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USING GEOGRAPHIC INFORMATION SYSTEMS TO DEVELOP A CAVE POTENTIAL MAP FOR WIND CAVE, SOUTH DAKOTA

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The cave potential map concept was originally developed to address management concerns, but other uses rose to the forefront, including the likely maximum boundaries of Wind Cave, the potential surveyable length of the cave, and the possibilities of a connection with Jewel Cave. In addition, this method may provide means to judge the exploration potential for any section of the cave and to evaluate hypotheses regarding the cave's origin. The cave potential map was based on structural geologic factors, surface contour maps, cave survey data, surface blowhole locations, and hydrologic maps. Geographic information systems (GIS) were used to combine these data with GIS-generated triangular irregular networks, slope and aspect, orthophotoquads, a park boundary map, and land ownership maps. By combining these datasets and deriving buffers and overlays, it was determined that the current cave boundaries cover 1/10 of the total potential or maximum likely extent of the cave. The likely maximum potential boundaries are 97% inside of the current boundaries of Wind Cave National Park. Based on passage density, the length of the Wind Cave survey could range from 400-1760 km. Since the current 166 km of survey represents no more than 40% of the minimum predicted length of the cave or as little as 9% of the maximum predicted length of the cave, a tremendous amount of surveyable passage remains in the system.

Since its discovery in 1881, numerous cavers have been drawn to Wind Cave to explore its complex mazes. Although the first surveys were conducted in 1902 and produced about 1.6 km of survey (Willsie 1902), it was not until the mid-1950s that significant survey work began. Between 1955 and 1963, the South Dakota School of Mines and Technology in Rapid City mapped another 1.6 km of passage. The National Speleological Society's 1959 Wind Cave Expedition mapped an additional 5 km (Brown 1959). In 1960, the Colorado Grotto surveyed 0.8 km and begun a long-standing survey project (La Borde 1960). In 1962, seasonal Wind Cave ranger Alan Howard began surveying in the cave, mapping several hundred meters of passage. In the mid-1960s, Dave Schnute, Herb Conn, and Jan Conn surveyed 3.2 km and made numerous important discoveries. The most sustained survey in Wind Cave to date was a project begun by John Scheltens and the Windy City Grotto in 1970 (Scheltens 1970). During the 1970s, Wind Cave rangers also contributed another 4.80 km of passage and during the 1980s the National Outdoor Leadership School (NOLS) surveyed in the cave. As the survey grew, the boundaries of the cave expanded to 1.3 km north/south by 1.4 km east/west. In 1990, the Wind Cave Weekend survey project was started by the Colorado Grotto. Between 1990 and 1998, 30 km was added to the survey length. Since 1999, the Wind Cave Weekend has continued and, coupled with increased survey work by park staff, an average of 12 km a year is being surveyed. The total Wind Cave survey now exceeds 166 km

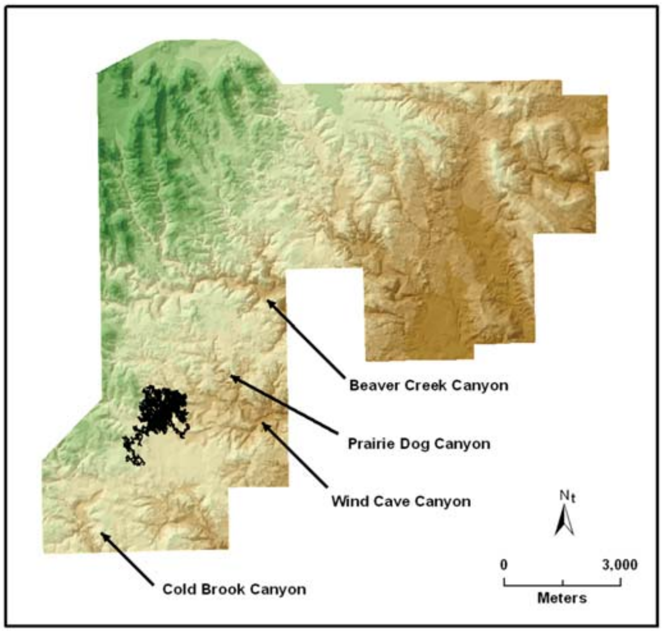

Figure 1. Location of Wind Cave within Wind Cave National Park. The Wind Cave survey lineplot (black) was generated using COMPASS software and imported to GIS format and georeferenced using the CaveTools extension for ArcView GIS. The cave data are plotted atop a digital elevation model (DEM), which has been shaded showing higher elevations in green and lower elevations in brown.

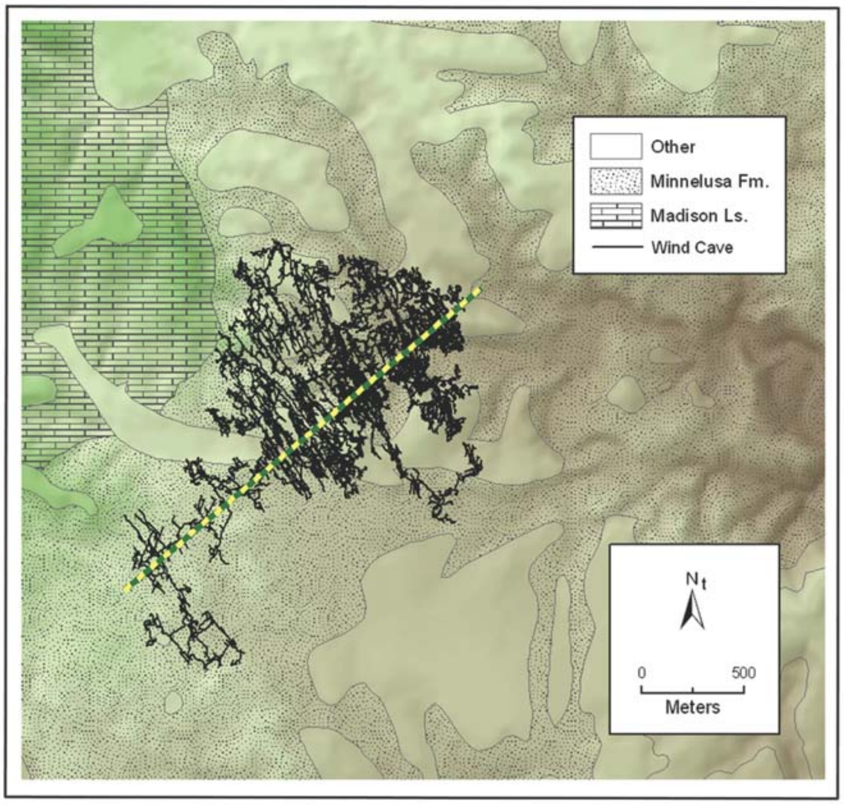

Figure 2. Relationship of the Madison Limestone outcrops to the Wind Cave survey. The major trend of the cave is marked with a yellow and green striped line. The Minnelusa Formation lies directly above the Madison limestone. This illustration was created by combining a shaded relief DEM, geology layer, and survey lineplot.

and the boundaries have expanded to fill a 1.6–1.9 km rectangle (Fig. 1).

Recently, cavers have been directed by the park cave resource management staff to concentrate their survey efforts on individual areas. This was done to facilitate the survey of the cave and to provide incentive for cavers to take ownership of "their" areas. The unforeseen result of this tactic was that the true complexity of Wind Cave was revealed. This information helped to substantiate a hypothesis that the major trend of the cave (Fig. 2) developed along a sulfate zone that paralleled the ancient shoreline (A. N. Palmer 2000 pers. comm.). It is common to hear cavers participating in the current survey effort remark about the "endless" potential of the cave. A famous diary quote by an early Wind Cave explorer, Alvin McDonald, said, "Have given up the idea of finding the end of Wind Cave" (McDonald 1891). This is as true today as it was in 1891.

For years, cavers based the potential size of Wind Cave on barometric wind studies done by Conn (1966). Those studies suggest that the current volume of surveyed cave represents only 2.5% of the total volume of 5.5×10^{10} m^3. The current volume of the surveyed portions of Wind Cave is 1.4×10^9 m^3 (M. J. Ohms 2001 pers. comm.). Others pointed out that the 5.5×10^{10} m^3 calculation was actually conservative, since the Snake Pit Entrance, numerous blowholes, and the elevator leakage were not considered. Recently, surveyors have noticed that cool windy air blows in many domes throughout the cave. It is thought that this air represents surface connections too small to penetrate or notice as blowholes on the surface. Additional entrances would suggest a greater total volume. It also is possible that the portion of Wind Cave that is accessible may be much smaller than the above estimate. The majority of the cave may be beyond unenterable cracks and small connecting passages, or it may be completely water filled and not contributing to the total airflow at all. This study speculated that a cave potential model might be a more accurate method to predict the amount of potential surveyable passage in Wind Cave than barometric wind studies could provide.

As the boundaries of the cave have enlarged, many hypotheses on passage extent have been proposed, including speculation on a connection with Jewel Cave, 29.4 km to the northwest. These hypotheses have proposed either an air-filled or a water-filled connection.

Wind/Jewel Cave connection hypotheses

It has been hypothesized that a connection between Wind and Jewel Caves may exist based on the observation that these two huge cave systems are both located in the Madison Limestone (locally known as the Pahasapa Limestone), which forms a continuous ring around the Black Hills (Zerr 1972). Others have suggested that the connection may not be air-filled but within the phreatic zone. Either potential connection may not be passable by humans.

Proponents of the air-filled connection hypothesis suggest that the caves behave as one giant cave system based on barometric wind measurements (Zerr 2001). However, a general observation concerning the barometric winds seems to argue against this air-filled hypothesis. The barometric winds from Wind Cave react to surface changes in atmospheric pressure as a balloon-shaped void, with all the passages relatively close to the entrance. Jewel Cave behaves as a cylinder, with much of that cave a great distance from its entrance (Conn 1966). Additionally, the smaller and concentrated maze passages of Wind Cave significantly differ from Jewel Cave's larger passages and broader footprint.

Survey data and geologic maps reveal that the southeast point of Jewel Cave is 313 m higher in elevation than the southwest corner of Wind Cave and that there are 4 folds and at least one significant fault between them. Analysis of the line plot of Wind Cave reveals an obvious concentration of passage development along a line, the major trend, roughly per-

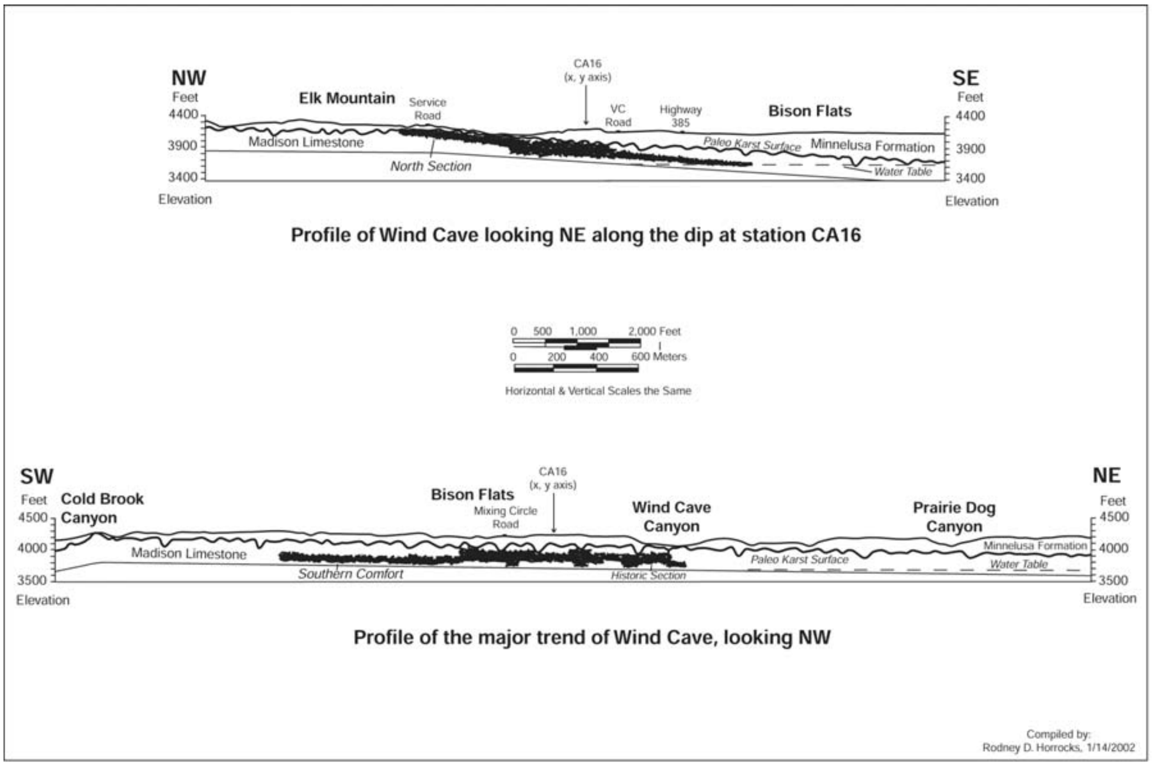

Figure 3. Profiles of Wind Cave along the major trends of the cave, showing the relationship of surveyed passages with the structural geology. Station CA16 was chosen because of its location at the intersection of the two major trends of cavern development. This illustration was compiled from the Wind Cave National Park and Vicinity 20-foot contour map, COMPASS data, geology maps, cave radio location data, and GIS hydrography layers.

pendicular to the dip of the beds (Fig. 2). When a profile of the Wind Cave survey is analyzed, it becomes apparent that the major trend of Wind Cave runs on a line extending N52ºE and plunges slightly to the northeast (Fig. 3). Following this major trend to the southwest, there is no reason to believe that this pattern would be abandoned with the cave trending to the west and then up to the northwest past the folds and up the significant elevation gain to Jewel Cave.

Even though the straight-line distance between the two caves is 29.4 km, the distance following the Madison Limestone-Minnelusa Formation contact is longer, 32 km, as the limestone outcrop strikes to the west before angling northwest towards Jewel Cave. This measurement approach was chosen since both caves lie underneath the Minnelusa exposures. If such a connection actually existed, the resulting cave would be on the order of 7200 km long and largely not explorable due to human limitations. This estimate assumes the same passage density along the entire distance as is found in the Wind Cave area and may represent a high estimate since Jewel Cave currently appears less complex than Wind Cave.

Others have suggested that a hydrological connection between the two caves may be possible via a connection below the potentiometric surface. The problem with a water-filled cave connection is that the potentiometric contour that trends through Wind Cave is 18 km to the south and 400 m lower in elevation with respect to any known passages in Jewel Cave (Carter & Driscoll 2001). However, a groundwater connection between the Jewel Cave area and Cascade Springs, a large spring on the southern tip of the hills, has been observed based on potentiometric studies (Carter & Driscoll 2001). Along the western flank of the Black Hills, the Madison aquifer flows to the southwest at 0.34-0.54 m^3/s. About 32 km from Jewel Cave, that flow arcs to the east and emerges after another 41 km at Cascade Springs (Carter & Driscoll 2001). However, on the eastern edge of the Black Hills, there is no groundwater flow connection between Wind Cave and Cascade Springs as all water flows to the southeast from Wind Cave at 0.0085-0.037 m^3/s (Carter & Driscoll 2001). Because the potentiometric contour that intersects Cascade Springs trends 4.0 km southeast of Wind Cave and is 120 m lower, and because it is unlikely that cave development continues much below the water table in that direction (see the Developing the Model section below), a phreatic connection between Wind Cave and Cascade Springs below the potentiometric surface is unlikely. Assuming a connection is unlikely makes it possible to analyze Wind Cave as a finite entity with definable boundaries that can be quantified in a cave potential model.

MANAGEMENT REQUIREMENTS

Traditionally, surface land management decisions have been based on whether or not activities were above known cave, but recent cave management projects have demonstrated that activities within the cave watershed could impact the cave just as easily. Not only are there sinking streams in the Park, but close hydrological connections between surface drainages and the cave system have been demonstrated through cave inventory (Nepstad 1996) and dye tracing projects (Alexander

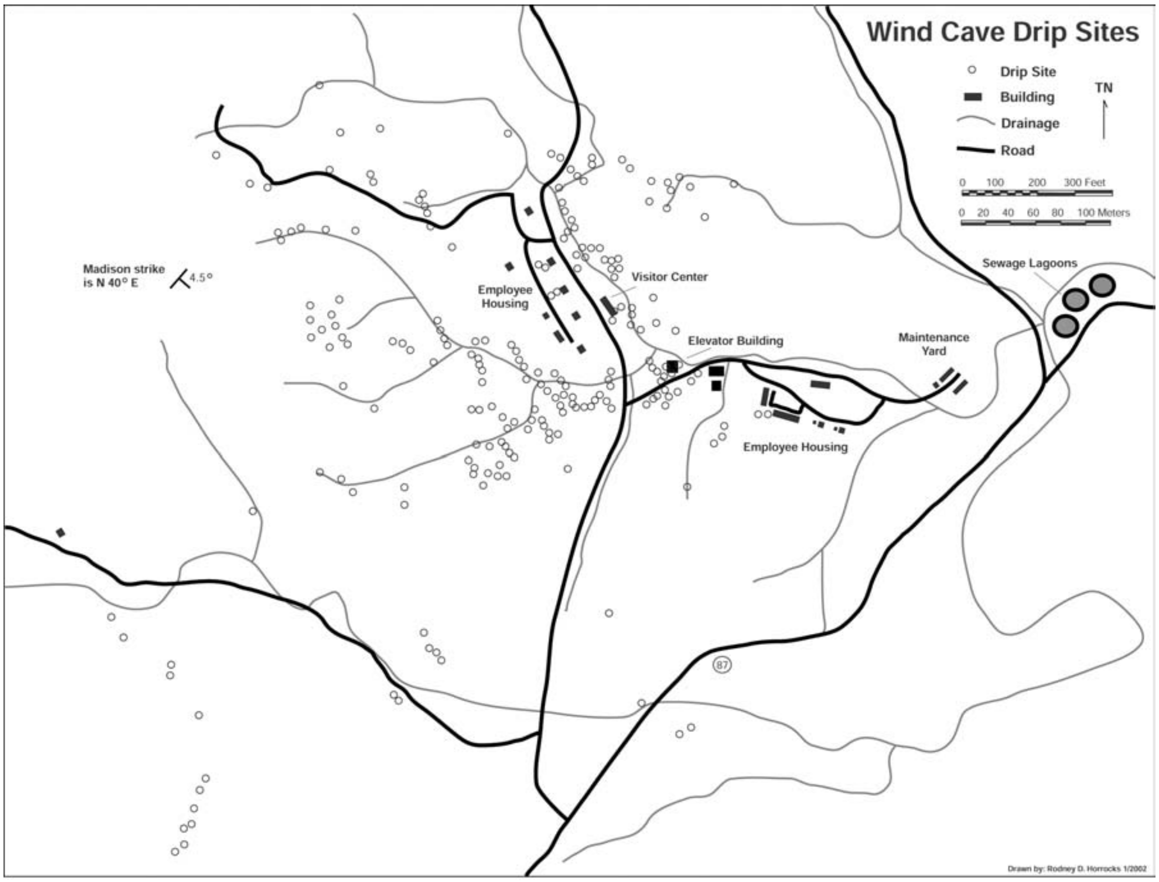

Figure 4. Relationship between dripping water in Wind Cave and the location of surface drainages. Notice that nearly all drip sites are near drainages or down dip from them. Map compiled by James Nepstad.

1986). The cave inventory demonstrated that wet spots in the cave are either located below surface drainages or just down-dip from those drainages (Fig. 4). The dye-tracing project recorded flow-through times as fast as six hours (Nepstad 1996) and documented increased hydrocarbons from parking lot runoff after a storm event (Venezky 1994).

Park facilities and infrastructure, which were built directly on top of the cave and within a window in the Minnelusa Formation that exposed the underlying Madison Limestone and produced the natural entrances (Fig. 2), historically provided the foremost threats to Wind Cave. Fortunately, the three most severe threats presented by these structures and facilities have either been mitigated or are in the process of being addressed. In 2001, 2400 m of the aging sewer system was replaced with dual-contained HDPE lines and inspection ports to check for inner line leaks. The park plans to replace the asphalt parking lot with Portland concrete and add a storm water treatment system that would catch the hydrocarbons washed off the lot during the first flush of precipitation events. It also plans to remove the inadequate sewage lagoons. Although these lagoons were outside the current boundaries of the cave, it was suspected that they could be over undiscovered cave (J. Nepstad 1999 pers. comm.).

Any scenario that would extend Wind Cave beyond the current park boundaries would necessitate partnerships with additional land managers as US Forest Service and private lands surround Wind Cave National Park. In the foreseeable future, pressure from surrounding development may threaten the cave. Housing tracts adjacent to Beaver Creek to the northwest of the park are being planned. This creek enters the park and a large portion of its flow disappears underground into Beaver Creek Cave in the Madison Limestone. Although this water has been dye traced to the parks well in Wind Cave Canyon, it has not yet been traced to Wind Cave (Alexander 1986). Likewise, using herbicides to control exotic weeds within the Wind Cave watershed to the west of the Park is a land management activity that could potentially impact the cave.

Historically, it had been difficult to get park managers to recognize that Wind Cave may extend beyond its current boundaries. Unless the cave survey extended into an area, managers assumed that no cave existed there (J. Nepstad 1999 pers. comm.). Although this concept of a cave potential map first developed after hearing about these attitudes, actual development of the model identified its limitations as a management tool.

DEVELOPING THE MODEL

As the model developed, it was decided that this model could address four issues: 1) the maximum likely extent of Wind Cave; 2) the surveyable length of the cave; 3) the Wind/Jewel Cave connection hypothesis; and 4) surface land management shortcomings that existed near known cave.

Although previous researchers have analyzed Wind Cave's potential extent based on individual disciplines, no one has attempted to use geology, hydrology, airflow, and cave survey data together to quantify the potential extent of Wind Cave. We initially analyzed the region surrounding Wind Cave and identified some preliminary large-scale factors that could limit cave passage development. We theorized that the current erosional surface and the water table could provide those limiting boundaries. Blowholes and the cave survey data also provided additional clues on the potential extent of the cave.

The Madison Limestone has been eroded away 2100 m to the northwest of the cave, eliminating the possibility that the cave could extend in that direction by more than 2100 m (Fig. 2). Additionally, 1100 m to the southwest of the known cave, a moncline dips 11° to the south. To the west of this monocline, the drainages north of Cold Brook Canyon have removed the upper 30-m of the Madison Limestone, probably representing the upper unit. This does not preclude the possibility of cave underneath those drainages, it only limits that potential. About 3200 m to the northeast of known cave, the Madison Limestone dips underneath Beaver Creek Canyon just downdip from the Beaver Creek Cave, the major insurgence for Beaver Creek. If the cave did continue all the way to Beaver Creek Canyon, it would likely be flooded and inaccessible to exploration. Actually, any passage development to the northeast along the major trend of the cave would likely encounter the water table only 240 m from the current eastern boundary of the cave (Fig. 3). These observations supplied us with three likely, but crude, limiting boundaries for the air-filled portion of the cave. The fourth was provided by the water table to the southeast.

Southeast of the cave, Wind Cave intersects the water table at an elevation of 1100 m (Palmer 1987). Although, divers have never penetrated the passages that continue down dip from the lakes and the deep point of the cave, it is unlikely that the cave continues an appreciable distance in that direction based on three observations: 1) there is no apparent upper level development in that section of the cave; 2) there are only a couple of places where the cave even approaches the water table; and 3) even in those areas, there is sparse cave development. This assumption may also be supported by the observation that where the water table is encountered, most cave development parallels the major trend of the cave and does not continue down dip. Based on these observations, we are assuming that the cave pinches in the southeast direction, with the water table representing the approximate southeastern boundary of the cave.

The earliest version of our cave potential map simply mapped out these four crude boundaries, while factoring in the lineplot of the cave, the location of blowholes, erosional surfaces, canyons, and the water table.

With this preliminary cave potential map in hand, we hypothesized that other geologic factors would also have had a significant effect on the development of Wind Cave. We also hypothesized that such data as the profile view of the Wind Cave survey, cave radio location depths, surface outcrops, cave levels, airflow, and passage density would all offer additional clues on the likely extent of Wind Cave. Once we identified these additional limiting factors and data sources, individual GIS layers provided buffers and overlays for further refining potential boundaries of the cave.

LIMITING FACTORS

Several geologic factors influence or limit the potential extent of Wind Cave, including erosional surfaces, structural geologic factors, mode of speleogenesis, and paleo-injection points. In the future, as we learn more about these limiting factors, the cave potential boundaries may need further modification.

To quantify the impact that the erosional surface had upon the cave, two profiles were created, one along the dip and the other along the major trend (Fig. 3). These profiles were created by combining the surface contours from the 20-foot "Wind Cave National Park and Vicinity, S. Dak." contour map with the profile views of the Wind Cave lineplot generated in COMPASS software (Fish 2002). The x,y base point chosen from the cave lineplot was station CA16, a station located at the intersection of the major trend of the cave with the major northwest/southeast trending lakes passages. Radio location depths and paleokarst surfaces were also incorporated into these profiles.

The structure and stratigraphy of the Madison Limestone are primary limiting factors of cave development. The thickness of the Madison Limestone, relief of paleokarst surfaces, dip of the beds, composition of individual beds, presence of folds and faults, presence of proto-cave passages, sulfate beds, and groundwater mixing zones all play major roles in delimiting the potential of Wind Cave.

The thickness of the Madison Limestone in the Wind Cave area and the relief of the paleokarst surface were important in the profile views (Fig. 3). The Madison Limestone is 80–114 m thick, with up to 46 m of vertical relief in the paleokarst surface at the top of the formation. However, the average vertical relief in the vicinity of Wind Cave ranges from 10-20 m (Palmer & Palmer 1989).

The cave slopes to the southeast between 4-5.5º, the same dip as the Madison Limestone. When the cave is examined in profile along its major trend, the cave slopes slightly to the northeast as this development does not exactly follow the stratigraphic strike (N52ºE vs. N40ºE). Continuing along this major trend to the southwest, a monocline dips 11º to the south at the edge of Cold Brook Canyon (Fig. 3). Several other folds lie to the west and northwest. Based on known patterns and theory, there is no reason to believe that this major trend would be abandoned with the cave trending to the west and then up to the northwest past these folds and up the significant elevation gain to Jewel Cave.

Five distinct "levels" have been identified within this three-dimensional network maze. These levels, based on morpho-

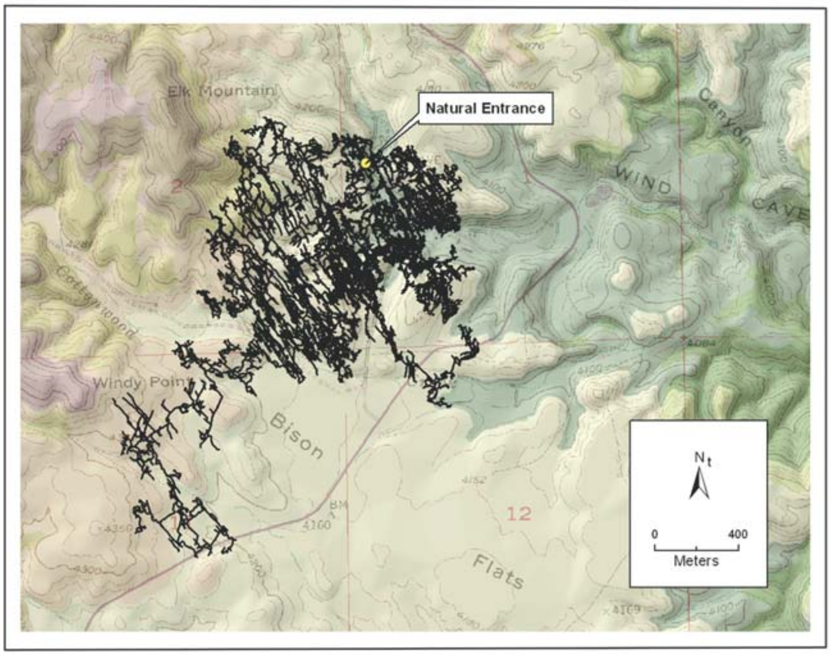

Figure 5. Wind Cave entrance location and surface relief. A DEM was used to create a surface upon which the Wind Cave USGS digital raster graphic (DRG) was draped, along with a hillshaded TIN derived from the DEM and the Wind Cave survey lineplot.

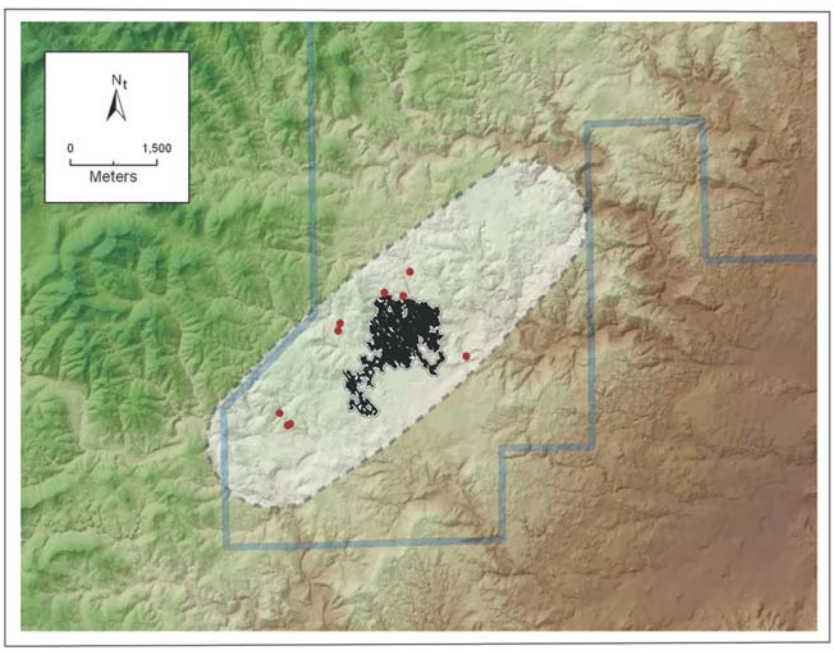

Figure 6. Cave potential boundary for Wind Cave representing the likely maximum extent of humanly accessible portions of Wind Cave. The boundary for cave development is shown in light gray. Surveyed cave passages are shown in black; blowholes are shown as red dots.

logical differences in the passages, have been attributed to the thickness, composition, bedding planes, and joints within the individual units of the Madison Limestone. The majority of Wind Cave was developed at the middle level, which has been subdivided into the Upper Middle, Middle, and Lower Middle Levels. Lower level cave development is absent in the northwestern section of the cave, with most of the lower level developed along the major trend of the cave. Along the major trend, the vertical relief between the highest and lowest levels of the cave can vary up to 76 m.

Proto-cave passages and sinkholes were an important path for the dissolution of Wind Cave. They formed about 310 Ma, when cave passages and sinkholes in a low elevation karstic plain developed at a mixing zone between sea and meteoric waters. These Mississippian karst features were filled with basal Pennsylvanian sediment (now paleofill) during a sea level rise about 300 Ma, when the Minnelusa Formation was deposited (Palmer & Palmer 1989).

One of the densest concentrations of passages in Wind Cave, which occurs along the major trend of the cave (Fig. 2), may correlate with a sulfate zone deposited parallel with the Mississippian shoreline (Palmer & Palmer 1989). This zone later became an important mixing zone for cavern development that probably predated the canyon entrenchment (A.N. Palmer 2001 pers. comm.).

The mode of speleogenesis had a significant impact on the extent of Wind Cave. It is intuitive that such a complex cave must have an equally complex speleogenetic history. Many theories have been proposed for the development of Wind Cave (Howard 1964; Bakalowicz *et al.* 1987; Palmer & Palmer 1989; Ford *et al*. 1993). This model is based on Palmer's (2000) view of cave development.

When the plan view of the cave map is analyzed, there is a noticeable bulge in passage development towards the northwest corner, which may represent a surface injection point of waters from the northwest (Fig. 5). Palmer (1981) noticed that an old erosional valley terminates to the northwest of the cave at about the contact of the Madison Limestone with the Precambrian instrusives. He has theorized that this paleo valley supplied some of the water for the mixing zone that was a major contributor to the dissolution of the cave. Another potential injection point is along the northwest-southeast trend that runs along the lakes passage. Helictite bushes are found along this entire passage. This may be evidence of injection of thermal waters through the floor crusts of these passages (Davis 1989). Other evidence of thermal waters is the cupolas in the upper level of the cave that look like convection features (Bakalowicz *et al*. 1987). These cupolas are throughout the cave, indicating that thermal waters may have been important contributors. Even today, a thermal spring (Buffalo Gap Spring) with a temperature 5ºC above the lakes in Wind Cave is only 8.8 km down dip from the cave.

USING GIS TO CREATE THE CAVE POTENTIAL MAP

A GIS was used to accomplish several tasks, including the development of a spatial model that was used to verify our preliminary cave potential map, the visualization of those results, and the development of maps to demonstrate cave potential and support management requirements and decisions. The GIS used ESRI's ArcView GIS, Spatial Analyst, 3D Analyst, and CaveTools, a third-party extension used to incorporate cave survey data into the GIS (Fig. 5).

GIS data layers were collected and derived from a variety of sources. Digital line graph (DLG) files were used to create hydrography, hypsography, and transportation layers. Contour lines from the DLG hypsography layer were used to generate a triangular irregular network (TIN) elevation model, from which slope, aspect, and other layers used for visualization were derived. Blowholes and cave entrance locations were imported from field GPS readings. Cave survey data were converted from COMPASS plot files to ESRI shapefiles format and georeferenced based on GPS locations of surface survey stations. Digitized park boundaries, digital orthophoto quads (DOQs), and geologic maps were also incorporated into the GIS.

One of the first maps produced using the GIS showed the relationship of the outcrop of the Madison Limestone to the current surveyed cave extent (Fig. 2). This map underscored the fact that the known cave does not lie below the surface exposure of the Madison, but rather is developed further down along the dip of the Madison, below the Minnelusa Formation exposures (Fig. 2).

Using the ArcView Spatial Analyst ModelBuilder, an interactive model diagram was constructed incorporating various spatial processes, such as buffering, proximity, and weighted overlays. A cave potential surface was generated by weighting proximity to certain features, such as known entrances and blowholes, and combining these derived cave potential surfaces using weighted overlays with other factors, such as geology, potentiometric surfaces, and current cave extents (Fig. 6). In addition, the volumetric constraints for cave potential were further defined by generating 3D surfaces that represented the limiting bounds of the intersection of the Madison Limestone along its strike and dip with the upper and lower limits of the historic and present water table elevations. Area calculations using the GIS were made of the known extent of the cave and the potential area for cave development, and these were used to calculate the potential cave length based on current parameters.

DISCUSSION

An estimation of the potential extent and surveyable length of Wind Cave and a means to address the Wind/Jewel connection theory constitute the main benefit of this model. Although this exercise was also instigated because managers can not wait until a cave of this magnitude has been completely surveyed to develop their management policies, it was realized that this model has limitations.

Developing the model demonstrated that potential cave to the NE would encounter the water table, which would limit humanly accessible passage. It also demonstrated that to the SW, minor structural and erosional features would be encountered. Although these may limit humanly accessible cave or even cave development in those directions, neither would necessarily prevent them.

Recognizing the management limitations of the Wind Cave Potential Map, Wind Cave National Park has chosen to manage any surface activities above the surface exposures of the Madison Limestone or within the cave and karst watersheds of the limestone, the same way they would manage activities directly above known cave. This policy is based on the assumption that the potential exists for other sizeable caves to exist in other areas of the park or for Wind Cave to extend beyond the likely maximum boundaries identified during this project. Indeed, a blowing well was found in the north part of the Park, blowing caves exist to the southeast of the Park, and there are numerous smaller caves scattered throughout the Park.

The Wind Cave Potential Map has shown that the US Forest Service of the Department of Agriculture manages most of the potential area that falls outside of the Park. Although a minor portion falls either under private lands or down dip from those lands, the probability that the cave extends near these areas is minor. Analysis of the two Wind/Jewel Cave connection hypotheses resulted in the conclusion that either type of connection is an unlikely scenario, although such a connection could not be totally eliminated as a possibility.

Once the analysis had been completed, we used the buffers and overlays to draw an outline around the area that represents the likely maximum extent of Wind Cave, creating the Wind Cave Potential Map. Approximately 97% of those boundaries fall inside of the current boundaries of Wind Cave National Park (Fig. 6). The current boundaries of the cave were found to be 1/10th of the area of the total potential of the cave, as identified by this exercise.

By calculating passage density for the current cave boundaries and then for the maximum potential boundaries, a minimum and maximum potential surveyable length was calculated for Wind Cave. Because passage density varies among various parts of the cave, we divided the cave into four zones of similar passage densities, the North, South, Lakes, and

Southern Comfort zones. We then identified a fairly complete surveyed part of each zone. After applying those survey lengths throughout each of the zones and then adding the four zones together, we predicted that the cave could have around 400 km of surveyable passage, if the cave is not extended beyond the current boundaries. If the cave is extended to all edges of the potential boundary, Wind Cave could have nearly 1800 km of surveyable passage, assuming similar passage density throughout the potential area. Since the current 166 km of survey represents no more than 40% of the minimum predicted length of the cave or as little as 9% of the maximum predicted length of the cave, it is obvious that a tremendous amount of surveyable passage remains in the system. However, based on airflow and cave development patterns, it is unlikely that the cave will continue in all directions to the edge of the identified cave potential boundaries; and even if it did, it is unlikely that cavers would be able to physically push the cave to those boundaries.

What should be noted is that this cave potential map only reflects the *likely* maximum extent of Wind Cave. For the southwest boundary, it does not preclude the possibility that the cave could extend beyond the identified boundary, it simply states that this is unlikely to happen based on our current understanding of how the cave formed and the geology of the area. Likewise, for the northeast boundary, it does not preclude the possibility that a significant portion of the cave in that particular direction is not water-filled. Thus, our calculations are limited to the potential air-filled portion of the cave, which points out the limitation of using this model as a management tool. In the future, the cave potential boundaries will likely be modified as we learn more about the limiting factors that determined the morphological shape and extent of Wind Cave and as we gather more data from the survey of the cave.

It should be pointed out that this cave potential model can not replace actual survey and inventory work in the cave for several reasons: 1) this is a simplified theoretical cave model; 2) only in-cave survey can identify point source impacts; and 3) a more complete survey and inventory will strengthen the speleogenetic theory on the development of the cave and the understanding of the hydrology of the region. Survey work, even in the interior of Wind Cave constantly makes new scientific discoveries that add to the Wind Cave knowledge base. If every effort is made to minimize the impact from survey work, the benefits outweigh the limited impact from those activities.

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