas, was needed to distinguish this different, but important, subset of karst.

4. Increase map accuracy and precision. Known errors in the map would be corrected and the map spot-checked for general accuracy against other available information. Improving the map's precision was important but beyond the scope of the project except in a very limited way in areas where maps showing more precise boundaries were known to exist.

5. Simplify map for easier use. A general, informative, visually attractive, and intuitively understandable map was needed for the booklet's broad audience. The map of Davies *et*

al. (1984) included a lot of detailed information that was hard to see on the map and not intuitively apparent without close examination. Those details were also not particularly useful to the general public or to researchers who would usually need even more site-specific information. The forum for the AGI karst map, publication in the nationally distributed booklet, would meet a sixth goal of making the map broadly and easily accessible for use.

The first step in drafting the AGI karst map was to select the CorelXara version 1.5 computer drawing program for the cartography. Admittedly, much of this decision was based on having the program already on my computer and my familiarity in its use. However, other important factors were its versatility in executing the drawings, importing other files, and exporting files that AGI could use.

The second step was to select basemaps for use. The map by Davies *et al.* (1984) was the foundation of the AGI map. Since it seemed basically correct, much of its information could be directly used. I scanned it into my computer and imported it into CorelXara to trace karst area boundaries. Those scans are shown in Figures 1 and 2 in this report at the resolution used to draw the new map. I also scanned karst maps of various regions into the computer that provided more precise and complete illustrations of the country's karst. I tried to review a complete range of karst maps for US areas but probably missed some regions with the limited time available. Maps that appeared to offer improvements to the Davies *et al.* (1984) map and were used in developing the AGI map were from Powell (1961) for Indiana, Daniel and Coe (1973) for Alabama, Hill, Sutherland, and Tierney (1976) for Wyoming, Quick (1979) for the Hudson River Valley, Smith and Veni (1994) for Texas, Vineyard (1997) for Missouri, Richards (1999) for Hawaii, and Weldon, Szumigala, and Davidson (2000) for Alaska.

For ease of manipulation, each scanned map was saved as its own layer in the drawing. Each layer could be made visible, invisible, editable, and uneditable as needed. The drawing itself was also saved in individual layers for each category of karst depicted: exposed carbonates, buried carbonates, exposed evaporites, buried evaporites, volcanic pseudokarst, and unconsolidated pseudokarst. The text was also saved as a separate layer, as was the map AGI provided that showed the borders of the 50 US states. A rectangular border (not shown in the final map) was added to precisely register each of the drawn layers; there were no visible variations in the borders at a magnification of 3000%.

The fourth step was to illustrate the map in a clear and easy to grasp manner. Since most of the geologic details found on the earlier map were not used, a simple application of color was possible. Red was selected as the most intuitive color for volcanic pseudokarst. Gold, blue, and green were respectively selected as distinctive colors for unconsolidated sediments, evaporite karst, and carbonate karst. Buried karst was illustrated by a lighter shade of the appropriate primary color: light blue and light green were used for buried evaporites and car-

bonates.

Several challenges arose in drafting the new map. The first was a matter of scale. Since the new map would be smaller than the Davies *et al.* (1984) map, some details had to be altered. The smallest karst areas were deleted because they would not be visible as anything more than undistinguishable dots. Karst areas in close proximity to other karst areas were connected when they would appear connected when reproduced at the scale for publication. These modifications were determined by printing out test versions of the map to see which changes, if any, were needed.

The second challenge was to adjust for different map projections. Almost every map used was drawn at a different projection or suffered some shrink-swell changes in the paper versions so that the state borders could not be perfectly overlaid. Figure 1 shows an example. Two maps are overlain: the Davies *et al.* (1984) map and the new AGI karst map drawn on a different projection of the US state borders (the projection type was not determined). The maps are registered to match the state borders in the Yellowstone area at the junction of Idaho, Montana, and Wyoming. In southwestern Wyoming, the borders are slightly off. As the nearby southern Idaho border sweeps westward past that state, it is off by nearly 30 km where it reaches California. In addition to the discrepancies in the borders, the differences in the karst areas are also apparent. The color areas reflect the karst areas traced from the older map and show them offset from those areas which are shown in black and white. The new karst map had to continually be shifted and registered in different locations relative to the older scanned maps, and only the karst areas immediately adjacent to the registered areas were then traced.

The third and more difficult challenge was to determine which karst boundary to follow when Davies *et al.* (1984) differed from other karst maps. The greatest discrepancy occurred in Wyoming, as illustrated in Figure 2. The black and white map shows the karst boundaries drawn by Davies *et al.* (1984) and the color boundaries are based on Hill, Sutherland, and Tierney (1976). While there is perfect concordance in the Black Hills area, the north-central and western parts of the state show moderate differences, and the southeastern area shows little in common between the two maps. In the case of Wyoming and other areas where I lack personal knowledge of local karst development, I did what research I could to determine which map is most likely correct and generally defaulted to the local experts who should know their areas best.

The fourth and greatest challenge was to define undefined karst areas. More precisely, I defined pseudokarst areas. Karst areas were usually delineated on lithology where it is safe to assume that most mapped carbonates and evaporites produce karst. However, the chances of pseudokarst being present in volcanic rocks and unconsolidated sediments are far lower, so such generalizations could not be made. Richards (unpub. data, 1999) provided helpful maps of volcanic pseudokarst in Hawaii, which I supplemented from maps of cave locations in other areas of the state. Bernie Szukalski (pers. comm., 2000;

2001) sent information on two unconsolidated pseudokarst areas that have recently been found by cavers in southern California. Their extents have not been well delineated, so using geologic and other maps plus Szukalski's descriptions, I conservatively delineated those areas. Cavers exploring those areas in the future will determine how well I estimated the boundaries.

When I finished drawing the map, I drew in some lines pointing to various locations around the country and added text that discussed some unique or important aspect of those areas. In order to show the diversity of karst and its importance nationwide, I sought a variety of examples and topics. I then added the following explanation and caveat, which is important to repeat here:

This map is a general representation of U.S. karst and pseudokarst areas. While based on the best available information, the scale does not allow detailed and precise representation of the areas. Local geologic maps and field examination should be used where exact information is needed. Karst features and hydrology vary from place to place. Some are highly cavernous, and others are not. Although most karst is exposed at the land surface, some is buried under layers of sediment and rock, yet still affects surface activities.

The final step in producing the map was to send it to AGI for the final graphics work. They turned it over to graphics artist Julie DeAtley of DeAtley Design. She added background color to the map, created a shadow effect, created and/or laid out the legend, caption, and other text, and used an actual rock photograph to fill in and color the letters "karst" in the title. In June 2001, the map was published in the *Living with karst* booklet as shown here in Figure 3.

FUTURE MAPPING OF US KARST

Having recently completed the AGI karst map, I state without reservation that it is an improvement over the previous map by Davies *et al.* (1984), yet it needs to be redone. The new map is deficient in five main areas.

1. "Karst" is not defined. While most outcrops of carbonate rocks can correctly be assumed to form karst, there are some areas where the presence of karst is arguable. A standard definition of karst needs to be defined and applied. For example, Worthington, Schindel, and Alexander (2001) propose the use of six specific testable properties to differentiate karst aquifers from porous media aquifers: tributary flow to springs, turbulent flow in conduits, troughs in the potentiometric surface, downgradient decreases in hydraulic gradient, downgradient increases in hydraulic conductivity, and substantial scaling effects in hydraulic conductivity. Clear and testable defining criteria should be established and applied in karst mapping.

2. "Pseudokarst" is not defined. Like karst, criteria for pseudokarst should be defined. For example, is there a sufficient density of pseudokarst features in the southern Great Plains to justify the large unconsolidated pseudokarst areas shown in Figure 3, or should those areas be shrunk to smaller

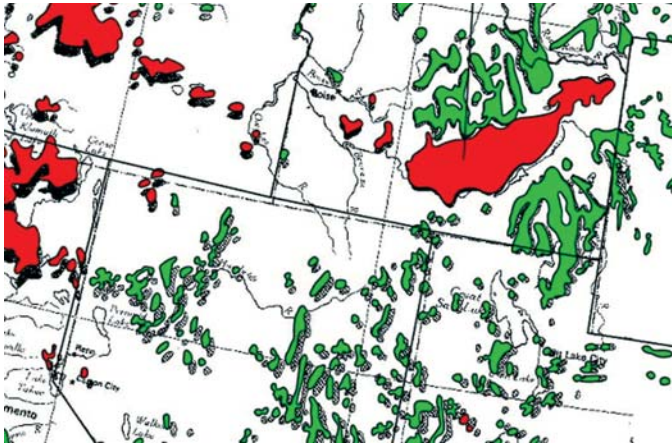


Figure 1. Projection differences in two overlaying maps become significant with increased distance from the Yellowstone area where they are aligned.

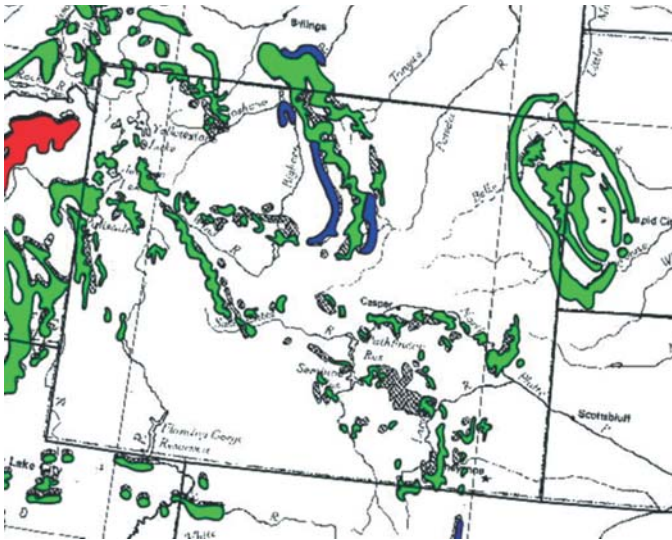


Figure 2: Two maps of Wyoming karst show considerable differences, producing a challenge to determine which map is correct.

areas where pseudokarst features are known to exist? Should the map illustrate the potential for pseudokarst or the known existence of pseudokarst? If the map will illustrate the potential for pseudokarst, that must also be defined in a clear and testable manner that is useful to scientists, land managers, and cavers, and not misleading in its implications for the potential development of pseudokarst.

3. Karst and pseudokarst boundaries are not precisely mapped. The boundaries shown in Figure 3 are generalizations and while often close, do not precisely delineate those areas. Approximations will always be made according to the scale of mapping, but greater precision is possible at the scale of Figure 3 (reduced from its original size for publication here).

4. Precise adjustments are needed for differences in map projections. Figure 3 was developed by manually shifting maps to adjust for differences in map projections or irregularities. Consequently, some areas are more precisely drawn than others. Computer programs are available and should be used to automatically and properly adjust for projection differences and to uniformly correct for other irregularities.

5. Pseudokarst and buried karst areas are underrepresented. While careful mapping in the future will reveal karst areas not previously included, the biggest changes will be in the representation of pseudokarst and buried karst areas. Numerous unconsolidated and volcanic pseudokarst areas occur for which I could not find sufficient information to add them to Figure 3. Martinez, Johnson, and Neal (1998) found evaporites, especially buried evaporites, underlying 35-40% of the 48 contiguous US states. This is far less than shown in Figure 3, and certain generalizations in their mapping prevented their inclusion in Figure 3. One aspect of buried karst that needs to be defined is the depth of burial that will be considered for mapping. The depth should be sufficient to include the reasonable potential for subsidence or other land management problems to occur.

The USGS proposed development of a national karst map in 2001 (Epstein *et al.* 2001) and has begun that work. The map may be digitally prepared and include hot-links to references of detailed source maps, generalized descriptions of the karst areas, reports on the effects of karst on land management, summaries of the geology and karst features in selected areas, and annotated bibliographies for those areas. Features that may be included on the map are exposed carbonate and evaporite units, intrastratal karst, karst beneath surficial overburden, and percentage area covered by karst. This USGS report was presented during a Project KarstMap symposium at the 2001 NSS Convention. The members of the NSS Section of Cave Geology & Geography, USGS, National Cave and Karst Research Institute, and National Park Service have since met to pursue developing a complete and accurate karst map of the US. This should prove a fruitful association; the federal agencies have the resources to develop a fine and accessible map and the NSS has the expertise to evaluate the accuracy of the karst areas they delineate.

Based on my experience, especially from developing the AGI karst map and association with Project KarstMap, I offer the following recommendations:

- 1. Define terms and parameters.** The first task in developing a karst map should define karst and pseudokarst, identify the intended audience for the map, and set the scale, level of details, and other map parameters accordingly.
- 2. Consult experts to ensure completeness.** Karst experts from around the country should be consulted to draw or evaluate the proposed boundaries for highest accuracy and precision in the states or regions where they have expertise. This will greatly reduce the chance for errors and help ensure that important areas are not overlooked.

U.S. Karst Map

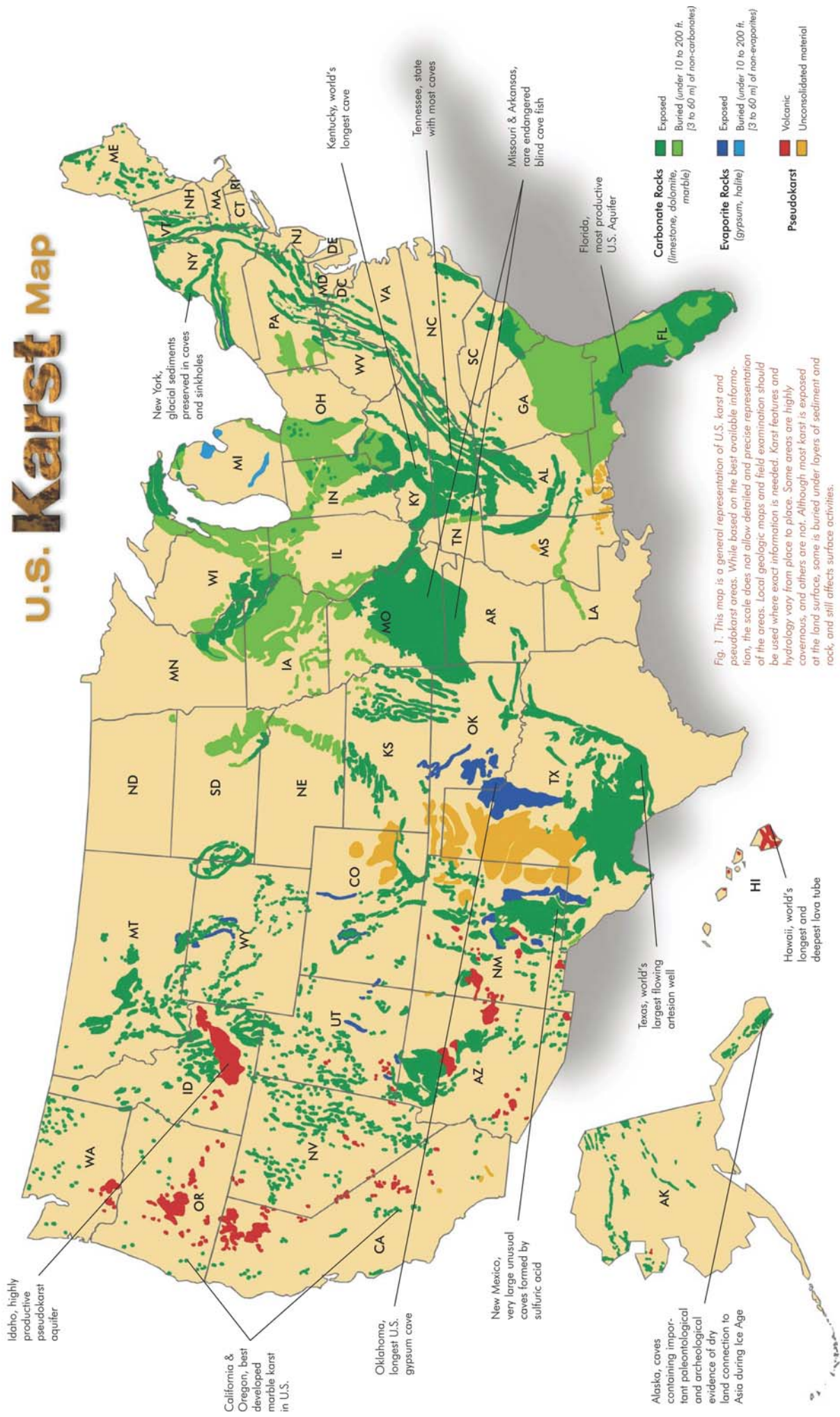


Figure 3: Karst map of the US published by AGI (Veni et al. 2001).

3. Keep it simple but versatile. The map should be prepared in simple layers identifying major karst types and their distribution. Detailed geologic information should be available in other graphic layers and/or as hot-linked text. The layering should allow development of personalized maps according to individual needs to show as many or as few layers and spatial relationships as desired. The map should be drawn as vectorized images to allow sharp enlargement and reduction of the map scale without needing to redraft it.

4. Link to specialty maps. Drainage basin, land management, and other specialty maps should be left to state and regional agencies, which in many cases are currently conducting the detailed research needed to develop those maps. However, those maps should be hot-linked to the karst map and the karst map updated as needed based on their results.

5. Keep it current and accessible. The proposed digital format of the karst map should allow easy updating to correct for errors or new information. The USGS is currently only discussing the illustration of karst on their new map, but pseudokarst areas and other information could be drawn on separate digital layers to continuously update and improve the map over time. With the increasing national interest in karst, the map should be well publicized and made easily accessible on compact disk and through the Internet.

ACKNOWLEDGMENTS

I thank the following people: William B. White for conceiving and promoting Project KarstMap; AGI and Julie Jackson for prompting me to develop a new U.S. karst map; Julie DeAtley of DeAtley Design for making my bland karst map look good in print; the USGS for recognizing the need for a new karst map, taking the lead in that effort, and working with the NSS to ensure that it will be a high quality product; three anonymous reviewers for their helpful comments; and Karen Veni for proofreading my manuscript and her unfailing support.

REFERENCES

- Daniel, T.W., Jr. & Coe, W.D., 1973, Exploring Alabama caves. Bulletin 102, Geological Survey of Alabama, 99 p.
- Davies, W.E., Simpson, J.H., Ohlmacher, G.C. Kirk, W.S. & Newton, E.G., 1984, Engineering aspects of karst, national atlas, 38077-AWNA-07M-00, 1 sheet p.
- Elliott, W.R. & Veni, G., 1994, The caves and karst of Texas. National Speleological Society Convention Guidebook: Huntsville, Alabama, 342 pp. + 13 pls. p.
- Epstein, J.B., Orndorff, R.C. & Weary, D.J., 2001, U.S. Geological Survey national karst map [abs]: National Speleological Society Convention Program Guide, Great Saltpetre Cave Preserve, Kentucky, p. 87.
- Hill, C., Sutherland, W. & Tierney, L., 1976, Caves of Wyoming: Bulletin 59, Geological Survey of Wyoming, 230 p.
- Martinez, J.D., Johnson, K.S. & Neal, J.T., 1998, Sinkholes in evaporite rocks: American Scientist, v. 86, no. 1, p. 38-51.
- McGill, W.M., 1933, Caverns of Virginia. Bulletin 35, Educational series no. 1, State Commission on Conservation and Development, Commonwealth of Virginia, 187 p.
- Moore, G.W. & Sullivan, G.N., 1978, Speleology: The study of caves: Teaneck, New Jersey, Zephyrus Press, 150 p.
- Powell, R.L., 1961, Caves of Indiana. Circular No. 8, Geological Survey, Indiana Department of Conservation, 127 p.
- Quick, P., 1979, Cave formation in western new England, An introduction to caves of the northeast: National Speleological Society 1979 convention guidebook, p. 9-10.
- Smith, A.R., 1971, Cave and karst regions of Texas, in Lundelius, E.L. & Slaughter, B.H., ed., Natural history of Texas caves, p. 1-14.
- Smith, A.R. & Veni, G., 1994, Karst regions of Texas, The caves and karst of Texas, National Speleological Society 1994 convention guidebook, p. 7-12.
- Szukalski, B., 2001, Cave development in Rainbow Basin National Natural Landmark [abs]: National Speleological Society convention program guide, Great Saltpetre Cave Preserve, Kentucky, p. 74.
- Veni, G., DuChene, H., Crawford, N.C., Groves, C.G., Huppert, G.H., Kastning, E.H., Olson, R. & Wheeler, B.J., 2001, Living with karst: a fragile foundation. Environmental awareness series, American Geological Institute, 64 pp. + 1 pl.
- Vineyard, J.D., 1997, Missouri, the cave factory: An introduction to the geology of Missouri: Exploring Missouri caves, National Speleological Society 1997 convention guidebook, p. 27-45.
- Weldon, M.B., Szumigala, D.J. & Davidson, G., 2000, Generalized geologic map of Alaska. Alaska Geological and Geophysical Surveys, 1 sheet p.
- White, W.B., 2001, The karstmap project: progress and status [abs]: National Speleological Society convention program guide, Great Saltpetre Cave Preserve, Kentucky, p. 86.
- Worthington, S.R.H., Schindel, G.M. & Alexander, E.C. Jr., 2001, Hydraulic characterization of carbonate aquifers focusing on water level data [abs]: National Speleological Society convention program guide, Great Saltpetre Cave Preserve, Kentucky, p. 87.