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PHYSICAL CONTROLS ON KARST FEATURES IN THE OZARK PLATEAUS OF MISSOURI, U.S.A., AS DETERMINED BY MULTIVARIATE ANALYSES IN A GEOGRAPHIC INFORMATION SYSTEM (GIS)

FIZIKALNA POGOJENOST KRAŠKIH OBLIK DOLOČENA Z MULTIVARIALNIMI ANALIZAMI V GIS-U (GEOGRAFSKI INFORMACIJSKI SISTEM), PLATO OZARKOV, MISSOURI, ZDA

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David J. Weary & Randall C. Orndorff: Fizikalna pogojenost kraških oblik določena z multivarialnimi analizami v GIS-u (geografski informacijski sistem), plato Ozarkov, Missouri, ZDA

Fizikalna pogojenost nastanka in prostorske razporeditve kraških oblik je lahko določena z analizami podrobnega geološkega kartiranja in analizo kraških podatkov kot je položaj jam, izvirov in razporeditev vrtač. Naša študija je preverila vplive geoloških struktur in stratigrafskih položajev, kjer so razporejene jame, izviri in vrtače na 625 km^2 veliki površini platoja Ozarkov v južno-osrednjem Missouriju. Matično kamnino predstavljajo skoraj horizontalni Kambrijski in Ordovicijski dolomiti, peščenjaki in roženci. Meritve razpok na 1121 mestih smo interpolirali, tako da smo določili mreže, ki predstavljajo lokalne strukturne porazdelitve. Strukturne linije, ki smo jih dobili s terenskim kartiranjem, smo uporabili za interpolacijo mrež, ki predstavljajo površine plastnatosti na obravnavanem terenu. Mreže smeri pobočja in mreže naklonov smo dobili iz strukture površja, ki smo jih vzporejali z znanim položajem kraških oblik. Gostota kraških oblik na enoti litostratigrafske karte ne predstavlja dobrega statističnega podatka, ker kaže le izraženost krasa na karti površja in ne prikazuje resnične razporeditve glede na stratigrafijo, ki je 3-dimenzionalna. Te metode so lahko uporabne na relativno horizontalnih karbonatnih kamninah, za upodobitev con postopnega kraškega razvoja.
Ključne besede: kras, geografski informacijski sistem, prostorska analiza, plato Ozarkov, Missouri, ZDA.

Abstract UDC: [659.2:004]:91:551.44(77)
551.44:[659.2:004]:91(77)

David J. Weary & Randall C. Orndorff: Physical controls on karst features in the Ozark Plateaus of Missouri, U.S.A., As determined by Multivariate analyses in a Geographic Information System (GIS)

Physical controls on the genesis and aerial distribution of karst features can be identified through analyses of detailed geological mapping and karst data such as cave spring and doline locations. Our study tests the effects of geologic structures and stratigraphic position on the distribution of caves, springs, and dolines in a 625 km^2 area in the Ozark Plateaus Province of south-central Missouri. The bedrock in the region is relatively flat-lying Cambrian and Ordovician dolomite, sandstone, and chert. Joint attitude measurements at 1121 locations were interpolated to produce grids representing local structural grain. Structure contours derived from detailed field mapping were used to interpolate a grid representing the attitude of bedding surfaces across the study area. Aspect and slope grids were generated from the structure surface and correlated with known locations of karst features. The density of karst features per lithostratigraphic map unit was calculated and found to be a misleading statistic because it reflects only the map surface expression of karst and not its true distribution in the stratigraphy, which is 3-dimensional. These methodologies may be useful in other areas of relatively flat lying carbonate rocks to delineate zones of enhanced karst development.
Key Words: karst, geographic information system, spatial analysis, Ozark Plateaus, Missouri, USA.

INTRODUCTION

Understanding the physical controls on speleogenesis as well as the aerial distribution of karst features will enable scientists to better characterize and map karst areas. We are attempting to isolate some of the geologic controls on cave and karst development and develop methodologies that will enable prediction and characterization of the areal extent of karst using geologic datasets in a geographic information system (GIS).

Our study area is located in the south-central part of the state of Missouri in the Ozarks plateaus physiographic region of midcontinent USA (Fig. 1). This study area comprises about 625 km^2 within four 1:24,000-scale quadrangles for which the geology has been mapped in detail. The average elevation is about 300 meters and relief is about 150 meters. This area is important because it lies within the recharge basin for Big Spring, the largest karst spring in the Ozark National Scenic Riverways, National Park Service, and one of the largest springs in USA. We are mapping the geology and studying the hydrogeologic framework to contribute to multidisciplinary studies of potential effects of proposed underground lead-zinc exploration and mining in the area on groundwater quality.

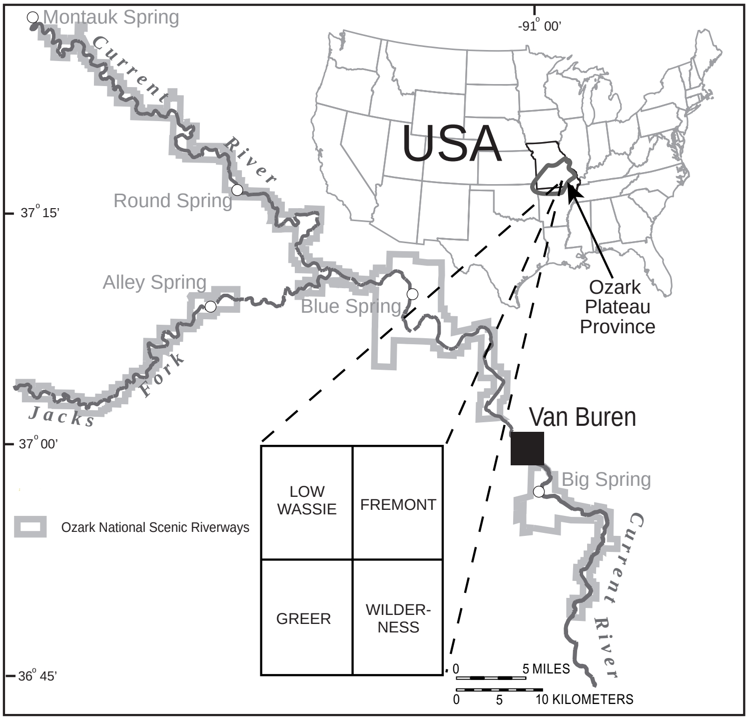

Fig. 1: Map showing location of the study area. Quadrangles with geology mapped at 1:24,000-scale are: Greer (McDowell, 1998); Low Wassie (Weems, in press); Fremont (Orndorff, 2001 unpublished data); and Wilderness (Harrison, 2001 unpublished data).

Sl. 1: Karta raziskovanega terena. Geološke karte kartirane v merilu 1:24.000 so: Greer (McDowell, 1998); Low Wassie (Weemes, v tisku); Fremont (Orndorff, 2001 neobjavljeni podatki) in Wilderness (Harrison, 2001 neobjavljeni podatki).

GEOLOGIC SETTING

Most of the bedrock in the region is Upper Cambrian and Lower Ordovician dolomite with some sandstone, chert, and chert breccia (Fig. 2). Bedding is nearly horizontal with a slight dip towards the south away from a central uplift which exposes igneous basement rocks of Late Proterozoic age (Fig. 3). Strike-slip faults with small vertical displacement are the most common structures in the area. The area is also pervasively jointed with vertical or near-vertical fractures in all of the sedimentary rock units. These joints developed during the Pennsylvanian-Permian Ouachita Orogeny that folded the Ouachita Mountains to the south. The entire area is karstified with abundant dolines, caves, and springs.

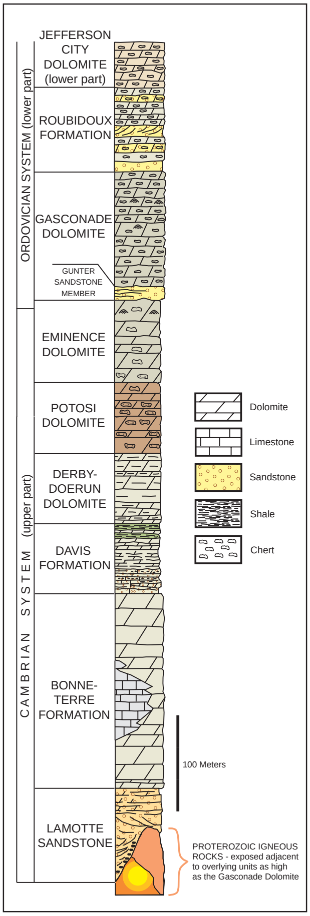

Fig. 2: Stratigraphic column of south-central Missouri.
Sl. 2: Stratigrafski stolpec južno-osrednjega Missourija.

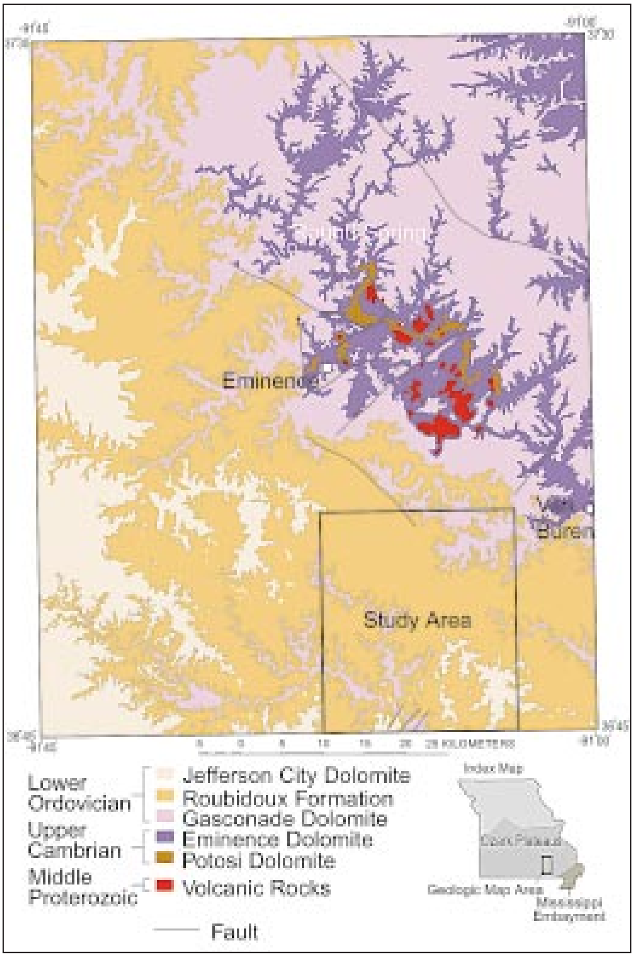

Fig. 3: Generalized geologic map of the study area.
Sl. 3: Splošna geološka karta obravnavanega terena.

GIS ANALYSIS OF KARST FEATURES

Joint sets in the study area that are oriented parallel to the dip direction of the bedding planes in outcrop are often preferentially enlarged by solution from meteoric and shallow vadose water. To test whether this alignment might be a preferential direction for carbonate dissolution in the subsurface as well, ESRI's ArcInfo[1] and ArcView 3.2[1] with the spatial analyst extension were used for GIS analyses of geologic data. All of the analyses performed were grid analyses. Grids are produced by dividing the map area into square grid cells and assigning each cell an attribute value. Attribute values can be assigned from other grids, polygon data, interpolation of contour or point data, or as the result of arithmetic operations on or between preexisting grids (Fig. 4). All of the grids in our analyses were constructed with 60 meter by 60 meter grid cells.

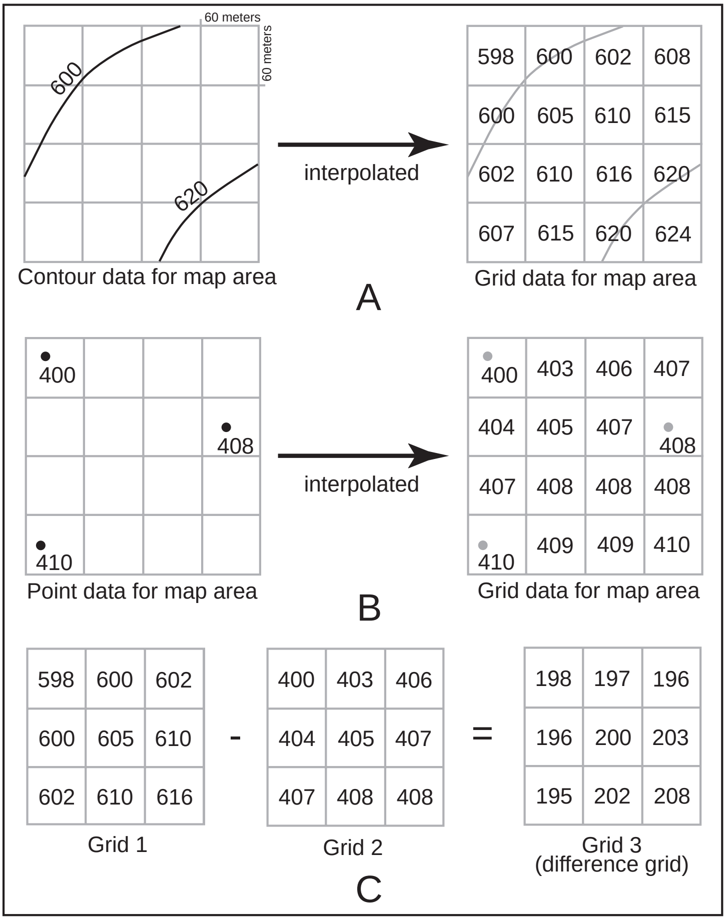

Fig. 4: Hypothetical examples of grid operations: A. Interpolation of contour data into a grid, B. Interpolation of point data into a grid, C. Subtracting one grid from another to produce a new grid.
Sl. 4: Hipotetični primeri mrežnih operacij: A. Interpolacija linijskih podatkov v mrežo, B. Interpolacija točkovnih podatkov v mrežo, C. Odštevek ene mreže od druge, da ustvarimo novo mrežo.

[1] *Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.*

Explanation of the karst database

We have compiled 3 sets of karst data: doline polygons, cave entrance points, and spring points. The doline polygons were acquired from 1:24,000 scale 7.5 minute quadrangle topographic maps by tracing the highest closed contour around each depression. The cave and spring locations were from a database supplied in ArcInfo format by the U.S. Forest Service. These were converted to grids where any grid cell lying within or intersected by a doline or any grid cell containing a cave entrance or spring were labeled as karst. All other cells were labeled with a zero value. The three grids were then combined to produce a single karst feature grid for the study area. It is assumed that the locations of these features are roughly indicative of the true distribution and density of caves within the study area. We are aware that the apparent distribution of karst features may be misleading as large portions of the area are mantled with residium or colluvium which ranges up to 50 meters in thickness and probably obscures many dolines and cave entrances.

Analysis of the structural data

We first generated a grid representing the base of the Roubidoux Formation within the study area (Fig. 5). This was done by interpolating from structural contour data compiled from 1:24,000 scale geologic mapping and well logs. It is assumed that this surface reflects the shape of structures on the overlying and underlying strata as well. Of special interest are the conspicuous anticline and syncline in the southwest quadrant of the area.

We next generated a grid representing the slope values of the structural surface using the ArcView slope function (Fig. 6). This function fits a plane to a square neighborhood of 3 by 3 cells about each cell in the grid and calculates the maximum rate of change for that plane. Slope values generated range from 0° to 26°. The slopes over most of the study area are in the 0° to 2° degree range, reflecting the generally flat-lying strata in the region. Higher slopes occur adjacent to the faults and on the flanks of the anticline and syncline in the southwest part of the area (Figs. 5, 6).

The aspect of the structural surface is closely related to the slope and an aspect grid is generated in nearly the same way. The aspect is the azimuth of the down slope direction of a plane fit to a grid cell and its' neighbors. The spatial distribution of aspect of the structure surface for the study area is shown on Fig. 7A. A histogram of the area represented by each direction class shows that more area slopes to the south, which coincides with the regional dip (Fig. 7B). When the karst grid is overlain on the aspect grid, and the density of karst area in each direction class calculated and graphed, we see that there is a greater density of karst in the northwest and north facing structural slopes (Fig. 7C).

It is not clear why aspect may be a factor. Perhaps it may be the result of some complex interaction between bedding and local moisture supply on north-facing dip slopes as opposed to other slopes, or it may relate to the interaction of bedding and the local hydrologic gradient, which slopes in the opposite direction to the south. If ground water is flowing down a hydrologic gradient but up the dip of bedding it will probably use joints for vertical movement, whereas water flowing in a gradient parallel to the bedding dip is likely to use the bedding planes. Localization of water flow in the joints, especially at joint intersections could result in enhanced solution and development of caves and dolines.

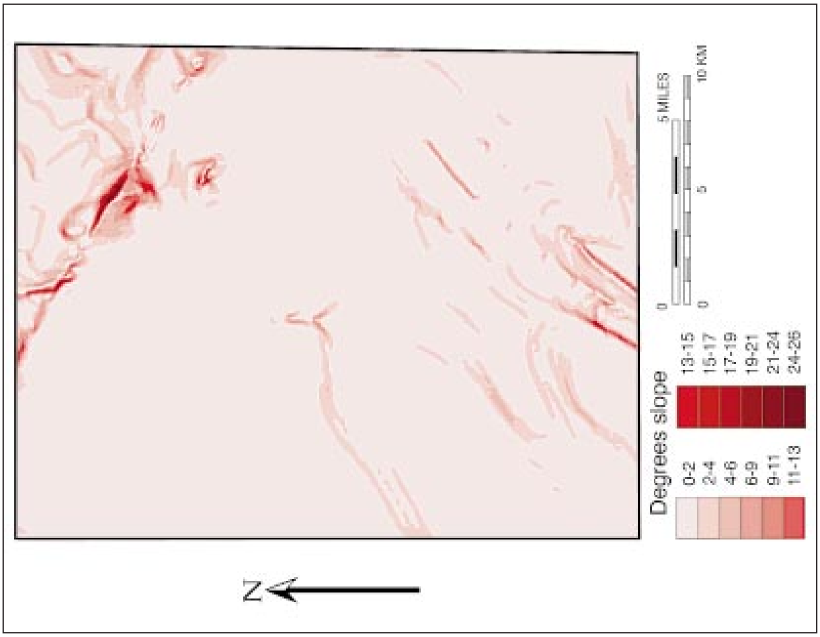

Fig. 6: Grid representing the slope values of the structural surface at the base of the Roubidoux Formation.
Sl. 6: Mreža, ki predstavlja naklone strukturnega površja v talnini Roubidoux formacije.

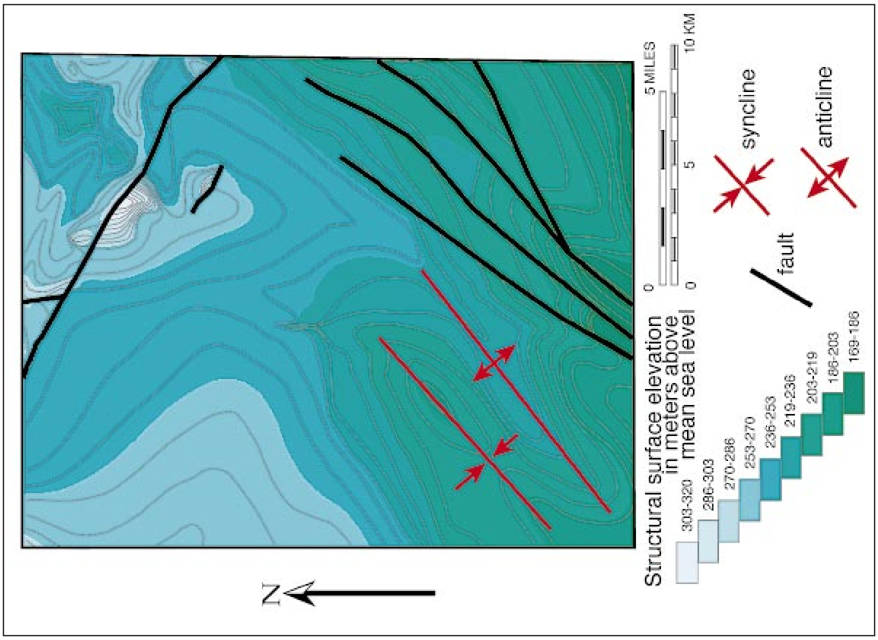

Fig.5: Grid of structural surface at the base of the Roubidoux Formation.
Sl. 5: Mreža strukturnega površja v talnini Roubidoux formacije.

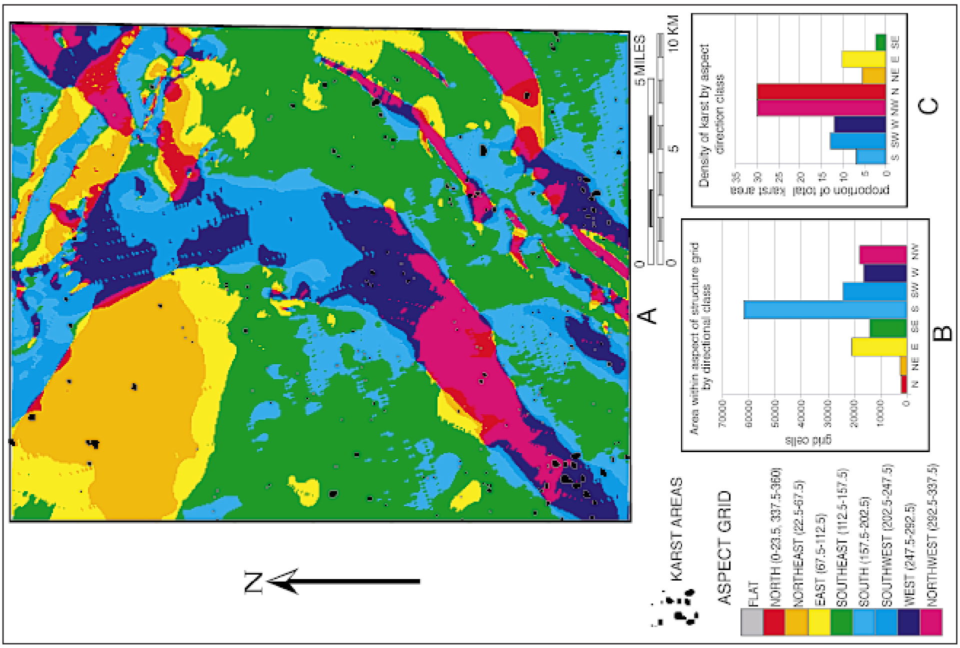

Fig. 7 - Text on page 189; Sl. 7 - Besedilo na strani 189.

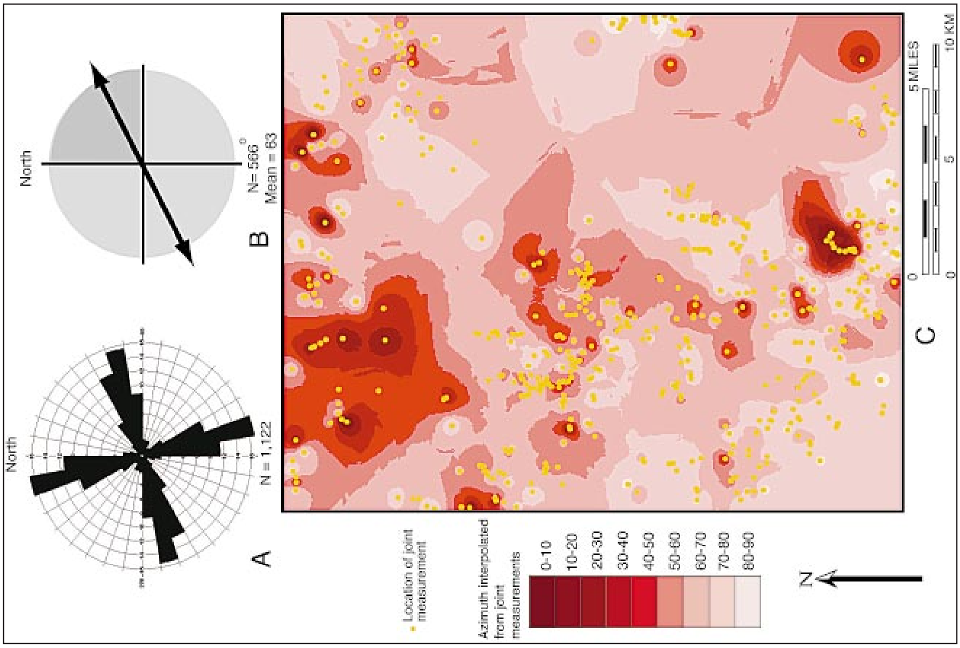

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Fig. 7 (on page 188): Aspect values for the structural surface: A. aspect grid with karst feature grid overlain, B. histogram of area within each aspect direction class, C. histogram of density of karst features within each aspect direction class.
Sl. 7 (na strani 188): Vrednosti smeri za strukturno površje: A. Mreža smeri prekrita z mrežo kraških oblik, B. Histogram področja z vsakim razdelkom smeri. C. Histogram gostote kraških oblik z vsakim razdelkom smeri.

Fig. 8 (on page 188): Grid representing the grain of the northeast directed joint set: A. compass rose diagram of all joints from the study area, B. diagram showing the average directions for the northeast directed joint set, C. joint direction grid for the northeast directed joint set.
Sl. 8 (na strani 188): Mreža, ki predstavlja porazdelitev SV usmerjenih razpok: A. Diagram-rozeta razpok obravnavanega terena, B. Diagram, ki kaže povprečje smeri za SV razpoke, C. Mreža smeri razpok za SV usmerjene razpoke.

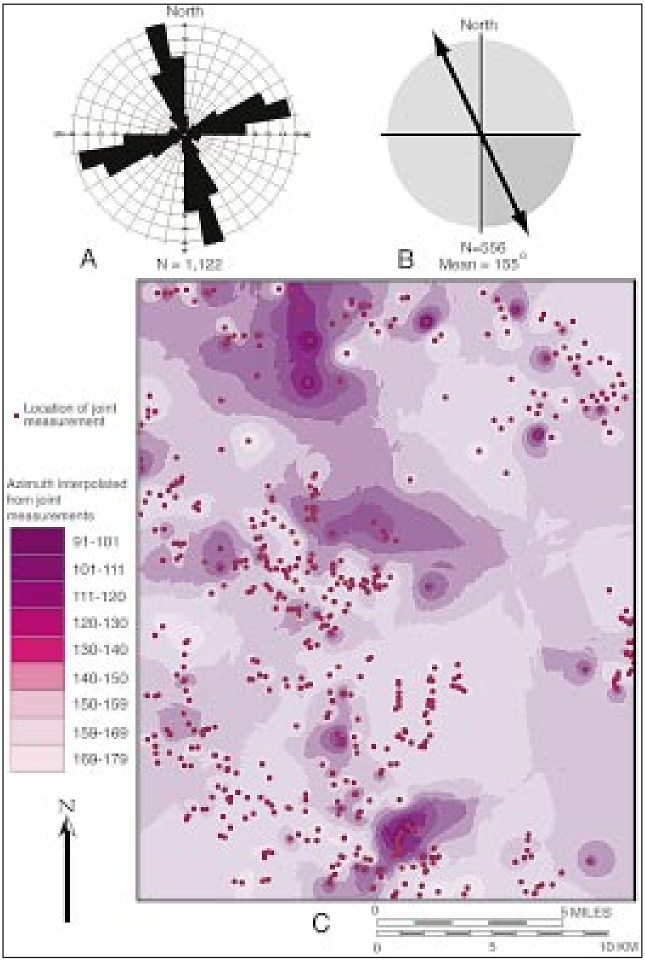


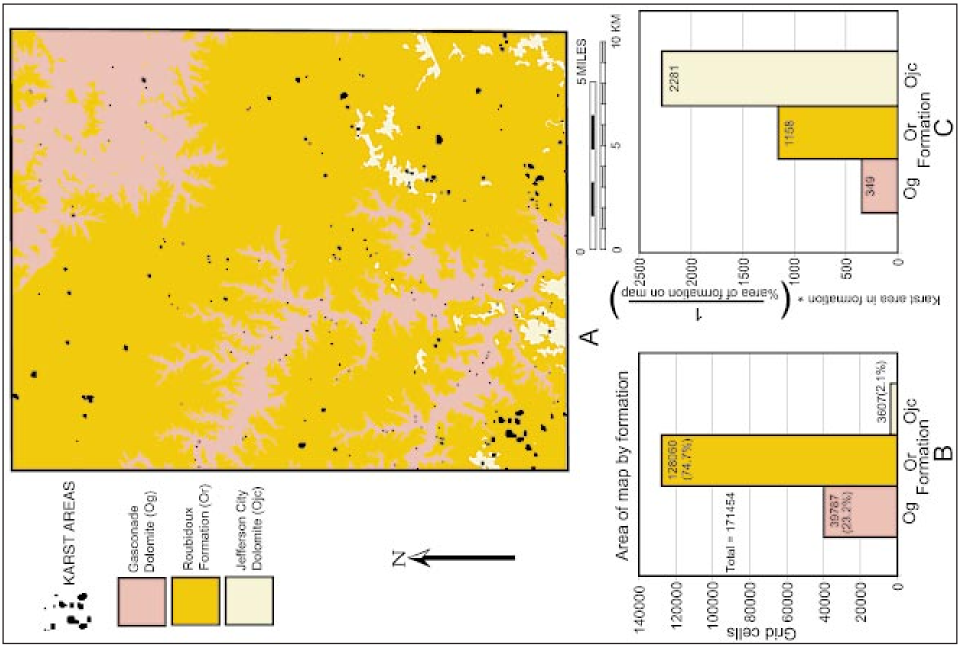
Fig. 9: Grid representing the grain of the northwest directed joint set: A. compass rose diagram of all joint measurements from the study area, B. diagram showing the average directions for the northwest directed joint set, C. joint direction grid for the northwest directed joint set.
Sl. 9: Mreža, ki predstavlja porazdelitev SZ usmerjenih razpok: A. Diagram-rozeta razpok obravnavanega terena, B. Diagram, ki kaže povprečje smeri za SZ razpoke, C. Mreža smeri razpok za SZ usmerjene razpoke.

The study area is pervasively jointed with vertical joints in two conjugate sets at nearly right angles to each other, one oriented northeast-southwest and the other northwest-southeast (Figs. 8 & 9). The point data for each joint sets were interpolated, using values of the nearest 12 points, to produce a grid surface across the map area representing the joint grain (Figs. 8 & 9). Each joint grid was then subtracted from the aspect grid to produce grids representing the angular difference between joint direction and the direction of slope of the structural surface. Since the joint sets are nearly 90° from each other, the northwest directed difference grid has a virtually identical pattern, except the values are reversed. Only one, the difference grid for the northeast directed joints is shown (Fig. 10A), with the karst location grid plotted over it. The difference data has been arbitrarily divided into 9 difference classes. In some areas, such as the southwest corner, it appears that the karst locations correlate to areas where the joints are nearly parallel to the slope of the structural surface. And since the two joints sets are nearly normal to each other, karst areas lying in areas of near 90° difference from the northeast directed joints are nearly parallel to the northwest directed set.

The density of karst within the difference classes for each of the joint sets is presented in figure 10B. The density was calculated by multiplying the area of karst within each difference class by the reciprocal of the percentage of the total map area represented by that difference class. This was done to correct for sampling bias caused by the unequal areas. If the density of karst features are directly correlated to the joints being parallel to the dip of the structure surface, then we would expect to see peaks at each end of the scale near 0° and 90°. Instead, we see a higher density of karst at about 30° difference from the northeast joint set, and more karst density at about 60° from the southeast set. Since the two joint sets are at nearly 90° to each other, these peaks are complimentary and probably a response to a similar phenomenon. If we visualize the northeast joint set having an average trend of 63° and the northwest joint set an average trend of 155°, then two structural slope trends are mutually compatible with both joint sets along lines

Fig. 10 (on page 191): The difference between the joint directions and the aspect of the structural surface: A. grid representing the angular difference between the aspect of the structural surface and the direction of the northeast directed joint set with karst feature grid overlain, B. graph of density of karst within each angular difference class for both joint sets.
Sl. 10 (na strani 191): Razlika med smerjo razpok in smerjo strukturnega površja: A. Mreža, ki predstavlja kotno razliko med smerjo strukturnega površja in smerjo SV usmerjenih razpok, mreža kraških oblik prekriva to mrežo, B. Graf gostote krasa znotraj vsakega intervala kotne razlike za obe glavni smeri razpok.

Fig. 12 (on page 191): Comparison of karst features with lithostratigraphic units: A. Distribution of formations and karst features in study area with karst feature grid overlain, B. histogram of area of map covered by each formation, C. density of karst in each formation.
Sl. 12 (na strani 191): Primerjava kraških oblik z litostratigrafskimi enotami: A. Razporeditev nastanka kraških oblik na obravnavanem terenu, ki jo prekriva mreža kraških oblik, B. Histogram področja karte, ki ga prekriva vsaka formacija, C. Gostota krasa v vsaki formaciji.



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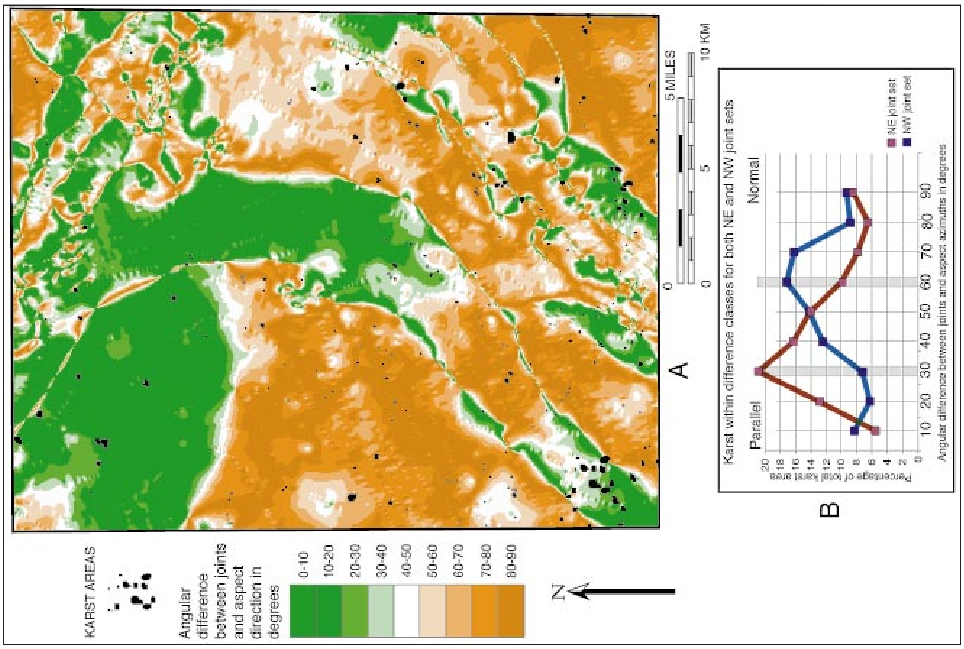

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with azimuths of about 94° (East-West) and about 214° (Northeast-Southwest) (Fig. 11). The 94° azimuth is about the direction of the regional hydrologic gradient which slopes from higher ground in the west towards the Mississippi River about 170 km to the east. The higher density of karst may be the result of enhanced solution by water flow where the structural surface dips in the same direction as the groundwater flow.

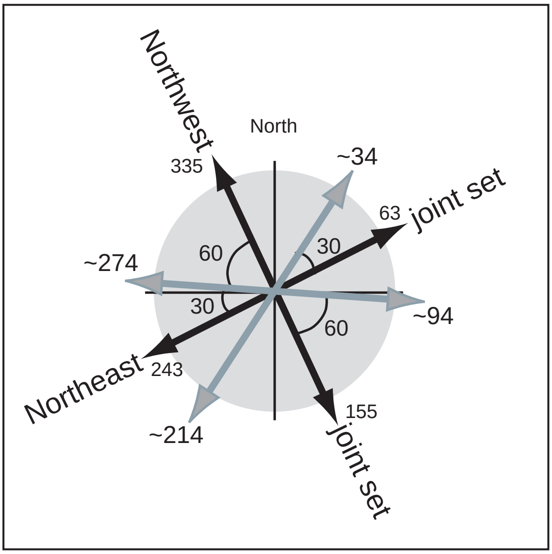

Fig. 11: Compass rose diagram showing the northeast and northwest directed joint set averages and two vectors that are 30° from the northeast set and 60° from the northwest set.
Sl. 11: Diagram, ki kaže povprečno vrednost SV in SZ usmerjenih razpok ter dva vektorja, ki sta odklonjena 30° od SV razpok in 60° od SZ razpok.

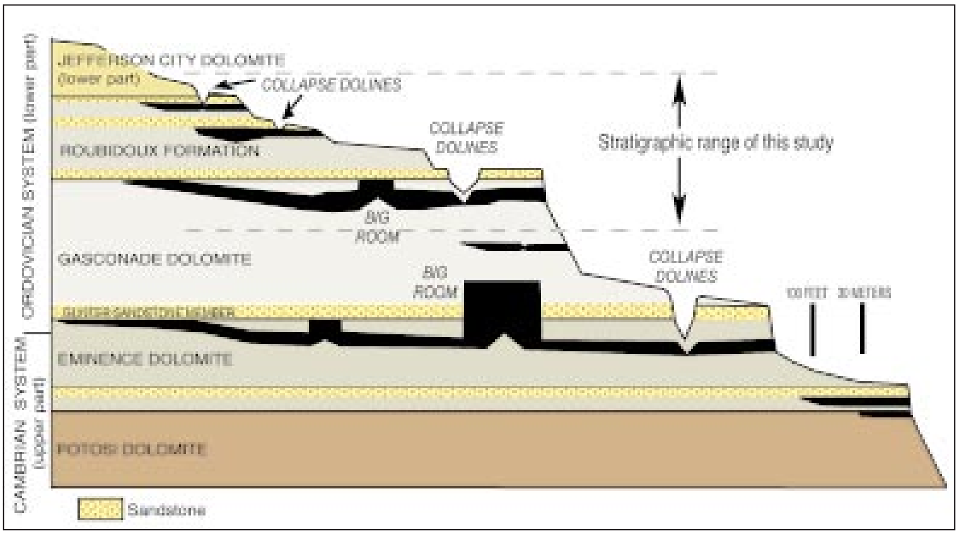

Fig. 13: Generalized conceptual model of cave and doline distribution within the stratigraphy of the study area.
Sl. 13: Splošen konceptualni model razporeditve jam in vrtač znotraj stratigrafije obravnavanega terena.

Analysis of stratigraphic control

As a test of possible stratigraphic control on karst we calculated the density of karst within each stratigraphic unit in the study area using 1:24,000 scale digital geologic map data (McDowell, 1998; Weems, in press; Orndorff, 2001 unpublished data; Harrison, 2001, unpublished data). When sample size is normalized the Jefferson City Dolomite contains a higher percentage of karst, with the Roubidoux Formation and Gasconade Dolomite next in rank (Fig. 12). These are similar to previous statistics generated for a much larger surrounding area with preliminary 1:100,000 scale data (Orndorff, Weary, and Lagueux, 2000). These statistics are misleading, however, as we know from field observations and cave and spring registers, that the Gasconade Dolomite contains most of the caves in the region. This is an example of how looking at karst, which is a three-dimensional entity, in the two dimensions of a surface map can be problematic.

Our observations show that caves in this region tend to be formed beneath sandstone horizons, with the upper part of the Eminence Dolomite and the upper part of the Gasconade Dolomite being the primary cave producing intervals (Fig. 13). Caves in these intervals often form large rooms beneath the overlying sandstones and sometimes stope up through the sandstone and collapse as they near the surface, forming dolines. Many dolines observed from the surface are rimmed with sandstone or chert blocks.

This particular study area contains outcrop of the stratigraphic interval from the upper part of the Gasconade Dolomite into to lowest part of the Jefferson City Dolomite. Many of the dolines, which map on the lower part of the Roubidoux Formation, are collapsing through the basal sandstones into caves in the Gasconade Dolomite. Dolines in the lower part of the Jefferson City Dolomite are collapses into caves beneath the upper sandstone of the Roubidoux Formation.

CONCLUSIONS

Within our study area there is a greater density of karst in the northwest and north facing structural slopes. We raise the possibility that this may be the result of water flowing preferentially down vertical joints, where the local hydrologic gradient is opposed to the dip of the rocks. This agrees with the conceptual model of Orndorff et al. (2001). There is a higher density of karst features, not where joints are parallel to the structural slope, but at 30° to the northeast directed joint set and 60° to the northwest directed joint set. This is where the dip of the structural surface is in the same direction as the regional hydrologic gradient facilitating water transport and enhancing solution. It is apparent, at least in this region, that the orientation of the vertical joints is less important than the orientation of the structural surface. The interaction of the structural surface and hydrologic gradient may be the more important factor in controlling the density of karst features. Detailed potentiometric or even paleo-potentiometric surface maps (if such could be constructed) will be required to test this hypothesis.

Trying to characterize karst density simply based on lithostratigraphic unit in map view is shown to be ineffective in this principally dolomite terrain. Techniques combining 3 dimensional GIS with finer subdivisions and characterization of the lithologic units are required and may still not work without additional datasets such as potentiometric surfaces, detailed hydrologic gradients, and even paleo-hydrologic gradients.

Future studies may include identifying which factors are most important in determining where caves and other karst features will form and apply that knowledge to produce predictive maps of karstification for large areas, especially areas where a residuum cover hides surface expression of many karst features.

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FIZIKALNA POGOJENOST KRAŠKIH OBLIK DOLOČENA Z MULTIVARIALNIMI ANALIZAMI V GIS-U (GEOGRAFSKI INFORMACIJSKI SISTEM), PLATO OZARKOV, MISSOURI, ZDA

Povzetek

Z uporabo mrežnih geo-razporeditvenih analiz in GIS-a smo določili večjo gostoto kraških oblik na SZ in S usmerjenih plasteh na področju platoja Ozarkov, Missouri, ZDA. Predlagamo, da je to lahko posledica preferenčnega odtekanja vode navzdol po vertikalnih razpokah, kjer je lokalni hidrološki gradient nasproten vpadu kamnin. Opazujemo tudi večjo gostoto kraških oblik in to ne tam, kjer je slemenitev razpok vzporedna s strukturo pobočja, ampak pod kotom 30° od SV usmerjenih razpok in pod kotom 60° od SZ usmerjenih razpok. To so razpoke, ki so vzporedne z regionalnim hidrološkim gradientom, ki lahko usmerja več vode in omogoča povečano raztapljanje. V Ozarkih je očitno, da je primerjava usmerjenosti vertikalnih razpok z nečim drugim kot strukturnim površjem, pomembnejša za pogojenost gostote in položaja kraških oblik.

Določitev gostote kraških oblik na podlagi litostratigrafskih enot se je pokazala kot neustrezna za ta močno dolomitni teren. Čeprav priporočamo uporabo metod, ki vključujejo 3-D GIS s podrobnejšimi podrazdelitvami in značilnostmi litoloških enot, pa te metode lahko še vedno ne bodo delovale brez uporabe dodatnih podatkov, ki opisujejo druge faktorje. Naš cilj je določiti kateri faktorji so najpomembnejši za določitev, kje se oblikujejo jame in druge kraške oblike. To znanje bi radi uporabili za izdelavo kart predvidevanja zakrasevanja za večja področja, še posebno tam kjer so kraške oblike zakrite s prstjo.