Sinkhole Conference

Multidisciplinary Conference on Sinkholes & the Engineering and Environmental Impacts of Karst

"Integrating Science and Engineering to Solve Karst Problems"

The 13th Sinkhole Conference
Program with Abstracts

May 6-10, 2013
Carlsbad, New Mexico, USA

National Cave and Karst Research Institute

PELA

EDWARDS AQUIFER AUTHORITY

Barton Springs Edwards Aquifer Conservation District

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Barry Beck in a cave entrance on Mona Island, Puerto Rico (ca. 1976).

Official Program with Abstracts

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Carlsbad, New Mexico, USA

Credits
Program with Abstracts prepared by Brian A. Smith and Brian B. Hunt, Barton Springs/Edwards Aquifer Conservation District, Austin, Texas.

Cover photograph by NCKRI. Aerial view of Jim's Water Service Sinkhole, northern Eddy County, New Mexico about six weeks after initial collapse.

Photos of Barry Beck courtesy of Dr. Penny Lukin.

Sinkhole Conference

Multidisciplinary Conference on Sinkholes & the Engineering and Environmental Impacts of Karst

"Integrating Science and Engineering to Solve Karst Problems"

6 May 2013

Welcome Karst Engineers and Scientists!

We are delighted to be your hosts for the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. For the past 29 years, this series of meetings has been among the most important in developing a better understanding of karst processes that result in environmental problems, and in creating effective measures that identify those problems before they occur, remediate them when they occur, and prevent them from occurring in the first place.

Since our last meeting in January 2011, this conference series has come under the management of the National Cave and Karst Research Institute (NCKRI). Shortly before his fatal illness, Sinkhole Conference founder Dr. Barry Beck contacted NCKRI about potentially taking on this role. He felt the conference needed a home with an organization that is dedicated to the study of karst phenomena and designed to conduct and host conferences. While NCKRI now manages this conference, the Organizing Committee of distinguished karst engineers and scientists from around the USA remains intact. The success of this meeting is the result of their fabulous work.

This year's Sinkhole Conference offers an excellent series of papers, thought-provoking keynote addresses, a fascinating and fun field trip, and ample time for you to meet new and old friends to discuss and collaborate on karst engineering and environmental research projects. Don't forget to visit the booths of our generous exhibitors and sponsors and support them for supporting the Sinkhole Conference! If you have any questions or concerns about the meeting, please tell us directly or leave a message at the registration desk and we will address them as soon as possible. We look forward to visiting with you soon.

Sincerely,

George Veni
Conference Co-chairman
Executive Director
National Cave & Karst Research Institute

James W. LaMoreaux
Conference Co-chairman
President
P.E. LaMoreaux and Associates

History of Conference

The First Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst was held in Orlando, Florida, October 15-17, 1984. Subsequently, a second and third conference was held under the sponsorship of the Florida Sinkhole Research Institute, a division of the University of Central Florida in Orlando, in 1987 and 1989. These conferences were established to meet a critical need for applied research information on the very complex hydrogeological environment of karst areas of the world.

In 1992, Dr. Barry F. Beck, the former director of the Florida Sinkhole Research Institute, joined the staff of P.E. LaMoreaux & Associates, Inc. (PELA) and opened the company's Oak Ridge, Tennessee office. Beginning with the Fourth Multidisciplinary Conference in 1993, PELA sponsored the continuation of this important series of conferences along with many other distinguished organizations. The Geo-Institute of the American Society of Civil Engineers took the lead in sponsoring the conference in 2003, 2005, and 2008 after which PELA took over the sponsorship again for the 2011 conference. Since the 2011 conference, this conference series has come under the management of the National Cave and Karst Research Institute (NCKRI). As a government-established non-profit organization, NCKRI is focused on karst phenomena and organized in part to conduct and support such conferences; PE LaMoreaux & Associates, Inc., as cosponsor, and the Organizing Committee remain an integral part of the conference.

The proceedings of these conferences have been valuable additions to karst libraries around the world. Below is a list of the proceedings from the beginning conference to 2011 which details the topics covered and the sponsors of each:

Previous Conferences and Proceedings

(1st, 1984, Orlando, FL)
Sinkholes: Their Geology, Engineering and Environmental Impact
Proceedings of the First Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Orlando, Florida, October 15-17, 1984, Edited by Barry F. Beck; Sponsored by Florida Sinkhole Research Institute, College of Engineering, University of Central Florida.

(2nd, 1987, Orlando, FL)
Karst Hydrogeology: Engineering and Environmental Applications
Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Orlando, Florida, Feb. 9-11, 1987; Edited by Barry F. Beck & William L. Wilson, Assisted by Laura Feldman, Shannon Joyce, Kathy McDonald & Sharron Mikesell; Sponsored by Florida Sinkhole Research Institute, College of Engineering, Univ. of Central Florida.

(3rd, 1989, St. Petersburg Beach, FL)
Engineering and Environmental Impacts of Sinkholes and Karst
Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, St. Petersburg Beach, Florida October 2-4, 1989 Edited by Barry F. Beck, Assisted by Adrianne Hagen, Scott Cavin, Brian Barfus & Virginia Merkle; Sponsored by Florida Sinkhole Research Institute, Division of Sponsored Research, and University of Central Florida.

(4^{th}, 1993, Panama City, FL)
Applied Karst Geology
Proceedings of the Fourth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Panama City, Florida, January 25-27, 1993; Edited by Barry F. Beck; Sponsored by University of Central Florida, Division of Sponsored Research, and P.E. LaMoreaux & Associates, Inc.

(5^{th}, 1995, Gatlinburg, TN)
Karst GeoHazards: Engineering and Environmental Problems in Karst Terranes
Proceedings of the Fifth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Gatlinburg, Tennessee, April 2-5, 1995; Edited by Barry F. Beck, Assisted by Felicity M. Pearson; Sponsored by P.E. LaMoreaux & Associates, Inc., National Ground Water Association, American Society of Civil Engineers (Tennessee Section); University of Tennessee Institute for Geotechnology, and Karst Waters Institute.

(6^{th}, 1997, Springfield, MO)
The Engineering Geology and Hydrogeology of Karst Terranes
Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Springfield, Missouri, April 6-9, 1997; Edited by Barry F. Beck & J. Brad Stephenson, Assisted by J. Gayle Herring; Sponsored by P.E. LaMoreaux & Associates, Inc., Southwest Missouri State University, Department of Geography, Geology & Planning, American Society of Civil Engineers, Mid-Missouri and St. Louis Sections, National Ground Water Association, Association of Ground Water Scientists and Engineers, Association of Engineering Geologists, and Karst Waters Institute.

(7^{th}, 1999, Harrisburg/Hershey, PA)
Hydrogeology and Engineering Geology of Sinkholes and Karst—1999
Proceedings of the Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Harrisburg/Hershey, Pennsylvania, April 10-14, 1999; Edited by Barry F. Beck, Arthur J. Pettit, and J. Gayle Herring; Sponsored by P.E. LaMoreaux & Associates, Inc., U.S. Department of Transportation,, Federal Highway Administration, U.S. Environmental Protection Agency, Pennsylvania Geological Survey, Geo-Institute of the American Society of Civil Engineers, Association of Engineering Geologists, National Ground Water Association, Virginia Water Resources Research Institute, Mid-Atlantic Karst Consortium, and Karst Waters Institute.

(8^{th}, 2001, Louisville, KY)
Geotechnical and Environmental Applications of Karst Geology and Hydrology—2001
Proceedings of the Eighth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Louisville, Kentucky, April 1-4, 2001; Edited by Barry F. Beck and J. Gayle Herring; Sponsored by P.E. LaMoreaux & Associates, Inc., Geo-Institute of the American Society of Civil Engineers, Association of Ground Water Scientists and Engineers of the National Ground Water Association.

(9^{th}, 2003, Huntsville, AL)
Geotechnical Special Publication No. 122
Proceedings of the Ninth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Huntsville, Alabama, Sept 6-10, 2003; Edited by Barry F. Beck; Sponsored by, Geo-Institute of the American Society of Civil Engineers, The National Ground Water Association, and P.E. LaMoreaux & Associates, Inc.

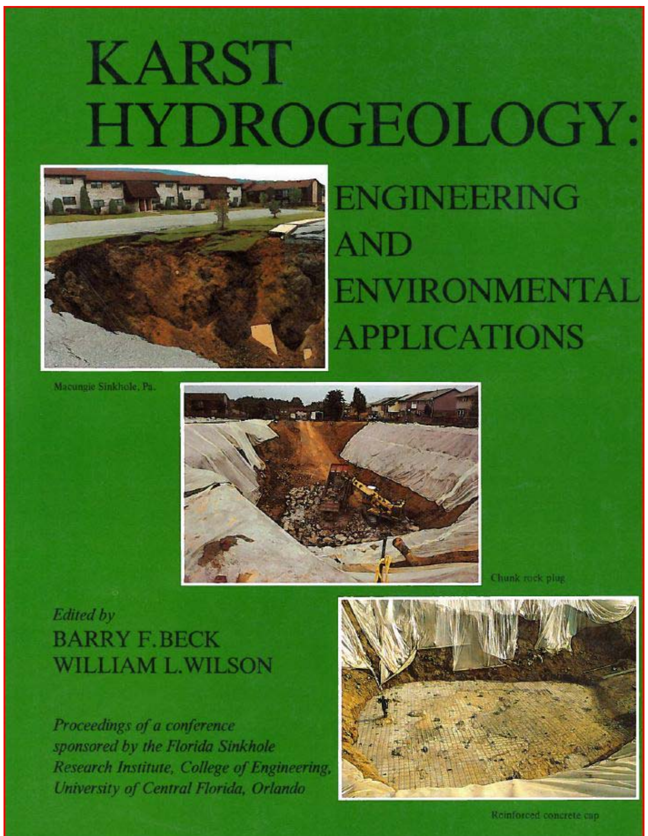
(10^{th}, 2005, San Antonio, TX)
Geotechnical Special Publication No. 144
Proceedings of the Tenth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, San Antonio, Texas, Sept 24-28, 2005; Edited by Barry F. Beck; Sponsored by, Geo-Institute of the American Society of Civil Engineers, The Edwards Aquifer Authority, P.E. LaMoreaux & Associates, Inc., Co-Sponsored by The Southwest Research Institute.

(11th, 2008, Tallahassee, FL)
Geotechnical Special Publication No. 183

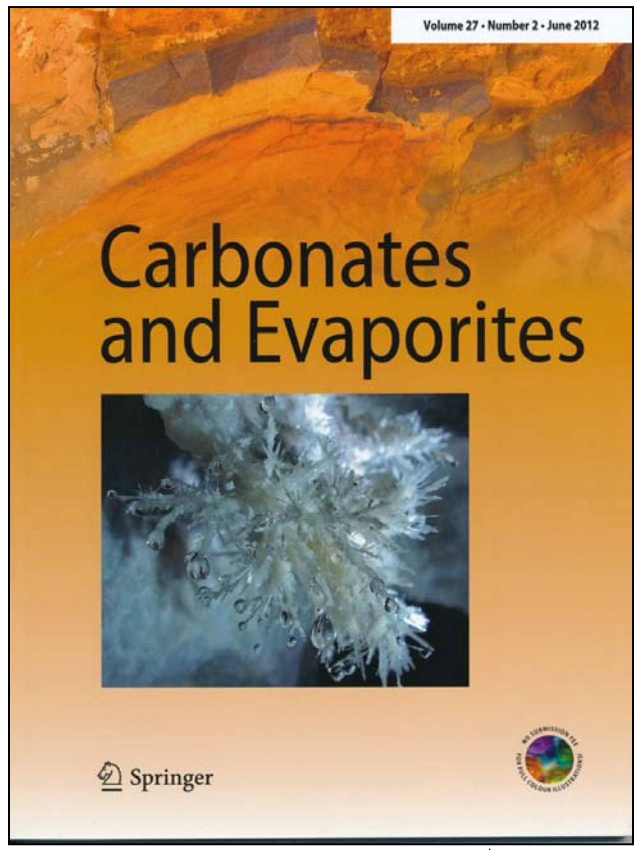
Proceedings of the Eleventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tallahassee, Florida, Sept 22-26, 2008; Edited by Lynn B. Yuhr, E. Calvin Alexander, Barry F. Beck; Sponsored by Geo-Institute of the American Society of Civil Engineers.

(12th, 2011, St. Louis, MO)
***Carbonates and Evaporites* volume 27, nos. 2-3**

Proceedings of the Twelfth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, St. Louis, Missouri, January 10-14, 2011; Edited by Lynn Yuhr and James Kaufman; Sponsored by P.E. LaMoreaux and Associates.



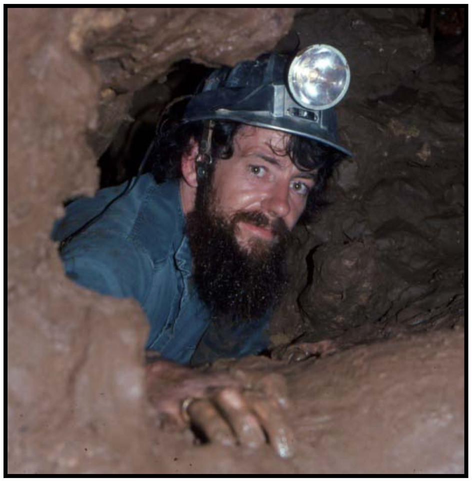
Cover from the Proceedings of the 2nd conference.



Cover from the Proceedings Part 1 of the 12th conference.

In Memory of Dr. Barry F. Beck, PhD, CPG

October 18, 1944 - November 28, 2011



This series of Multidisciplinary Conferences on Sinkholes and the Engineering and Environmental Impacts of Karst was founded in 1984 by Dr. Barry F. Beck, who was then Director of the Florida Sinkhole Research Institute at the University of Central Florida in Orlando. Barry continued to organize and lead this conference series while serving as Vice-President for Karst and Chief of Operations for the Oak Ridge, Tennessee, office of P.E. LaMoreaux & Associates, Inc. (PELA).

Barry was the primary force behind the first 11 "sinkhole conferences". In 2009, a stroke interrupted his planning for the 12th conference in January 2011, and medical complications from that stroke ultimately claimed his life in November 2011. As part of the 13th conference, a special memorial session will be held on Wednesday, May 8 at 5:00 pm that will include technical presentations about some of Barry's karst studies and remembrances by those that knew and worked with Barry.

This memorial page celebrates Barry's life and the legacy he left for those who live and work in karst. It also introduces him to those who never had the pleasure to know him. The Barry F. Beck Sinkhole Conference Student Scholarship has been established in his memory.

The following obituary appeared in the August 2012 issue of the NSS News and is reprinted here with permission.

Dr. Barry F. Beck passed away at the age of 67, following a series of severe blood disorders and a brain stem stroke. The stroke in 2009 left him debilitated with "Locked-in Syndrome."

Born in Hershey, Pennsylvania, Barry was raised by his parents, Daniel and Verna Beck, in an economically challenged neighborhood in Rochester, New York. He earned a Bachelor's degree in geology at Rensselaer Polytechnic Institute, followed by Master's and PhD degrees in geology from Rice University, Texas. His thesis and dissertation focused on the caves and karst of central Texas.

The beginnings of Barry's interest in caves and karst are uncertain, but that interest grew during his time at Rice University in the late 1960s. He was an advisor to a Boy Scout Explorer Post from the Houston area and led them on caving trips in Texas, Mexico, and other areas. In July 1969, Barry joined the National Speleological Society (NSS) and the Texas Speleological Association, where he served as chairman in 1971. He was instrumental in founding the short-lived Rice University Grotto and was a member of the Texas caving organization known as Carta Valley S.U.C.K.S. (Society of Underground Cavers, Karstologists and Speleologists). Foreshadowing events to come, Texas cavers bestowed Barry with the nickname "Rain God" because his participation in numerous caving trips seemed to invite heavy rain and associated challenges. During one expedition, several vehicles were washed from a campsite and nearly floated down the Colorado River, after which he was presented with a high water warning device.

After receiving his PhD in 1972, Barry's interest in caves led him and his family (including first wife Pat and son Erik) to Puerto Rico, where Hans and Jenny were born. In Puerto Rico, Barry worked for the Department of Natural Resources, conducting investigations in tropical karst and assessing the commercial potential of the Aguas Buenas Caves. He was active in the study and exploration of the Rio Camuy Cave system and studied the sea-margin caves on Isla Mona. Barry also hosted numerous expeditions for cavers exploring Puerto Rico and provided lodging (sofas and floors at his house) and transportation. Barry played a significant role in the attempt to rescue Francis McKinney, who fell 75 feet to his death while climbing from a pit in the Rio Camuy Cave System in 1975.

In 1976, Barry joined the Georgia Department of Natural Resources in Atlanta, where he applied electrical resistivity geophysical techniques to the detection of caves and other karst features. Subsequently, he moved to Americus, Georgia where he taught geology, hydrology, and geomorphology at Georgia Southwestern College (now known as Georgia Southwestern State University). He also met Dr. Penny Lukin, who would become his second wife and the love of his life, and had two more children, Daniel and Sonja.

During the late 1970s and early 1980s, Barry served as a review/associate editor for the NSS News and exploration editor for the NSS Bulletin. He was selected as a Fellow of the NSS in August 1977. Barry authored *An Introduction to Caves and Cave Exploring in Georgia* in 1980 and edited the proceedings of the Eighth International Congress of Speleology in 1981.

In 1981, Barry became the first and only director of the Florida Sinkhole Research Institute at the University of Central Florida in Orlando. In that capacity, Barry applied his research to the geotechnical and environmental issues associated with sinkhole collapse, land subsidence, and karst groundwater flow. In 1984, he organized the first in a series of Multidisciplinary Conferences on Sinkholes and the Engineering and Environmental Impacts of Karst. The first four "sinkhole conferences" were held in Florida.

In 1992, Barry joined P.E. LaMoreaux & Associates, Inc. (PELA), where he served as Chief of Operations for the Oak Ridge office and Vice-President for Karst. He managed a variety of sinkhole and karst consulting/research projects throughout the U.S. and around the world. He authored or coauthored numerous technical papers and articles on karst topics. With significant support from PELA, he continued to direct the sinkhole conferences, edit the proceedings, and host the meetings in karst regions around the U.S. Barry was the primary force behind the first 11 "sinkhole conferences". His stroke interrupted his planning for the 12th conference, which was held in St. Louis in 2011. The National Cave and Karst Research Institute (NCKRI) is taking the lead to continue Barry's legacy, hosting the 13th conference in Carlsbad, New Mexico during May 2013.

Barry was a member of the East Tennessee Grotto and explored caves in east Tennessee, as well as those associated with his project work around the world. In 2004, the NSS presented Barry with an Honorary Membership for his lifetime of contributions to the study of speleology and karst.

In addition to his professional endeavors, Barry was a loving father to Erik, Jenny, Hans, Sonja, and Daniel. He was an active, energetic, and passionate individual, biking or running almost daily. He was also an avid hiker and tennis player. Barry and Penny shared a passion for dancing, specifically clogging and various forms of folk dancing. At one time, Barry served as President of the Muckalee Mudstompers, a clogging group in Americus, Georgia. Barry loved to explore the world through travel, visiting karst regions in China, Guam, Italy, eastern Europe, Russia, Kuwait, and Argentina.

In 2010, the Weather Channel devoted an episode of "Storm Stories" to an incident in which Barry lived up to his "Rain God" nickname during a March 1979 trip to Anderson Spring Cave in Walker County, Georgia. Barry and six of his students from Georgia Southwestern spent 28 hours trapped underground when heavy precipitation caused flash flooding that completely submerged the cave's only entrance. Interviews shown in that documentary were recorded just days before the stroke that would trap Barry in his own body for the final two years of his life.

Barry leaves behind family, friends, and associates that will miss him and remember him fondly. His contributions to caves and karst will continue.

Memorial contributions may be made to the Nature Conservancy and earmarked for the Barry Beck Memorial Fund (http://tinyurl.com/barrybeck), which is designated for preservation of karst areas and research on caves and sinkholes. Memorial contributions to the Barry F. Beck Sinkhole Conference Student Scholarship (https://sites.google.com/site/sinkholeconference2013) will support the participation and professional development of at least one student at each conference.

Art Pettit, NSS #18565RL
J. Brad Stephenson, NSS #22755RL
Dr. Penny Lukin
Jim McLane, NSS #14628RG
Carl Kunath, NSS #6230RE (PH-FE)
Dr. Brian Smith, NSS #15208RE
Dr. Wanfang Zhou

Barry F. Beck Sinkhole Conference Student Scholarship

The Barry F. Beck Sinkhole Student Scholarship (Beck Scholarship) is a competitive grant awarded to one or more students who presents the results of their research at the bi-annual Sinkhole Conference. The award is being inaugurated at this year's conference in memory of the late Dr. Barry Beck, a pioneer in the scientific study of sinkholes who founded the Sinkhole Conference.

At least one Beck Scholarship will be awarded for the conference. Additional scholarships may be awarded if funded from donors for the conference. Beck Scholars receive:

1. One free Sinkhole Conference registration.
2. One free registration to a field trip and short course (pending space availability).
3. An award certificate.
4. Recognition through name badge ribbon, mention in the Sinkhole Conference program and website, and announcements at the opening ceremony and banquet.
5. Reimbursement for up to $1000 of personal individual travel, food, and lodging expenses associated with attending the Sinkhole Conference.

For more information about the Beck Scholarship and to fund future scholars, watch future Sinkhole Conference websites or contact the National Cave and Karst Research Institute at info@nckri.org or by calling 575-887-5518.

Dissolution slumping of the McMillan Escarpment into the McMillan Reservoir. This site was poorly situated on gypsum karst in 1893 and had to be abandoned; it will be visited as part of this conference's Evaporite Karst of the Lower Pecos Valley field trip. Photo by NCKRI.

Barry F. Beck Sinkhole Conference Student Scholarship Recipient

Dr. Marco Vattano, PhD (MSc Student)
Department of Earth and Sea Sciences, University of Palermo, Italy

Marco Vattano was born on 23 December 1973 in Catania (Sicily, Italy), where he grew up and graduated from high school. Then he moved to Palermo, where he began his graduate studies. In Palermo he began his caving activities thanks to a course organized by the Italian Alpine Club in 1996. Marco Vattano graduated with first class honors in 2005 in the Geology and Geodesy Department, Faculty of Science, University of Palermo, Italy. He then earned his Professional Geologist registration. In 2006, he started his PhD in Geology at the University of Palermo and in 2009 he successfully completed his thesis “Geomorphological evolution of evaporite karst areas in South-Central Sicily by relationship analysis between hypogean karst landforms and surface landforms”. Between 2006 and 2007, Marco was supported by a fellowship sponsored by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Palermo, concerning the geochemistry of dissolution waters in gypsum karst systems. In 2009, he won a four-year post-doctoral position funded by the Earth and Sea Sciences Department of the University of Palermo. During this period his research has mainly focused on the understanding of the geomorphologic evolution of karst areas in Sicily. He has been involved with karst and environmental studies in Italy, Spain, Russia, and Mexico. In the future, Marco would like to broaden his knowledge of sinkholes, learning new and more advanced techniques for monitoring, modeling, and prediction of sinkhole formation and development.

Photo courtesy of M. Vattano.

Organizing Committee

General Conference Co-Chairs

- George Veni, Ph.D., P.G., National Cave and Karst Research Institute (NCKRI), Carlsbad, NM
- Jim LaMoreaux, Ph.D., P.E. LaMoreaux & Associates, Inc., Tuscaloosa, AL

Program Co-Chairs

- Lynn B. Yuhr, P.G., Technos, Inc., Miami, FL
- Lewis Land, Ph.D., New Mexico Bureau of Geology & Mineral Resources and National Cave and Karst Research Institute, Carlsbad, New Mexico

Proceedings Managing and Assistant Editors

- Lewis Land, Ph.D., New Mexico Bureau of Geology & Mineral Resources and National Cave and Karst Research Institute, Carlsbad, NM
- Daniel H. Doctor, Ph.D., U.S. Geological Survey, Eastern Geology & Paleoclimate Science Center, Reston, VA
- J. Brad Stephenson, P.G., L.R.S., CB&I, Knoxville, TN

Field Trips

Lewis Land, Ph.D., New Mexico Bureau of Geology & Mineral Resources and National Cave and Karst Research Institute, Carlsbad, NM

Short Courses

E. Calvin Alexander, Jr., Ph.D., Department of Earth Sciences, University of Minnesota, Minneapolis, MN

Invited Speakers

Yongli Gao, Ph.D., University of Texas-San Antonio, San Antonio, TX

Beck Scholarship

- E. Calvin Alexander, Jr. Ph.D., Department of Earth Sciences, University of Minnesota, Minneapolis, MN
- Dianne Joop, National Cave and Karst Research Institute, Carlsbad, NM
- Ira D. Sasowsky, Ph.D., P.G., Geosciences, University of Akron, Akron, OH

Beck Memorial

- Jim LaMoreaux, Ph.D., P.E. LaMoreaux & Associates, Inc., Tuscaloosa, AL
- Dianne Joop, National Cave and Karst Research Institute, Carlsbad, NM
- Brian Smith, Ph.D., Barton Springs/Edwards Aquifer Conservation District, Austin, TX
- J. Brad Stephenson, P.G., L.R.S., CB&I, Knoxville, TN

Conference Management

- Dianne Joop, National Cave and Karst Research Institute, Carlsbad, NM
- Debbie Herr, National Cave and Karst Research Institute, Carlsbad, NM
- Suzanna Langowski, National Cave and Karst Research Institute, Carlsbad, NM

Circulars and Publicity

- Samuel V. Panno, CGWP, Illinois State Geological Survey, Prairie Research Institute, University of Illinois, Champaign, IL
- Harry L. Moore, P.G., Golder Associates, Atlanta, GA

Program with Abstracts

- Brian Smith, Ph.D., Barton Springs/Edwards Aquifer Conservation District, Austin, TX
- Brian Hunt, Barton Springs/Edwards Aquifer Conservation District, Austin, TX

Website

- Dianne Joop, National Cave and Karst Research Institute, Carlsbad, NM
- Gheorghe Ponta, P.G., P.E. LaMoreaux and Associates, Tuscaloosa, AL

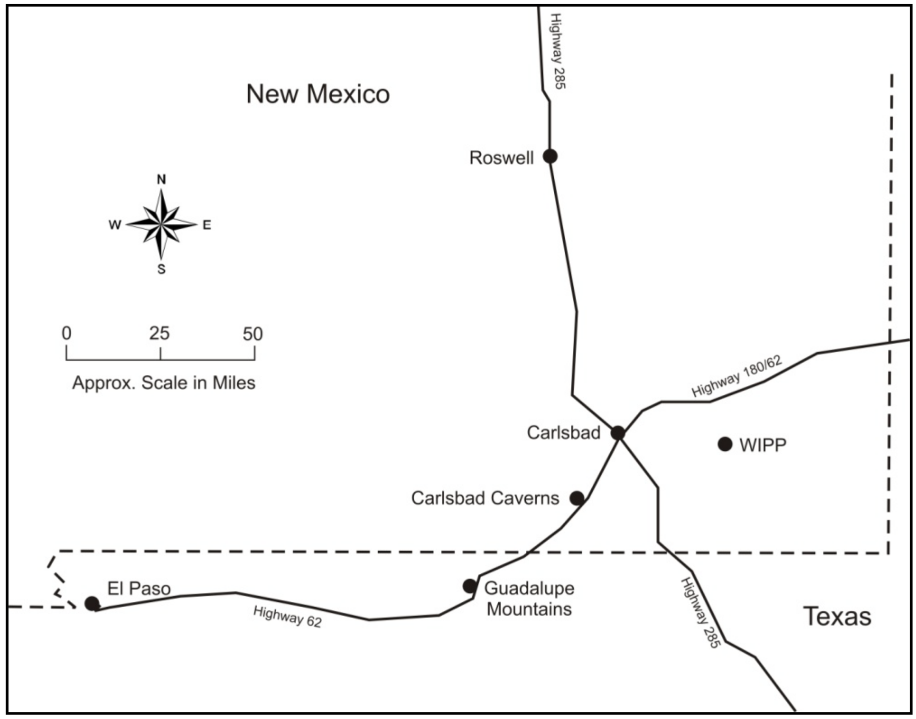
Session Chairs

- Engineering and Geotechnical Aspects of Karst - Joe Fischer, Ph.D., P.E., Geoscience Services, Clinton, NJ
- Evaporite Karst - Ken Johnson, Oklahoma Geological Survey, Norman, OK
- Geophysical Exploration in Karst Terrane - Mustafa Saribudak, Ph.D., P.G., Environmental Geophysics Associates, Austin, TX
- Formation Processes of Karst and Sinkholes - Harry L. Moore, Golder Associates, Atlanta, GA
- Hydrological Aspects of Karst - Geary Schindel, P.G., Edwards Aquifer Authority, San Antonio, TX
- Mapping and Management of Karst Regions - Samuel V. Panno, CGWP, Illinois State Geological Survey, Prairie Research Institute, University of Illinois, Champaign, IL

Session Subcommittees

- Tony Cooley, P.E., P.G., EEC-DEP Division of Waste Management, Solid Waste Branch, Closure Section, Frankfort, KY
- Jeff Schaumburg, P.E., Dynamic Earth, Chester, NJ
- Dave Weary, National Cooperative Geologic Mapping Program, U.S. Geological Survey, Reston, VA
- Phil Carpenter, Ph.D., Dept. of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL
- Thomas L. Dobecki, Ph.D., P.G., SDII Global Corporation, Tampa, FL
- Bruce Smith, U.S. Geological Survey, Denver Federal Center, Denver, CO

Host City: Carlsbad, New Mexico

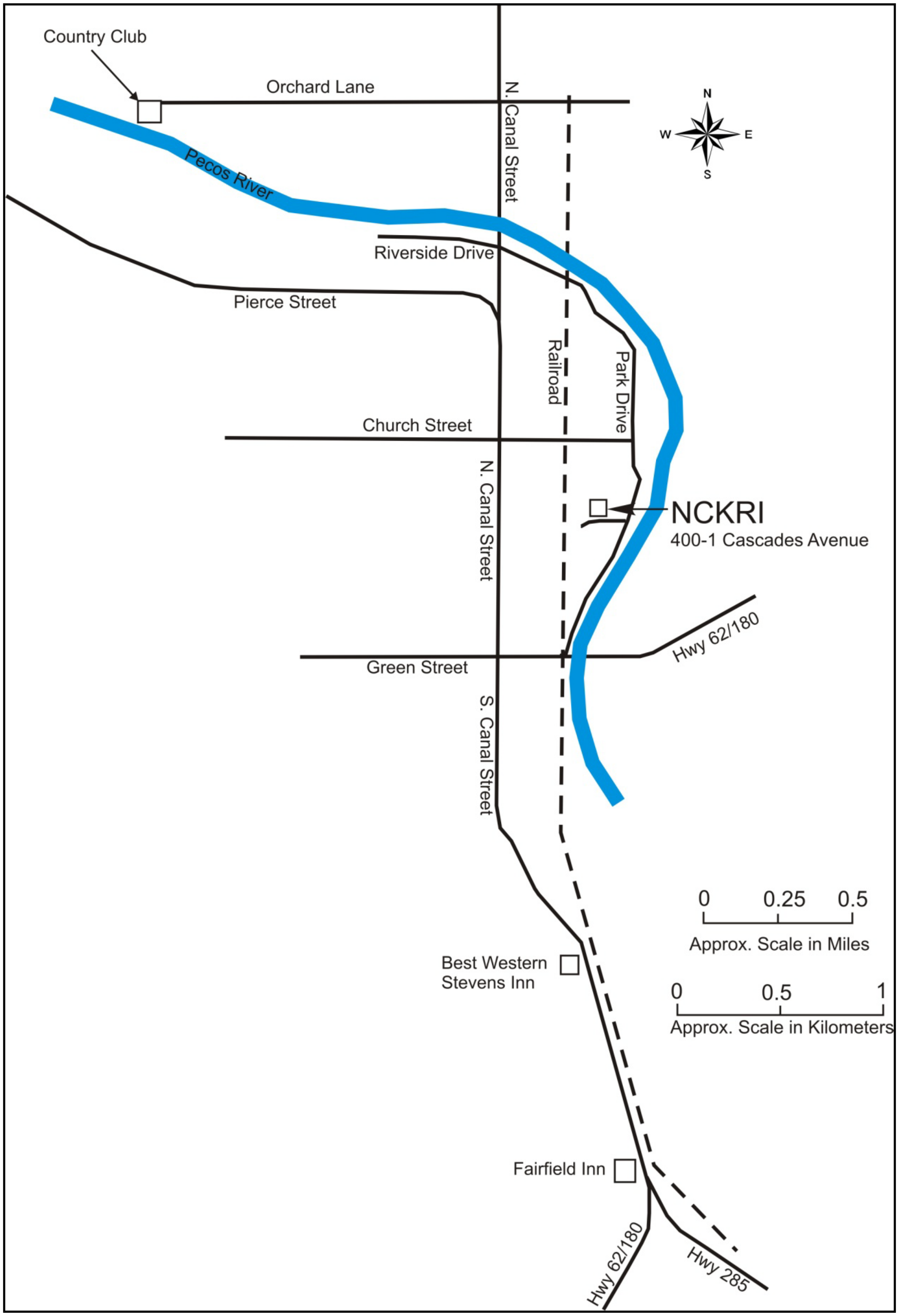


Carlsbad is a small but friendly community in southeastern New Mexico, with a population of about 30,000 people. The town was founded in the late 1800s by ranchers from west Texas, along a reach of the Pecos River where flow is supplied in part by karst springs in the bed of the river. The major industries in Carlsbad include tourism, potash mining (southeastern New Mexico contains the United States' largest known concentration of potash reserves), oil and gas production, agriculture, and activities associated with the Waste Isolation Pilot Plant (WIPP), a disposal facility for defense-related transuranic radioactive waste.

During the time of the conference, daytime high temperatures are likely to range between 80-95 °F (27-35 °C) with overnight lows of 50-70 °F (10-21 °C). Rain is unlikely but expect possible strong winds.

Among people interested in caves and karst, "Carlsbad" is synonymous with "Carlsbad Caverns National Park," located only 30 minutes by car to the southwest along Highway 62/180. Another 30 minutes farther and into Texas is Guadalupe Mountains National Park. These parks offer world-class views of middle Permian geology and hypogenic karst. Highway 62/180 traverses a striking and unique gypsum karst terrane that includes Parks Ranch Cave, the second-longest gypsum cave in the United States.

In downtown Carlsbad is the Carlsbad Museum and Art Center, which has an interesting exhibit on the region's history and often hosts excellent special or traveling exhibits. At the city's north end is the Living Desert State Park and Zoo, a beautifully developed display of flora and fauna of the desert southwest region of the U.S. About an hour's drive farther north, and especially if you fly in via Roswell, a visit to the International UFO Museum and Research Center is always entertaining.



Generalized map of Carlsbad and locations of Sinkhole Conference venues.

Conference Location:

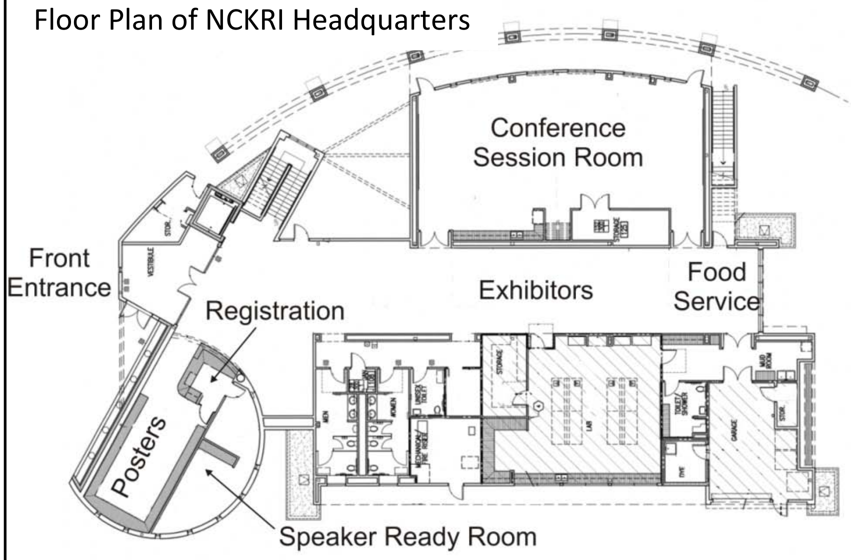
National Cave and Karst Research Institute (NCKRI)
400-1 Cascades Avenue
Carlsbad, New Mexico, 88220-6215 USA
http://www.nckri.org
Tel: 00.1.575.887.5518

NCKRI Headquarters is located near the center of Carlsbad along the Pecos River. It is part of a new social and retail center for Carlsbad that is currently under construction and is expected to be completed in 2-4 years. Construction of NCKRI is also on-going, but not during the conference, with plans underway to fill the main hall and lobby with interactive museum exhibits.

Conference sessions and most events, including three of the short courses, will be located on the ground floor. One workshop will be held upstairs. General conference information and pick-up of information is located just inside the lobby at the entrance to the future bookstore area. The poster sessions will be held in the future bookstore. For on-site registration and information if the ground floor desk is not occupied, please go upstairs to the office reception desk.

Amenities at NCKRI Headquarters include free wireless Internet (no password needed), a Speakers' Ready Room in the office behind the ground floor registration desk if you need a quiet space to review your presentation, bottled water and soft drinks in the refrigerator in the conference room, and hot drinks and snacks in the main hallway. NCKRI is also proud to host the conference in its environmentally-friendly facility. For details, ask any NCKRI staff member about the water and energy-saving features, as well as the recycled, low-VOC, and sustainability-produced materials.

Floor Plan of NCKRI Headquarters



Field Trips

Waste Isolation Pilot Plant

Monday, May 6, 7:00 am – 1:30 pm and repeated on Thursday, May 9, 7:00 am – 1:30 pm

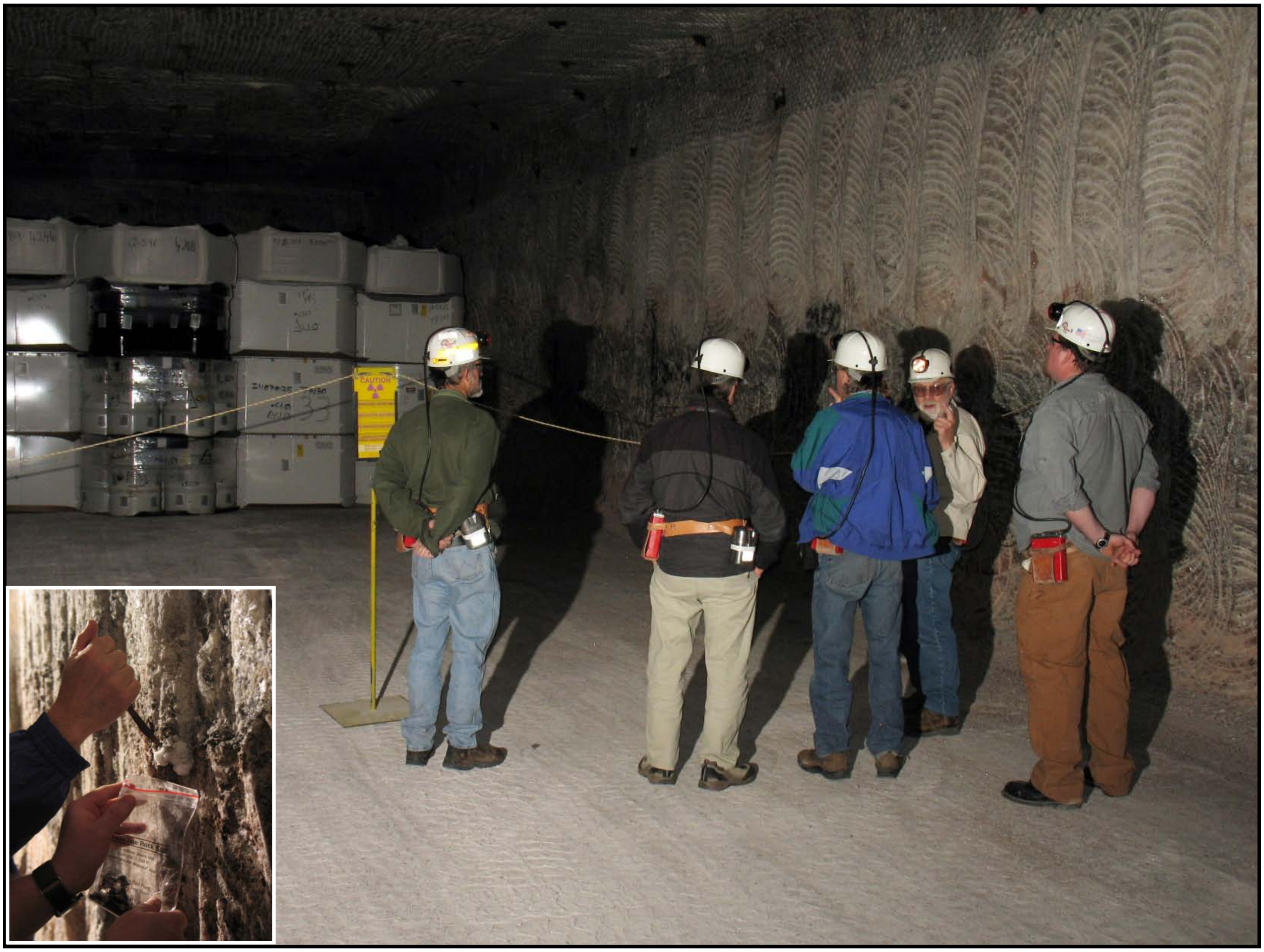
Trip Leaders: WIPP Staff

Assemble at: Stevens Inn 7:00 am; Fairfield Inn 7:15 am. Bus will proceed to Skeen-Whitlock (Department of Energy) Building for orientation and transfer to DOE vans.

On Monday morning, we are offering an underground tour of the Waste Isolation Pilot Plant (WIPP) east of Carlsbad for 10 people maximum for the Monday trip and 20 people maximum for the Thursday trip. The Waste Isolation Pilot Plant is currently the nation's only repository for permanent disposal of defense-related transuranic radioactive waste. A shuttle will provide transport to the WIPP site in eastern Eddy Co., where attendees will have the unique opportunity to tour the site both on the surface and 650 meters below ground level (generally public tours of WIPP are not available). This half-day activity will include a guided tour of surface operations, followed by an underground tour of the repository rooms, which have been excavated in bedded salt of the upper Permian Salado Formation. Attendees may collect hand samples of halite from the drifts at no charge. Lunch is available for purchase in the WIPP cafeteria after the underground tour.

The Salado was chosen as the host formation for WIPP because salt deforms in a ductile manner under high confining pressure. After the waste is deposited in the repository rooms, the salt will eventually (after a few years to decades) flow and envelop the canisters, crushing them and entombing the stored waste. The impermeable nature of rock salt prevents waste from leaking out of the repository and contaminating surface or groundwater resources. Abundant surface karst features are developed in the overlying Rustler Formation a few kilometers west of the WIPP site. Extensive research by Sandia National Lab and the Department of Energy indicates that a connection between these surface features and the WIPP repository is unlikely.

Note that for foreign nationals to attend they must have completed and submitted an Unclassified Foreign Visitor form no later than 15 March 2013, and provide a copy of their passport or visa and a photo ID when they arrive.



Geologists and engineers discuss permanent storage of transuranic waste (in the containers in the background) in deeply buried salt at WIPP. (Inset photo) Visitors at WIPP are welcome to collect their own samples of Permian age salt from the walls of the storage facility. Photos by NCKRI.

Evaporite Karst of the Lower Pecos Valley

Tuesday, May 7, 7:00 am – 5:30 pm
Trip Leader: Lewis Land

Assemble at Stevens Inn, 6:45 – 7:15 am; bus departs promptly at 7:15. Assemble and board bus at Fairfield Inn, 7:20 - 7:30 am; bus departs promptly at 7:30 am.

On Tuesday we offer a full-day surface tour of sinkholes and other gypsum karst features of the Lower Pecos Valley between Carlsbad and Roswell, NM. Evaporite karst processes have played a fundamental role in shaping the geomorphology of the lower Pecos region and controlling groundwater flow patterns. This trip will focus on engineering and environmental hazards associated with gypsum karst, including the formation of anthropogenic sinkholes associated with brine well operations, and the role of evaporites as confining beds in the Roswell Artesian Basin. The trip will end at Bottomless Lakes State Park east of Roswell, where giant gypsum cenotes serve as groundwater discharge outlets at the downstream end of the regional artesian aquifer system in the Roswell Basin. Box lunch provided. Hats, sunglasses, sunscreen, and sturdy shoes are advised.

Loco Hills Sinkhole during its initial collapse before swallowing some of the adjacent storage ponds. This sinkhole was later filled and the site will be visited during the Evaporite Karst field trip. Photo by NCKRI.

Walking Tour of Carlsbad Caverns Big Room

Friday, May 10, 12:30 – 5:30 pm

Trip Leader: George Veni

Buses depart from NCKRI at 12:30 pm.

On Friday afternoon we are offering a walking tour of the Big Room in Carlsbad Caverns, a classic example of hypogenic-sulfuric acid speleogenesis. A shuttle will depart from the conference center at 12:30 pm. Lunch will be available for purchase at the Carlsbad Caverns visitors center, and the tour will begin after lunch at 2:00 pm. Return to NCKRI will be at 5:30 pm. Access will be via elevator into the Big Room 230 m below ground level. Carlsbad Caverns is generally considered to be one of the most spectacularly-decorated large caves on earth, and is a UNESCO-designated World Heritage Site. The cave is developed in the middle Permian Capitan Reef Formation and associated backreef carbonates. Primary sedimentary structures associated with the Capitan Reef are still visible in the Big Room. A complete circuit of the Big Room will take about 2.5 hours on paved trails. The park provides in-cave artificial lighting, but the cave experience is greatly enhanced when visitors also bring their own light source.

Carlsbad Caverns natural entrance, National Park Service photo by Peter Jones.

Short Courses

Monday, May 6, 2013

Grouting in Karst Terrane

Instructors:
Joseph A. Fischer, P.E., Geoscience Services
Matt VanRensler, P.E., Compaction Grouting Services

Location: NCKRI Conference Room A

Course length: 4 hours (8:30am to 12:30pm)

In the U.S., the term karst terrane describes landscapes formed through the dissolution of carbonates at or near the surface. Thus, karst terrane mineral composition and structural conditions vary greatly, making environmental hazards challenging remediation scenarios. This short course focuses on grouting alternatives in karst terrane remediation. Participants will receive an overview of the characteristics of various subsurface conditions in relation to their impact on remediation alternatives and a review of various grouting techniques, materials, and equipment types. Instructors will present various grouting techniques including, grouting with high mobility grout, compaction grouting with low mobility grout, and the advantages of onsite mixing. Participants will gain insight to the advantages and disadvantages of grouting and drilling methods, as well as the pros and cons of various techniques from the prospective of both the grouting contractor and the geotechnical engineer. Participants will also gain an understanding for establishing grouting programs, preparing specifications, estimating drilling / grout requirements, and evaluating results.

Hydrophysics—Logging Wells in Karst

Using Advanced Borehole Geophysical and Hydrophysical Methods to Vastly Improve Groundwater Quality and Supply Investigations.

Instructor: William Pedler, President of RAS, Integrated Subsurface Evaluation

Location: NCKRI Conference Room A

Course length: 4 hours (1:00pm – 5:00pm)

Accurately characterizing heterogeneous aquifers - specifically the water bearing intervals - can be extremely challenging. However, despite these challenges, advanced methods for characterizing subsurface flow have been developed and are being applied on a routine basis in a wide variety of aquifer and borehole settings. Integration of traditional borehole geophysical methods, borehole image logs (acoustic and optical), hydrophysical logs, and hydrogeologic methods (single or straddle wireline packer systems) can provide a detailed understanding of the geology, structure, vertical hydraulic gradient and vertical distribution of water quality associated with the active water bearing units.

Important applications for integration of these methods include characterization studies associated with contaminated sites (RIFS); wellhead protection; water supply impacts related to resource development; and improved management of groundwater in relation to municipal, industrial and agricultural activities. These data have also been used in the development of defensible groundwater and aquifer monitoring programs.

Students will learn when and how to apply methods to improve the understanding of subsurface flow in karst hydrogeologic settings. The discussion will include a several case studies.

Environmental Investigations and Management of Karst Terranes

Instructors:
Geary M. Schindel, P.G., Chief Technical Officer, Edwards Aquifer Authority, San Antonio, Texas
E. Calvin Alexander, Jr., Ph.D., Professor of Earth Sciences, University of Minnesota, Minneapolis, Minnesota

Location: NCKRI Conference Room B

Course length: 7 hours (8:30am – 4:30pm)

Karst aquifers are self-organizing triple permeability systems. Karst aquifers present difficult problems for resource management, environmental protection, and site investigation efforts. This course emphasizes applied techniques for investigating environmental problems in karst. Participants will gain an understanding for the design and implementation of source water protection programs, hazardous materials release, emergency response, as well as spatial / temporal design and evaluation of groundwater monitoring systems. Instructors will discuss various systems including sentinel water quality parameters and monitoring equipment and techniques. Participants will gain insight on the application of surface and borehole geophysics, tracer testing, well construction techniques, and best management practices for urbanization of karst terranes. Instructors will use case histories from karst aquifers across the U.S. as learning models.

Electrical Resistivity Methods as a Tool for Investigations of Karst Phenomena

Instructors:
Lewis Land, Ph. D., Karst Hydrologist, New Mexico Bureau of Geology, and National Cave and Karst Research Institute

Location: NCKRI Board Room (second floor) and in the field

Course length: 7 hours (8:30 am – 4:30 pm)

This course will provide a one-day overview of the electrical resistivity method as applied to investigations of surface and subsurface karst phenomena. A morning classroom session will briefly describe theory and practice of the electrical resistivity method and its relationship to other geophysical techniques. The classroom session will be followed by a trip to the field south of Carlsbad, where students will assist in deployment of an AGI Supersting™ array over a known gypsum cave passage. Students will have an opportunity to enter the cave while in the field. When the survey is complete the class will return to NCKRI offices and participate in downloading and processing the data for final analysis.

Lewis Land conducting electrical resistivity survey of the I&W brine well cavity in Carlsbad; Stop 1 of the Evaporite Karst field trip. Photo by NCKRI.

Program at-a-Glance

Time	Monday May 6, 2013	Tuesday May 7, 2013	Wednesday May 8, 2013	Thursday May 9, 2013	Friday May 10, 2013
7:30-8:00	**WIPP Tour (7:30am-2:00pm)**; Registration Opens (7:30am)	**Evaporite Karst Field Trip (7:15am -6:00pm)**	Registration Opens (7:30am)	Registration Opens (7:30am); **WIPP Tour (7:30am-2:00pm)**	Registration Opens (7:30am)
8:00-8:30	**Short Courses (8:30am-12:30pm)**		**Engineering Keynote: Garasic** **Plenary Session (8:15am - 12:10pm)**	**Karst Formation Keynote: Parise** **Plenary Session (8:15am - 12:00pm)**	**Plenary Session (8:15 - 11:20am)**
8:30-9:00					
9:00-9:30					
9:30-10:00					
10:00-10:30					
10:30-11:00					
11:00-11:30					
11:30-12:00					
12:00-12:30			Catered Lunch (12:10 - 1:30pm)	Catered Lunch (12:00 - 1:30pm)	
12:30-1:00	Lunch On Your Own (12:30 - 1:30pm)				**Carlsbad Caverns Field Trip (12:30 - 5:30)**
1:00-1:30					
1:30-2:00	**Short Courses (1:00-5:00pm)**		**Regional Geology Keynote: DuChene** **Plenary Session (1:30 - 4:50pm)**	**Plenary Session (1:30 - 4:30pm)**	
2:00-2:30					
2:30-3:00					
3:00-3:30					
3:30-4:00					
4:00-4:30					
4:30-5:00					
5:00-5:30			**Beck Memorial/Wine and Cheese reception/Posters-Manned (5:00-7:00pm)**		
5:30-6:00					
6:00-6:30					
6:30-7:00		**Welcome Reception (6:30 - 8:30pm) at Stevens Inn**		**Banquet and Guest Speaker Bill Kochanov (6:30-9:00pm) at Country Club**	
7:00-7:30			**Planning Meeting for 14th Sinkhole Conf (7:00pm)**		
7:30-8:00	**Ken Johnson NCKRI Distinguished Lecture (7:30-9:00pm)**				
8:00-8:30					
8:30-9:00					

Beverage breaks Wednesday at 10:15 am and 3:10 pm, Thursday at 10:00 am and 2:30 pm, Friday at 9:40 am.

Detailed Program

Monday, May 6

7:30am	**Field Trip: Underground tour of Waste Isolation Pilot Plant (WIPP)—6 hours**	
8:30am	**Short courses** Grouting in Karst Terranes - 4 hours Borehole Hydrogeophysics - 4 hours Environmental Management of Karst Terranes - 7 hours Electrical Resistivity Methods - 7 hours	
7:30 PM	**Ken Johnson: NCKRI Distinguished Lecture; Evaporite Karst (open to public)**	**Salt Dissolution and Sinkholes in West Texas and Southeast New Mexico**

Tuesday, May 7

7:30am	**Field trip: Evaporite Karst of the Lower Pecos Valley**
6:30pm	**Welcome reception, Stevens Inn**

Wednesday, May 8

8:15am	**Introductory remarks - George Veni and Jim LaMoreaux (15 minutes)**	
8:30am	**Senator Udall's representative welcoming comments (5 minutes)**	
8:35am	**Keynote Speaker: Engineering Mladen Garašic (40 minutes)**	**Speleological, Hydrogeological and Engineering Geological Challenges of Tunneling in Karst Areas**
Plenary Session: Engineering and Geotechnical Aspects of Karst, Joe Fischer, chair		
9:15am	Robert Denton Jr.	Towards a karst assessment standard practice
9:35am	John Pusey Jr.	Geotechnical case history for sinkhole investigation and stabilization methods along a high pressure petroleum pipeline
9:55am	E. D. Zisman	Problems associated with the use of compaction grout for sinkhole remediation in west-central Florida
10:15am	**Break in exhibit hall (15 minutes)**	
10:30am	William Bangsund	Evaluating karst risk at proposed windpower projects
10:50am	Timothy Siegel	Application of stability charts and reliability concepts for simplified analysis of a void in soil overlying karst bedrock
11:10am	E. D. Zisman	If it's weight of hammer conditions, it must be a sinkhole?
11:30am	Joseph Fischer	Exploratory grouting of a subsurface detention/infiltration system
11:50am	Robert Bachus	An innovative approach to characterizing, permitting, and constructing landfills in karst geologic settings
12:10pm	**LUNCH (1 hour, 20 minutes)**	
1:30pm	**Keynote Speaker: Regional Geology Harvey R. DuChene (40 minutes)**	**Geologic Overview of the Permian basin of Southeastern New Mexico and West Texas**

Plenary Session: Evaporite Karst, Ken Johnson, chair		
2:10pm	Kenneth Johnson	Salt Karst and Collapse Structures in the Anadarko Basin of Oklahoma and Texas
2:30pm	Lewis Land	Evaporite Karst in the Permian Basin Region of West Texas and Southeastern New Mexico: The Human Impact
2:50pm	Kevin Stafford	Evaporite Karst and Hydrogeology of the Castile Formation: Culberson County, Texas and Eddy County, New Mexico
3:10pm	**Break in exhibit hall (20 minutes)**	
3:30pm	Kenneth Johnson	Gypsum Karst Causes Relocation of Proposed Cedar Ridge Dam, Throckmorton County, Texas
3:50pm	Anthony Cooper	The Role of Sulfate-Rich Springs and Groundwater in the Formation of Sinkholes over Gypsum in Eastern England
4:10pm	Kenneth Johnson	Gypsum Karst and Potential Problems in Siting Wind Turbines in Blaine County, Oklahoma
4:30pm	Daniel Doctor	Evaporite Karst in the Black Hills, South Dakota and Wyoming, and the Oil Play in the Williston Basin, North Dakota and Montana
5:00 PM	**Barry Beck Memorial Session (Wine and Cheese reception)**	
5:00pm	Brian Smith	Presentation on Barry Beck's work in Puerto Rico
5:20pm	Harry Moore	Presentation of USDOT karst project that Barry was involved with
5:40pm	Open Forum	
6:30pm	**Manned Poster Session**	
	Brian Conway	Monitoring Evaporite Karst Activity and Land Subsidence in the Holbrook Basin, Arizona using Interferometric Synthetic Aperture Radar (InSAR)
	Brian Hunt	Cover-Collapse Sinkhole Development in the Cretaceous Edwards Limestone, Central Texas
	Fuping Gan	Integrated geophysical methods for groundwater exploration in a karst areas with our without thin cover - a case study from Tai'an city, Shandong Province, China
	Henok Kiflu	Statistical Analysis of GPR and SPT Methods for Sinkhole Investigations in Covered Karst Terrane, West-Central Florida, USA
	Mingtang Lei	Typical methods for forecasting karst collapse in China
	James Neal	Variations in Evaporite Karst in the Holbrook Basin, Arizona
	Kevin Stafford	Clastic sinkhole and pseudokarst development in east Texas
	Melinda Faulkner	Delineation and classification of karst depressions using lidar: Fort Hood Military Installation, Texas
	Michael McGee	Challenges and lessons learned from managing a newly developed catastrophic sinkhole Lake located on multiple use managed public land in the Lower Pecos Valley, NM
	Mina Rahimi	Locating Sinkholes in LiDAR Coverage of a Glacio-fluvial Karst, Winona County, MN

	Ted Smith	Induced Sinkhole Formation Associated with Installation of a High-Pressure Natural Gas Pipeline, West-Central Florida
	Xiaozhen Jiang	Characterization of Karst Collapse Hazard based on groundwater fluctuations in Qingyun, Guigang, Guangxi, China
	Yongli Gao	Investigations of Large Scale Sinkhole Collapses, Laibin, Guangxi, China
	Xiaozhen Jiang	A calibration test of karst collapse monitoring device by Optical Time Domain Reflectometry (BOTDR) technique
7:00pm	**14th Sinkhole Conference Planning Meeting (concurrent with poster session)**	

Thursday, May 9

7:30am	**Underground tour of Waste Isolation Pilot Plant (WIPP)- 6 hours**	
8:15am	**Introductory remarks: George Veni and Jim LaMoreaux (5 minutes)**	
8:20am	**Keynote Speaker: Formation of Sinkholes** **Mario Parise (40 minutes)**	**Natural and Anthropogenic Sinkholes: from Identification, to Surveying, Studying and Modeling a Subtle Hazard**
Plenary Session: Geophysical Exploration in Karst Terrane, Mustafa Saribudak, chair		
9:00am	Marcus Gary	Geophysical investigations of the Edwards-Trinity aquifer system at multiple scales: Interpreting airborne and direct-current resistivity in karst
9:20am	Thomas Dobecki	Subbottom profiling investigation of sinkhole lake structure in Bay and Washington Counties, Florida
9:40am	David Harro	Improved imaging of covered karst with the multi-electrode resistivity implant technique
10:00am	**Break in exhibit hall (20 minutes)**	
10:20am	Michael Rucker	Reconnaissance evaluation of a potential future sinkhole using integrated simple surface geophysics and surface monitoring points
10:40am	Philip Carpenter	Ground-penetrating radar, resistivity and spontaneous potential investigations of a contaminated aquifer near Cancun, Mexico
Plenary Session: Formation Processes of Karst and Sinkholes part 1, Harry Moore, chair		
11:00am	Marco Vattano	Examples of anthropogenic sinkholes in Sicily and comparison with similar phenomena in southern Italy
11:20am	Sam Upchurch	Development of sinkholes in a thickly covered karst terrane
11:40am	Lin Mou	Paleokarst crust of Ordovician limestone and its capability in resisting water inrushes in coal mines of north China
12:00	**Lunch (1 hour 30 minutes)**	
Plenary Session: Formation Processes of Karst and Sinkholes part 2, Harry Moore, chair		
1:30pm	Calvin Alexander	Deep time origins of sinkhole collapse failures in sewage lagoons in southeast Minnesota
1:50pm	Mingtang Lei	Emergency investigation of extremely large sinkholes, Maohe, Guangxi, China
2:10pm	Gheorghe Ponta	Karst landforms in the Saraburi Group limestones, Thailand

2:30pm	**Break in exhibit hall (20 minutes)**	
Plenary Session: Hydrological Aspects of Karst, Geary Schindel, chair		
2:50pm	Arnauld Malard	Mapping flood related hazards in karst using KARSYS approach. Application to the Beuchire-Creugenat karst system (JU, Switzerland)
3:10pm	Jennifer Adkins	Conceptualization of Groundwater Flow in the Edwards Aquifer Through the Knippa Gap Hydrogeologic Constriction, Uvalde County, Texas
3:30pm	Nico Hauwert	Delineation source areas to cave drips and cave streams in Austin Texas, USA
3:50pm	Brian Cowan	Use of physical and chemical response in cave drips to characterize upland recharge in the Barton Springs segment of the Edwards Aquifer, Central Texas, USA
4:10pm	Shiloh Beeman	The Need for Presumptive Habitat Considerations in Working with Subterranean Aquatic Species of Concern: Three Ozark Region Case Histories, U.S.A.
6:30pm	**Banquet: Bill Kochanov, speaker**	**When the Carbonate Plumbing Goes Bad:** **Sinkholes, the Hydra, and the General Public**

Friday, May 10

8:15am	**Introductory remarks - George Veni and Jim LaMoreaux (5 minutes)**	
Plenary Session: Mapping and Management of Karst Regions, Sam Panno, chair		
8:20am	Mario Parise	Populating a chronological catalogue of sinkholes in Italy, as the first step for assessing the sinkhole hazard
8:40am	Mario Parise	Lessons learned from occurrence of sinkhole related to man-made cavities in a town of Southern Italy
9:00am	Kevin Theusen	Restoring Land and Managing Karst to Protect Water Quality and Quantity at Barton Springs, Austin, Texas.
9:20am	Samuel Panno	The use of drought-induced “crop lines” as a tool for characterization of karst terrane
9:40am	**Break in exhibit hall (20 minutes)**	
10:00am	Harry Moore	Mapping surface and subsurface karst geohazards for highway projects: SR 71 South Knoxville Blvd. Extension, Knox County, TN
10:20am	George Veni	Government Canyon State Natural Area: An Emerging Model for Karst Management
10:40am	Scott Alexander	Combining LiDAR, Aerial Photography, and Pictometric Tools for Karst Features Database Management
11:00am	Daniel Doctor and John Young	An evaluation of automated GIS tools for delineating karst sinkholes and closed depressions from 1-m LiDAR-derived digital elevation data
12:30pm	**Buses depart for Carlsbad Caverns field trip** Lunch at Carlsbad Caverns visitors center Airport shuttle departs for El Paso (departure time TBD)	

Invited and Keynote Speakers

Distinguished Lecture: A NCKRI lecture series offered to the general public and Sinkhole Conference attendees

Monday, May 6, 2013, 7:30pm

Salt Dissolution and Sinkholes in West Texas and Southeast New Mexico

Kenneth S. Johnson
Geologist, Norman, Oklahoma

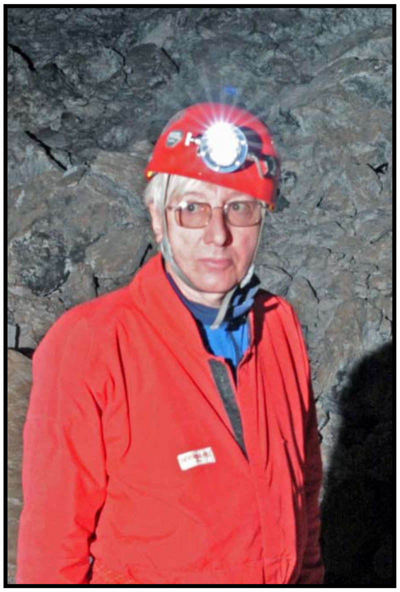
Thick salt deposits have been dissolved intentionally to produce salt-water brines in parts of West Texas and southeast New Mexico, and locally this has created large underground brine-filled cavities. Elsewhere, these salts have been dissolved accidentally during petroleum operations, thus leaving brine-filled cavities similar to those created in brining operations. Since 1980, some of these cavities have collapsed and created large sinkholes near Wink, TX, and the JWS and Loco Hills sinkholes in NM.

Collapse of these earlier cavities has raised concerns about a similar brine cavity in Carlsbad, NM. The I&W brine cavern, located at the "South Y" on the south side of Carlsbad, was ordered closed in 2008 because of its similarity to the JWS and Loco Hills brining operations. A series of geologic and geophysical studies have characterized the probable size, shape, and depth of the underground cavity and the site is now being monitored constantly to provide early warnings in the event of collapse of the cavity.

Biography:

Dr. Kenneth S. Johnson has been studying and characterizing problems related to natural and human-caused dissolution of salt and gypsum through the United States, with special emphasis on occurrences in the southwestern states of Oklahoma, Texas, and New Mexico. Previously, Ken was a research geologist and Associate Director of the Oklahoma Geological Survey at The University of Oklahoma, and now he is a consulting geologist in Norman, Oklahoma. His studies of salt dissolution and resultant collapse features started nearly 50 years ago, and since then he has published about 50 articles and abstracts on these subjects.

Wednesday, May 8, 2013, 8:35am



Speleological, Hydrogeological and Engineering Geological Challenges of Tunneling in Karst Areas

Mladen Garašic
University of Zagreb, Croatia

In the Classical Dinaric Karst of Croatia, over 11,500 caves have been explored so far, more than 1,000 of which were discovered during construction works. Caves discovered on the construction sites of highways lacked natural entrances on the surface. Over the past 20 years they have been systematically investigated and remediated to allow completion of the roads. Some special examples will be presented during the lecture, such as the large hall in the Vrata Tunnel of the Zagreb – Rijeka Highway, and caves in Croatia's longest tunnels. Due to the size, shape, position, and hydrogeological parameters of the cave within the karst system, it was necessary to design and construct a special bridge through the cave in the Vrata Tunnel. The cave's vaulted ceiling had to be reinforced and stabilized. This presentation will include video and photos of the most interesting karst and cave locations in Dinaric Karst.

Biography:

Mladen Garašic, PhD. Geology, Hydrogeology, and Geological Engineering. Born in Zagreb, Croatia, in 1951, Dr. Garašic graduated in geology and karst hydrogeology in 1977, master of science 1981, and doctorate in geosciences and geological engineering in 1986. He is a scientist, and a professor of geology, karst hydrogeology, applied geology, engineering geology and speleology at the University of Zagreb, and has authored more than 330 scientific and professional papers. He serves as a committee member for the Croatian Academy of Science and Arts, UNESCO World Heritage Team for the Dinaric Karst, International Association of Hydrogeologists, and International Association for Engineering Geology and the Environment.

Dr. Garašic started skiing in 1955 and won the Junior Skiing competition of Croatia in 1963. He has been a member of the Croatian Mountaineering Association since 1955 and was awarded by the Association in 1969 and 1981. He started caving in 1963 and is the founder and president of several caving clubs in Croatia. He served as first president of the Croatian Speleological Federation from 1990 to 2010 and is a life member of the U.S. National Speleological Society. Since 1993, he has served as Croatia's delegate to the International Union of Speleology and to the European Speleological Federation beginning in 2009.

Dr. Garašic has conducted research in, and explored and visited nearly 5,000 caves in 64 countries. He has led many speleological expeditions in the longest and deepest caves in Croatia, Europe, and the world. He has also studies about 1,000 caves without natural entrances, discovered by tunnels and quarries, and evaluated their hydrogeology and engineering geology.

Wednesday, May 8, 2013 1:30pm

Geologic Overview of the Permian Basin of Southeastern New Mexico and West Texas

Harvey R. DuChene
Vecta Oil and Gas, LP

Carlsbad, New Mexico is located in the north-central part of the Delaware basin, which is part of the greater Permian basin, one of the richest oil and gas provinces in the world. In Late Mississippian to Early Pennsylvanian time, the collision of South America-Africa with southern North America caused the Ouachita-Marathon orogeny and formed the deep structural basins and uplifts of the ancestral Rocky Mountains. Material eroded from uplifts progressively filled basins during Pennsylvanian and Permian time. Major structural components of the ancestral Rockies in the Permian basin region are the Midland and Delaware basins, separated by the Central Basin platform.

Paleozoic stratigraphy of the region can be divided into two broad packages. Older Paleozoic strata range from Cambrian to Mississippian age and were deposited in an ancestral depression known as the Tobosa basin. These strata are mostly carbonates and are truncated by a major Late Mississippian to Early Pennsylvanian regional unconformity. Strata of Pennsylvanian and Permian age were deposited in basins formed during the Marathon-Ouachita orogeny. The sediments consisted of interbedded, organic-rich shale, sandstone and carbonate deposited in basins rimmed by carbonate shelf margins. Typically, time-equivalent strata of Pennsylvanian and Permian age grade from mixed lithologies in basin centers to carbonate on shelf margins to mixed evaporite and clastic sediments on the basin shelf. Toward the end of Permian time, thick beds of evaporites were deposited atop older carbonate and clastic strata across the region.

Strata in the Permian basin were repeatedly impacted by changes in climate and sea level. Conditions suited to carbonate deposition dominated during times of high sea level with erosion occurring during times when sea level was low. Low stands were conducive to dissolution of carbonate and the development of karst. Many Permian basin oil fields are profoundly impacted by buried karst (“paleokarst”) which, in some cases, enhanced porosity and permeability. More commonly, paleokarst negatively impacted hydrocarbon reservoirs by causing early encroachment of water along fractures, or by occluding matrix porosity and filling fractures with secondary cement resulting in compartmentalization.

Development of the modern landscape began with the onset of Laramide tectonism in Late Cretaceous and Early Tertiary time. Regional compression caused the gradual rise of a north-trending arch that extended from Wyoming to northern Mexico known as the Alvarado Ridge. Uplift culminated approximately 35 ma when structural failure caused by attenuation of the earth’s crust resulted in the opening of the Rio Grande rift along the axis of the Alvarado Ridge.

As the Alvarado Ridge rose, progressively older strata were stripped from uplands and deposited on the flanks of the arch. Erosion exposed Paleozoic carbonates that became recharge areas for aquifers that introduced meteoric water into the Permian basin. Carbonate aquifers carried oxygenated meteoric water down the east flank of the Alvarado Ridge toward the Delaware basin where it mixed with hydrogen sulfide-rich connate water to form copious sulfuric acid. The acid dissolved vast amounts of limestone, creating the huge caverns of the Guadalupe Mountains such as Carlsbad Caverns. This type of karst is hypogenic, and lacks many of the surface features typical of epigenic karst terranes.

In southeast New Mexico and west Texas, erosion related to the rise of the Alvarado Ridge exposed Permian evaporites. Meteoric water dissolved these evaporites, resulting in karst topography characterized by closed drainage depressions, shallow caves and sinkholes. Evaporite karst is common along the Pecos River and its tributaries, which comprise the principle surface drainage conduit for the region.

The Permian basin has been heavily drilled for petroleum, resulting in the discovery and development of thousands of oil and gas fields. Production of oil and gas requires significant infrastructure, including pipelines, water supply wells, and brine disposal wells. The rapid rate of dissolution of evaporites can damage pipelines and well casings. In some cases, leaking casings in wellbores introduced water into evaporite beds, causing dissolution that resulted in large, near surface cavities. Some of these cavities have collapsed, resulting in man-made sinkholes.

Biography:

Harvey DuChene is a graduate of the University of New Mexico, earning B.A. (1968) and M.S. (1973) degrees in geology. He has 39 years of experience as a petroleum geologist, working for Amoco Production Company, Davis Oil, Axem Resources and others. He currently is a limited partner in Vecta Oil and Gas, LP, an oil and gas exploration and production company headquartered in Dallas, Texas. His primary area of expertise is petroleum exploration in basins of the Rocky Mountain province and west Texas, with additional experience in the midcontinent, Appalachian basin and offshore West Africa.

Harvey has also more than 30 years studying the speleogenesis of hypogenic caves, particularly those formed by sulfuric acid. He is interested in the connection between the evolution of hypogenic cave systems and the tectonic and geologic history of regions.

Harvey is a member of the Geological Society of America, American Association of Petroleum Geologists, American Geological Institute, Rocky Mountain Association of Geologists, New Mexico Geological Society, West Texas Geological Association and Karst Waters Institute, and he is a Fellow of the National Speleological Society.

Thursday May 8, 2013, 8:20am

Natural and Anthropogenic Sinkholes: from Identification, to Surveying, Studying and Modeling a Subtle Hazard

Mario Parise
National Research Council of Italy, Institute of Research for the Hydrogeological Protection

Sinkholes are the most common hazard in karst, being related to the presence of natural caves, and to their interaction with the ground surface. In the last decades, however, the study of sinkholes widened well beyond the boundaries of karst, including situations where cavities produced by man in different epochs and for different purposes interact in some way with the built-up environment, and represent a likely threat to the society. As a matter of fact, several urban areas in many countries worldwide have been recently affected by sinkhole occurrence which caused severe damage; sinkholes in Guatemala City, and other events in Italy, Germany and Turkey are only some of the many that characterize the last several years.

In terms of civil protection issues, the topic has become of high interest in Italy, and much work has been devoted to it at CNR-IRPI. This presentation briefly describes the activities carried out, as they concern both natural and anthropogenic sinkholes, and to share the experiences so far developed. These latter cover all the phases of sinkhole analysis: from the identification of the sinkhole-prone areas, to surveying the underground environment (by combining speleological techniques and modern technologies in order to get reliable and precise surveys), to recognizing the type of rock failures and characterizing the rock mass in terms of mechanical properties, to eventually modeling the case studies through numerical codes in order to forecast the likely evolution of underground failures, their upward propagation, and evaluating the possibility of sinkhole occurrence at the ground surface. A particular focus will be given to historical research, and its use in identifying ancient and/or buried caves, as the first step in the assessment of the sinkhole susceptibility and hazard. All of this will be illustrated through a number of case studies in southern Italy, dealing with natural karst caves and anthropogenic cavities as well. The final part of the presentation will also cover some issues related to land-use problems in sinkhole-prone areas, and the utilization of the outcomes from sinkhole studies in civil protection programs at the local and national level, aimed at safeguarding and protecting private and public properties and the local populations.

Biography:

After graduating with honors in Geology in 1988 at the Faculty of Sciences of the University of Naples, Mr. Parise received grants from the National Research Council of Italy and spent several periods working in cooperation with the U.S. Geological Survey at Golden, Colorado, and the University of South Florida at Tampa, Florida. Since 1994 he has worked as a Research Geologist at the National Research Council, Institute of Research for Hydrogeological Protection (CNR-IRPI) in Bari, Italy. He has organized and convened several international workshops and conferences on the topics of karst, karst hazards, and slope movements

(European Geosciences Union Assemblies, Geological Society of America Meetings, Italian Forums of Earth Sciences), and is the scientist responsible for several projects between CNR-IRPI and different public administrations and private companies.

Since 1990, Mr. Parise has developed research mainly into the geological and geomorphological analysis of slope movements. Much of his research deals with the identification of areas susceptible to different types of slope movement (debris flows, deep-seated gravitational slope deformations, mass wasting processes, etc.) by means of stereoscopic interpretations of aerial photographs and field surveys. Particular focus is given to multi-temporal analyses, aimed at understanding the likely evolution of slopes, even in relationship with anthropogenic activities, and/or as a consequence of specific triggering events (rainstorm, earthquakes, etc.). For several sites in southern Italy, he has created a framework of the influence of weathering in the predisposition of slope movements. He has also contributed to the analysis of rapid landslides (debris avalanches, rock avalanches) in different geological settings in Italy and abroad, and to studying the occurrence of debris flows and erosional processes in areas recently affected by wildfires.

He began caving in 1998 and since 2002 he also works in the field of karst research, focusing on the evaluation of natural and anthropogenic hazards that occur in karst territories, with particular regard to sinkholes related to both natural caves and man-made cavities. He is the author of over 100 papers published in international journals and proceedings of international conferences. He has given several presentations in international symposia and workshops. Mr. Parise has guest edited 10 special issues for ISI international journals, published two books with the Geological Society of London, and reviews papers for several international journals.

Thursday May 8, 2013, 6:30pm

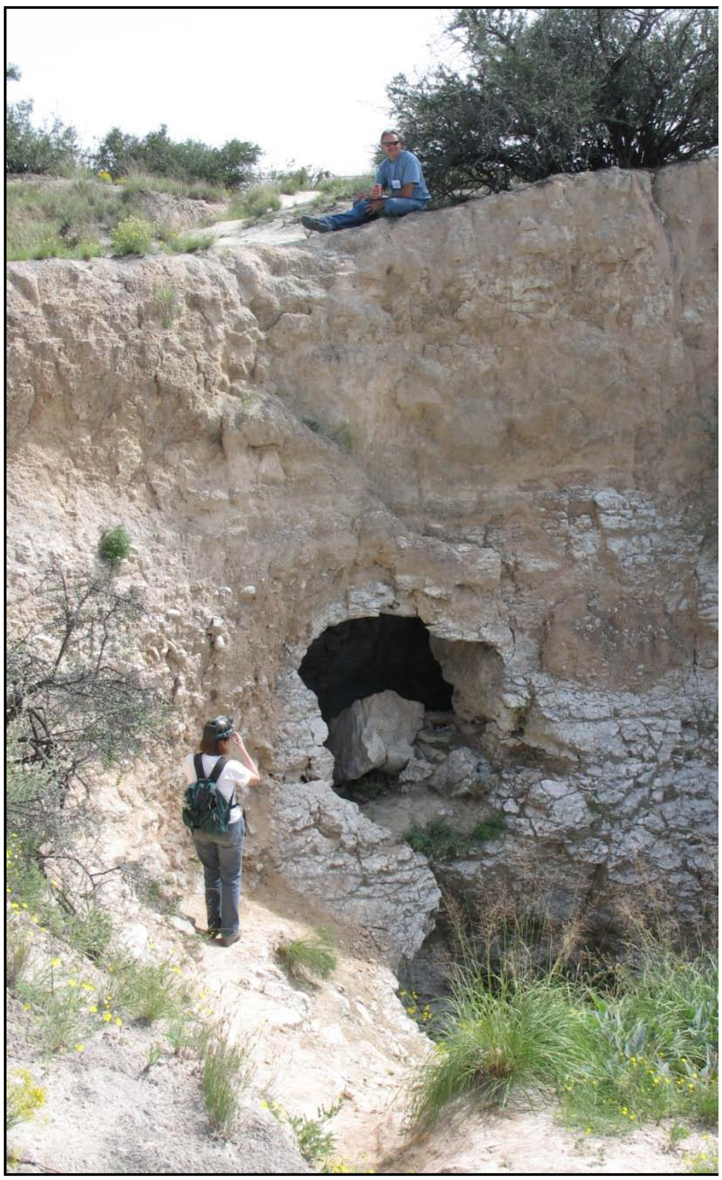
When the Carbonate Plumbing Goes Bad: Sinkholes, the Hydra, and the General Public

William Kochanov
Pennsylvania Department of Conservation and Natural Resources

In 1985, a program was initiated by the Pennsylvania Geological Survey to inventory (catalog) existing sinkholes and to map areas of potential sinkhole development. The program was developed to provide general background information for the initial stages of site investigations, aid in sinkhole remediation efforts, and serve as a tool for developing regional land-use planning strategies. Although the methods of data collection and distribution have evolved over the past 25 years, it has been interesting to note that the practicing professional continually has had to refine the means of sorting and sifting data much like that of a forensic specialist; each investigator having their own special challenges as the clues for remediation often lie hidden beneath the veneer of urbanization, are squirreled away in files of the local Historical Society or are muted for fear of liability. Bill will take you on a savage journey through the karstlands of Pennsylvania to marvel at some of its many wonders, examine yawning portals to the underworld, grapple with the paradox of the cultural hydra, and the ultimate in trepidation, entering the lair of the general public.

Biography:

William (Bill) Kochanov (pronounced KO-CHAN'-OFF) is a Senior Geologist with the Pennsylvania Department of Conservation and Natural Resources, Bureau of Topographic and Geologic Survey, Geologic Mapping Division. Since 1985, he has been actively mapping geologically hazardous areas within the limestone regions of Pennsylvania and maintains the Bureau's sinkhole database. He has also conducted bedrock mapping projects spanning much of the Paleozoic from Pennsylvania's northern anthracite coal field and Endless Mountains Region to the Chester Valley of southeastern Pennsylvania. Bill is most noted for authoring the series of county reports, specifically designed to characterize karst surface features, their distribution, and their relation to physiographic setting. He is strongly involved with the Survey's outreach programs; translating the geology of Pennsylvania for, as Joe Fischer puts it, "the greater unwashed." Bill lives in the suburbs of Harrisburg with his wife Jane and children, Natalie and Alex, close to the forests of Stony Creek where he spends many hours tracking down the elusive edibles of the mushroom world.



The main sinkhole entrance to Parks Ranch Cave, the second longest gypsum cave in the US, which will be the test subject of the Electrical Resistivity Short Course. Photo by NCKRI.

Presentation Abstracts
(in order of presentation)

Wednesday May 8
9:15am-12:10pm
Engineering and Geotechnical Aspects of Karst

Towards a Karst Assessment Standard Practice

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The assessment of karst conditions and putative karst geohazards prior to residential and commercial development is currently in its infancy, from a scientific aspect. Borrowing from the medical lexicon, most karst features at proposed building sites are dealt with using an approach wherein the "symptoms and conditions" are treated (e.g. sinkhole remediation), often only after site development activities have commenced. If karst hazards are suspected, roadways, foundations and specific at-risk areas may be investigated using various geophysical methods; however the results of these investigations require specialized knowledge to be interpreted and understood. Thus stakeholders without geological training may find the investigator's results indecipherable, often leading to unnecessary and expensive supplemental studies, the need for which is entirely based on the non-technical stakeholder's faith in the investigator's judgment.

In contrast, a recent trend among consulting firms is to attach cursory karst "assessments" to due diligence study reports, particularly Phase I Environmental Site Assessments. These combined assessments are often performed by individuals who are inexperienced in geology, often without any specific training in karst geology. Not unexpectedly, this can lead to numerous mistakes, errors, and oversights. More troubling, these studies often report a lack of karst risks at the site under study, a result that the stakeholders may initially embrace, but which later can result in substantial financial loss and/or significant threats to human health and the environment.

To address these concerns, we propose a proactive, "preventative" standard practice for karst assessments. Ideally, this proactive approach will help to delineate potential karst hazards so that they can be avoided, managed, or corrected by remediation. Requirements for investigators, a proposed scope of services, fieldwork and data review checklist, and a template for a follow-up karst management plan are presented.

It is our hope that if carried out and reported accurately, the proposed assessments should allow even a non-technical stakeholder to make informed decisions regarding the relative risk of karst geohazards, the need for further studies, and potential corrective actions that site development may entail.

Geotechnical Case History for Sinkhole Investigation and Stabilization Methods Along a High Pressure Petroleum Pipeline

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Installation of underground pipelines through unpopulated land situated over pinnacled carbonate bedrock can lead to the development of sinkholes. The formation of sinkholes beneath buried pipelines has the potential of damaging the pipeline and more importantly causing hazardous environmental incidents. This paper presents a case history at a site where significant sinkholes developed within and adjacent to a 400 foot (112 meters) long section of high pressure petroleum pipeline right-of-way that crosses under a local creek in Plymouth Meeting, Pennsylvania. Various geophysical investigation techniques consisting of microgravity, multi-channel analysis of surface waves (MASW), and two dimensional electrical resistivity testing were performed in addition to confirmatory testing borings to effectively evaluate the subsurface conditions at the site. Three options were considered as a solution to the active sinkholes present within the pipeline right-of-way. These options include: 1) subsurface grouting within the right-of-way 2) structurally supporting the pipeline on a deep foundation system or 3) relocating the pipeline to a less sinkhole prone portion of an adjacent property. Following the investigation process, relocating the pipeline in conjunction with pre-installation ground improvements via subsurface grouting represented the most cost-effective, lowest risk solution at the site.

Problems Associated with the Use of Compaction Grout for Sinkhole Remediation in West-central Florida

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Compaction grouting is a widely used method for sinkhole remediation. It is generally less costly than other methods of remediation and provides a less intrusive method of repairing adverse subsurface conditions. However, we believe that many engineers in preparing specifications and contractors in construction practice have improperly applied compaction grouting as a method of remediation. In some cases, improper use of compaction grout has resulted in the deterioration of marginal subsurface conditions significantly increasing the cost of repair and inconvenience to the homeowner. Another consideration in the selection of compaction grout is the occurrence of subsurface conditions in which deep foundation support should be used rather than the seemingly less expensive compaction grout method. This manuscript discusses techniques in the proper use of compaction grouting and the precautions that should be taken before, during and after compaction grouting. It also discusses potential conditions when compaction grouting should be supplemented or replaced with deep foundations. Included in the manuscript are compaction grouting case studies and recommendations for the proper application of compaction grout.

Evaluating Karst Risk at Proposed Windpower Projects

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Karst can cause a litany of problems for a windpower project, and it is good practice to evaluate karst risk before proceeding with a proposed project. Windpower projects involve widely-spaced structures with small footprints that can cost $2 million to $5 million each. Financial viability can prove difficult, so it is important to find useful, inexpensive procedures for evaluating karst risk. The karst-risk-review process we have used can be split into the two categories outlined below.

Desktop studies:

- Search for relevant literature
- Review aerial-photo and map, and analyze lineament
- Search for existing well and boring logs
- Survey local experts—landowners, U.S. Geological Survey, state geological survey, cavers, etc.

Field studies:

- Perform site reconnaissance
- Conduct pit tests if bedrock is shallow
- Drill—A normal geotechnical investigation includes one boring per turbine, while karst investigations may include multiple borings per turbine
- Use a downhole camera—May be useful in evaluating extent of voids and convincing clients of risk.
- Conduct geophysical studies

Effectively communicating with developers is critical. They want to know the location of the problem sites and may ask, If there is a cave, what is the chance that a turbine will fail? The geo-professional needs to do the following effectively:

- Explain the short-term (collapse) and long-term (settlement) risks, and mitigation options
- Explain the uncertainty
- Negotiate liability
- Costs of investigation and mitigation
- Get developers to determine how much to spend while understanding how much incremental-risk reduction they will receive.

The discussion of karst risk should be ongoing and investigations may proceed on a step-by-step basis as new information is gathered. It's important to determine whether to investigate all sites underlain by a potentially karstic unit or try to rank the sites based on risk before focusing the investigation on those with potentially higher risk. Per-turbine karst investigation costs can easily reach $20,000 and more, so investigating each site in a 100-turbine development can be a significant commitment. When possible, start karst evaluation early, manage available cash with a stepwise approach, and communicate.

Application of Stability Charts and Reliability Concepts for Simplified Analysis of a Void in Soil Overlying Karst Bedrock

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The karst belt stretching from Alabama to New England is dominated by limestone/dolostone rocks which are observed to weather in-place forming a layer of residual clay soil above a highly weathered rock surface. As part of the natural weathering process, subterranean voids frequently develop in the overburden soil, which can lead to surface subsidence or collapse (sinkholes). Furthermore, construction activities can

promote instability, especially where a portion of the soil overburden is removed. A rational method for addressing the potential for void collapse may involve the use of simplified charts to perform probabilistic analysis for likely ranges of void and soil conditions. This paper demonstrates the application of simplified stability charts and reliability concepts for evaluating the collapse potential of voids within the soil overlying the rock surface.

If it's Weight of Hammer Conditions, It must be a Sinkhole?

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In a Florida sinkhole investigation, many people (engineers, geologists, lawyers, insurance agents, public adjusters and media) interpret weight of hammer (WH) and weight of rod (WR) as a void, and by association, a sinkhole (author is a Florida Neutral Evaluator). This causes some to allege the site contains a sinkhole damaged home--damage that is likely related to poor maintenance, construction or design issues. The concept of finding WH/WR conditions has resulted in many sinkhole investigations becoming a gamble with the homeowner or their representative wagering against the insurance company that there will be WH/WR conditions found and therefore a sinkhole present under the building likely giving the homeowner a payoff for a sinkhole. The rules for the game are mandated in Chapter §726.706 of the Florida Statute that ultimately results in who can be more successful in convincing a jury that a given set of conditions is or is not a sinkhole. Since the WH/WR conditions plays a significant role in sinkhole determinations, this paper will discuss the causes of WH/WR conditions and its meaning in terms of stress that develops during soil sampling. It will further consider the distribution of stress and the potential for these conditions to influence a structure at the ground surface. Conversely, it will also discuss the factors necessary for these conditions to impact a structure and other conditions that can give false indications of sinkhole activity. Also provided are examples of case studies where critical subsurface conditions were resolved using considerations discussed in this manuscript.

Exploratory Grouting of a Subsurface Detention/ Infiltration System

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In 2007, a geotechnical investigation was performed for a student center at a New Jersey college. Even after reviewing the results of that study, the Municipality recommended incorporating a subsurface detention/ infiltration system below the parking lot adjacent to the student center.

The project area is underlain by solution-prone Beekmantown Formation dolomites. Mapped just to the northwest is the conformable solution-prone Allentown Dolomite. The Allentown likely dips shallowly below the Beekmantown. This local suite of carbonate bedrock lies within a fault-bounded block of these Cambro-Ordovician rocks.

Sinkholes formed beneath and adjacent to the basin and parking area and remediation was attempted by others. Repairs reportedly included the removal of basin fill materials, low-mobility grouting and stone backfill placed in subsurface voids. Shortly thereafter, more sinkholes opened, some within the area remediated.

Technical problems at the site included a lack of reliable subsurface information; the basin functioning in a manner that allowed infiltration; having the likely need to vary the grout and delivery procedures based upon encountered conditions and probe hole locations in relation to the basin; the need to remediate solution features trending beyond the original area of interest; and the possibility of unrecognized solution features outside the area of interest and below the student center.

These potential problems were brought to the attention of the current college administration. They quickly recognized the concerns and requested a different geotechnical firm to develop specifications for remediation and to help in choosing a suitable contractor.

To address the concerns, site-mixed grout using cement, water, mason sand and bentonite, in varying proportions, delivered under varying pressures, and using two different grout mixing methods was deemed the most appropriate remedial alternate. During the field operations, liaison and cooperation between the grouting engineers, the grout crew, and the college administration and maintenance personnel provided useful insight and support.

The various procedures used and the bases for their use are discussed in this paper. A total of 41 probe holes were drilled where a total of 157 m³ (205 cubic yards) of grout was placed.

Voids as large as 5½ m (18 feet) in vertical extent were encountered and a maximum of 18.6 m³ (24.3 cubic yards) of grout were pumped into any single probe hole. Subsurface connection between probe holes was evidenced as grout was seen to travel at least 3 m (10 feet) laterally.

Need for a Standardized Approach to Characterizing, Permitting, and Constructing Landfills in Karst Geologic Settings

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The challenges presented by geohazards play a significant role in the permitting of environmental facilities, particularly those situated in karst geologic settings. With regards to landfills, and specifically to municipal solid waste (MSW) landfills, regulators have a significant responsibility to protect the environment and must make decisions regarding the siting and permitting of these facilities. While these decisions are based on their objective assessment of site-specific characterization information, their decisions are often scrutinized by the public and by the owner/permittee, entities that often (and usually) have contrasting interpretations of the same site characterization information. The Florida Department of Environmental Protection (FDEP) has initiated an innovative approach to help the agency in the decision-making process by convening a Technical Advisory Group (TAG), comprised of several agency- and industry-recognized experts who are experienced in the investigation, characterization, permitting, and construction of engineered facilities in karst settings. Through a process involving the compilation and assessment of various site-specific factors, the TAG is working with FDEP personnel to develop specific and objective guidelines that can be used by owners, permittees, consultants, and the agency in developing investigation, characterization, design, construction, operations, and monitoring strategies for facilities overlying karst geologic conditions. The activities of FDEP and its TAG are actively reviewed by the public, who have also been requested by FDEP to participate in the process of developing these guidelines. The objectives for making this presentation are twofold, specifically to provide information to and then solicit information from the conference participants (and readers). The approach being taken by FDEP and the TAG focuses on technical issues regarding the investigation, characterization, design, and construction of engineered facilities in karst geologic settings. The authors recognize that these technical issues impact all engineered facilities, not just those constructed for environmental applications. Therefore, the approach developed by FDEP may benefit other agencies, owners, and consultants who face similar challenges. The participants at this conference likely have specific experiences and can offer recommendations that will ultimately be beneficial to the DEP and the TAG. In this presentation, the authors will actively engage the participants and will request input based of their experience and expertise.

Wednesday May 8
2:10pm-5:00pm
Evaporite Karst

Salt Karst and Collapse Structures in the Anadarko Basin of Oklahoma and Texas

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Permian bedded salt is widespread in the Anadarko Basin of western Oklahoma and the Texas Panhandle, where partial or total dissolution of the shallowest salt in some areas has resulted in subsidence and/or collapse of overlying strata. Groundwater has locally dissolved these salts at depths of 10–250 m. The distribution (presence or absence) of salt-bearing units, typically 80–150 m thick, is confirmed by interpretation of geophysical logs of many petroleum tests and a few scattered cores. Salt dissolution by ground water is referred to as “salt karst.”

Chaotic structures, collapse features, breccia pipes, and other evidence of disturbed bedding are present in Permian, Cretaceous, and Tertiary strata that overly areas of salt karst. The dip of Permian and post-Permian strata in the region normally is less than one degree, mainly towards the axis of the Anadarko Basin. Where strata locally dip in various directions at angles of 5–25 degrees or more, and underlying salt units show clear evidence of dissolution, these chaotic dips must result (mostly, if not totally) from subsidence and collapse into underlying salt-dissolution cavities.

Gypsum karst and resultant collapse of overlying strata have been proposed in many parts of the Anadarko Basin. However, the gypsum beds typically are only 1–6 m thick and more than 100 m deep, and cannot contribute to disruption of outcropping strata—except where they are within 10–20 m of the surface.

Typical areas of disturbed bedding comprise several hectares, or more, with outcrops of moderately dipping strata—as though large blocks of rock have foundered and subsided into large underground cavities. Other examples of disturbed bedding are small-diameter breccia pipes, or chimneys, that extend vertically up from salt-karst cavities, through several hundred meters of overlying strata. The best evidence of these chimneys are collapsed blocks of Cretaceous strata, chaotically dropped some 50 m, or more, that are now juxtaposed against various Permian formations on the north flank of the Anadarko Basin. Any study of surface or shallow-subsurface geology in the Anadarko Basin must consider the influence of subsurface salt karst on the structure and distribution of overlying rocks.

Evaporite Karst in the Permian Basin Region of West Texas and Southeastern New Mexico, USA: The human impact

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A significant minority of sinkholes in the greater Permian Basin region of west Texas and southeastern New Mexico are of human origin. These anthropogenic sinkholes are often associated with historic oil field activity, or with solution mining of Permian salt beds in the shallow subsurface. The well-known Wink Sinks in Winkler Co., Texas formed in 1980 and 2002 within the giant Hendrick oil field. The Wink Sinks were probably the result of subsurface dissolution of salt caused by fresh water leakage in improperly cased abandoned oil wells. In 2008 two catastrophic sinkhole events occurred a few months apart in northern Eddy Co., New Mexico, and a third formed a few months later in 2009 near Denver City, Texas. All three sinkholes were the result of solution mining operations for brine production from Upper Permian salt beds. The Eddy Co. sinkholes formed within the giant Empire oil and gas field, several kilometers from populated areas. In the aftermath of these events, another brine well operation was identified within the city limits of Carlsbad, New Mexico as having a similar geologic setting and pumping history. That well has been abandoned and geotechnical monitoring of the site has been continuous since 2008. Although there is no indication of imminent collapse, geophysical surveys have identified a substantial void in Permian salt beds beneath the brine well extending north and south beneath residential areas, a major highway intersection, a railroad, and an irrigation canal.

Evaporite Karst and Hydrogeology of the Castile Formation: Culberson County, Texas and Eddy County, New Mexico

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Karst development in Permian Castile evaporites has resulted in complex speleogenetic evolution with multiple phases of diagenetic overprinting. More than 10,000 surficial features, primarily sinkholes, occur throughout Culberson County, Texas, and Eddy County, New Mexico, based on GIS-analyses where laminated Castile sulfates crop out. Cave development is largely the result of hypogene processes, where ascending fluids from the underlying Bell Canyon Formation migrate near vertically through the Castile Formation, creating caves up to 100 meters deep and over 500 meters long, which have been breached through a combination of collapse and surface denudation. Numerous small and laterally limited epigene features occur throughout the region, as well as the anomalously large Parks Ranch Cave System with more than 6.5 kilometers of cave development and multiple large, incised, sinkhole entrances. Hypogene caves exhibit varying degrees of epigenic overprinting as a result of surficial breaching.

Water resources in the Castile Formation are directly related to karst development with extremely heterogeneous flow networks. Most springs in the region discharge sulfate-rich waters, contain high levels of hydrogen sulfide, and support sulfate-reducing bacterial colonies. Isolated stream passages in northern Culberson County provide locally significant water resources that do not exhibit elevated hydrogen sulfide concentrations. Local water tables vary greatly over the region and few caves access base-level conditions. Upward migration of hydrocarbons complicates regional hydrology and diagenesis, resulting in extensive evaporite calcitization, which greatly modifies both fluid/rock interaction and permeability structures.

Gypsum Karst Causes Relocation of Proposed Cedar Ridge Dam, Throckmorton County, Texas

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Cedar Ridge Dam and Reservoir will be built to supply water for the city of Abilene, Texas. The original damsite (CR) was to be located on Clear Fork of Brazos River in Throckmorton County, but initial coring of the damsite encountered unsuspected gypsum beds in the Permian-age

Jagger Bend/Valera Formation. Gypsum is a highly soluble rock that typically contains karst features, and its presence in a dam foundation or impoundment area could allow water to escape from the reservoir. A decision was made to look at potential sites farther upstream (to the southwest), where west-dipping gypsum beds would be deeper underground and karst problems would be minimized or eliminated.

The first phase of the relocation was a comprehensive field study of Clear Fork Valley, upstream of the original damsite, to identify gypsum outcrops; gypsum was exposed at only one location, just above damsite CR. The second phase of the study was examination of nearly 100 petroleum-test geophysical logs to identify, correlate, and map the subsurface gypsum and associated rock layers upstream of the original damsite. The gypsiferous sequence is 30–45 m thick, and consists of 8 gypsum beds, mostly 1–3 m thick, interbedded with red-brown and gray shale units 1–10 m thick. Gypsum beds comprise 25–30% of the gypsiferous sequence. Gypsum beds dip uniformly to the west at about 7 m/km (about 0.4 degrees), and thus the uppermost gypsum is at least 23 m beneath the newly proposed damsite (A), about 8 km to the southwest.

Subsequent coring and other studies of the new damsite confirm that gypsum beds are 23 m beneath the newly proposed dam. There is no evidence of solution channels or other karst features beneath this site, and thus there is little likelihood of water loss from the reservoir at the new site due to gypsum karst.

The Role of Sulfate-Rich Springs and Groundwater in the Formation of Sinkholes over Gypsum in Eastern England

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Heavily karstified gypsum and dolomite aquifers occur in the Permian (Zechstein Group) of Eastern England. Here rapid active gypsum dissolution causes subsidence and abundant sinkholes affect an approximately 140-km by 3-km area from Darlington, through Ripon to Doncaster. The topography and easterly dip of the strata feed artesian water through the dolomite up into the overlying gypsum sequences. The shallow-circulating groundwater emerges as sulfate-rich springs with temperatures between 9-12°C, many emanating from sinkholes that steam and do not freeze in the winter (such as Hell Kettles, Darlington). Water also circulates from the east through the overlying Triassic sandstone aquifer. Calcareous tufa deposits and tufa-cemented gravels also attest to the passage and escape of this groundwater.

The sizes of the sinkholes, their depth and that of the associated breccia pipes is controlled by the thickness of gypsum that can dissolve and by the bulking factors associated with the collapsed rocks. The presence of sulfate-rich water affects the local potability of the supply. Groundwater abstraction locally aggravates the subsidence problems, both by active dissolution and drawdown. Furthermore, the gypsum and dolomite karstification has local implications for the installation of ground-source heat pumps. The sulfate-rich springs show where active subsidence is expected; their presence along with records of subsidence can inform planning and development of areas requiring mitigation measures.

Gypsum Karst and Potential Risk in Siting Wind Turbines in Blaine County, Oklahoma

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Gypsum, a highly soluble rock, is readily dissolved to form karst features identical to those associated with limestones and dolomites. Investigations in Blaine County, in northwestern Oklahoma, evaluated potential problems that subsidence due to gypsum karst may pose for the proposed Watonga Wind-Power Project, a wind-turbine project just east of Watonga. Catastrophic collapse of a wind turbine is clearly unacceptable, and minor settlement could also be a risk. Differential settlement by even 3 cm across a 15-m-wide turbine foundation could lead to the turbine tilting out of tolerance, requiring remedial repairs.

Gypsum beds of the Permian Blaine Formation underlie all parts of the Project Area, at depths ranging from 10 to 45 m below ground level. The Blaine Formation here is about 29 m thick: it consists of four gypsum beds, each 0.6 to 4 m thick, interbedded mainly with red-brown shales. The Blaine is overlain by the Permian Dog Creek Shale and by unconsolidated Quaternary sands, clays, and gravels that may obscure karst features. Field studies, aerial-photo analysis, and literature review show that there is no evidence of gypsum karst in the Project Area.

Although lacking direct evidence of karst in or near the Project Area, we recognize there is some potential for subsidence due to dissolution of shallow gypsums. Additional mitigation of this risk can be achieved by placing wind turbines at sites where the gypsum beds are deepest: we believe that where gypsum is 25 m below ground level, or deeper, the risk related to gypsum karst is low. Placing turbines at sites where gypsum beds are less than 25 m deep would pose a medium or high risk. To minimize this risk, a map was prepared showing areas of low, medium, and high risk, related to potential gypsum karst.

Evaporite Karst in the Black Hills, South Dakota and Wyoming, and the Oil Play in the Williston Basin, North Dakota and Montana

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Subsurface red beds of the Permo-Triassic age Spearfish Formation in the Williston Basin has recently been touted as “another Bakken Oil Boom for North Dakota”. The senior author, totally uninformed about the subsurface geology of North Dakota, was requested by INFOCAST* to discuss petroleum potential in the Spearfish based on his field experience in the outcrop belt of the Black Hills in neighboring Wyoming and South Dakota. That request was extended to a discussion of the surface and subsurface evaporite-karst features in four formations ranging from Pennsylvanian to Jurassic age. Dissolution of these rocks, which has resulted in sinkholes, caves, springs, breccia pipes, and subsurface collapse, has apparently gone on since the Black Hills were formed during the Early Tertiary, and continues today. The formation of salt-dissolution paleokarst in the Williston Basin and adjacent Powder River Basin has been documented to have occurred many times in the geologic past, between the mid-Paleozoic through the Tertiary. Reported subsurface collapse has affected rock characteristics, including local structure, fracturing, porosity, and permeability. These significant effects of evaporite karst in the Williston Basin, as well as in subsurface evaporite-bearing sequences nationally, should be of concern to any oil exploration efforts, as well as for such surface infrastructure development as pipeline right-of-way.

Wednesday May 8
6:30pm-7:30pm
Poster Session

Monitoring Evaporite Karst Activity and Land Subsidence in the Holbrook Basin, Arizona Using Interferometric Synthetic Aperture Radar (InSAR)

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The Holbrook Basin located in east-central Arizona is home to more than 500 evaporite karst depressions. The Arizona Department of Water Resources (ADWR) recently acquired, processed, and interpreted archived Interferometric Synthetic Aperture Radar (InSAR) data to evaluate historical deformation patterns in the Holbrook Basin in preparation for monitoring potential future subsidence related to planned potash mining activities around the Petrified Forest National Park. Three land subsidence features were identified by ADWR using InSAR data from the European Space Agency’s ERS 1 and 2 satellites between 1992 and 1997. Continued subsidence in two of the three features was also identified by ADWR using InSAR data from the Japan Aerospace Exploration Agency’s ALOS satellite collected from 2006 to 2011.

In June 2012 Arizona Geological Survey (AZGS) and ADWR staff visited one of the more prominent subsidence features identified using InSAR. Numerous steep-walled evaporite karst sinkholes were observed en route to the field site. These roughly circular collapse features ranged in size from 40-130 m across and 10-30 m deep. The subsidence features identified through InSAR are much more extensive, up to 1,100 m across; are not as deep, up to 15 m; and do not have steep walls. Local subsidence has resulted in broad closed basins with drainage reversals and numerous expanded joints in the Coconino sandstone at the surface. A thin sandy soil above the Coconino covers the basin floor except where collapsed into open joints. Expansion along both joint orientations was observed. Which orientation was expanded depended on location relative to ongoing subsidence. Based on field observations and comparison with other collapse features in the region these three subsidence features are relatively young, constitute different collapse morphology than nearby sinkholes, and warrant further study. InSAR will remain a critical remote-sensing tool for monitoring land subsidence in the Holbrook basin.

Cover-collapse Sinkhole Development in the Cretaceous Edwards Limestone, Central Texas

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Sudden cover-collapse sinkhole (doline) development is uncommon in the karstic Cretaceous-age Edwards limestone of central Texas. This paper presents a case-study of a sinkhole that formed within a stormwater retention pond (SWRP) in southwest Austin. Results presented include hydrogeologic characterizations, fate of stormwater, and mitigation of the sinkhole.

On January 24, 2012, a 11 cm (4.5 in) rainfall filled the SWRP with about 3 m (10 ft) of stormwater. Subsequently, a sinkhole formed within the floor of a SWRP measuring about 9 m (30 ft) in diameter and 4 m (12 ft) deep. About 26.5 million liters (7 million gallons) of stormwater drained into the aquifer through this opening.

To determine the path, velocity, and destination of stormwater entering the sinkhole a dye trace was conducted. Phloxine B was injected into the sinkhole on February 3, 2012. The dye was detected at one well and arrived at Barton Springs in less than 4 days for a minimum velocity of 2 km/day (1.3 mi/day).

Review of pre-development 2-foot topographic contour and geologic maps reveals that the SWRP was built within a broad (5,200 m^2; 6 acre), shallow depression bounded by two inferred NE-trending fault zones. Photographs taken during SWRP construction showed steep west-dipping bedrock in the northern SWRP wall. Following collapse of the sinkhole, additional hydrogeologic characterization included excavation to a depth of 6.4 m (21 ft), surface geophysics (resistivity), and rock coring. Geologic materials consisted mostly of friable, highly altered, clayey limestone consistent with epikarst in-filled with terra rosa providing a cover of the feature. Dipping beds and fractured bedrock support proximity to the mapped fault zone. Geophysics and surface observations suggested a lateral pathway for stormwater flow at the junction between the wet pond's impermeable geomembrane and compacted clay liner for the retention pond. The collapse appears to have been caused by stormwater down-washing poorly consolidated sediments from beneath the SWRP and into a pre-existing karst conduit system.

Mitigation of the sinkhole included backfill ranging from boulders to gravel, a geomembrane cover, and reinforced concrete cap. Additional improvements to the SWRP included a new compacted clay liner overlain by a geomembrane liner on the side slopes of the retention pond.

Integrated Geophysical Methods for Groundwater Exploration in Karst Area with or Without Thin Cover- A Case Study from Tai'an City, Shandong Province, China

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Because of heterogeneity and anisotropy, it is very difficult to optimize groundwater exploration drilling locations in karst areas using only hydrogeological information. However, the integrated application of the audio frequency telluric method and electrical resistivity tomography has proved to be efficient for groundwater exploration in karst areas with or without thin cover. In the case studies presented here, audio frequency telluric profiling is used to roughly determine the location and strike of a karsted or fractured zone where the cover thickness is less than 30 m, then an electrical resistivity profile perpendicular to the strike of the zone is designed to reconstruct the resistivity structure with a Schlumberger array. By combining the geophysical results with available hydrogeological data, an optimal drilling site can be established. This integrated geophysical approach for karst water exploration has been used in several projects and the results show that the method is reasonable and useful.

Statistical Analysis of GPR and SPT Methods for Sinkhole Investigations in Covered Karst Terrain, West-Central Florida, USA

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Sinkholes and sinkhole-related features in west-central Florida are commonly identified from surface penetration test (SPT) borings, which are located, in part, based on the results from ground penetrating radar (GPR) surveys. SPTs and GPR profiles yield complementary information—SPTs can indicate the presence of low-density soils or voids, while GPR profiles can resolve shallow stratigraphic indicators of subsidence. In GPR profiles collected at 103 residential sites in covered-karst terrain in west-central Florida, sinkhole-related anomalies were identified where GPR reflectors show downwarping, discontinuities, or sudden increases in amplitudes. We analyze the degree to which the shallow features imaged in GPR correlate spatially with the N-values (blow counts) derived from SPTs at 103 residential sites. Results are used to examine (1) which SPT indicators show the strongest correlations with GPR anomalies, (2) the degree to which GPR surveys improve the placement of SPT borings, and (3) what these results indicate about the structure of sinkholes at these sites. We find a statistically significant correlation between GPR anomalies and low SPT N-values with a confidence level of 90%. Logistic regression analysis shows that the strongest correlations are between GPR anomalies and SPT values measured in the depth range of 0-4.6 m. The probability of observing a GPR anomaly on a site will decrease by up to 84% as the minimum SPT value increases from 0 to 20. Boreholes drilled on GPR anomalies are statistically significantly more likely to show zones of anomalously low SPT values than boreholes drilled off GPR anomalies. The odds ratio depends on how the threshold criteria for low N-values are defined, with a maximum observed odds ratio of 2.89. Several statistical results suggest that raveling zones that connect voids to the surface may be inclined, so that shallow GPR anomalies are laterally offset from deeper zones of low N-values.

Typical Methods for Forecasting Karst Collapse in China

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The aim of this paper is to describe improvements in the accuracy of forecasting karst collapse by summarizing the methods and analyzing their advantages and disadvantages. The forecasting methods were classified as geophysical surveys, monitoring of triggering factors, and strain measurements using optical fibers. Geophysical surveys can directly identify soil cavities, but the precision and depth of exploration are limited by equipment parameters and geological conditions. For example, ground penetrating radar can discover a soil cavity when the overburden layer is less than 15 m thick, and frequent scanning can determine changes in the soil cavity and predict sinkhole collapse when combined with a balance arch model. Monitoring of triggering factors is widely used to forecast karst collapse when the opening is caused by pumping, as the dynamic groundwater conditions can be acquired in real-time. However, the prediction criteria can be very difficult to obtain. In this paper we recommend a method based on the relationship between the times when anomalous monitoring data appear and the time a sinkhole opens. Using optical fibers to forecast karst collapse is the most advanced technology currently available in China. The location and time of sinkhole opening can be forecast by this method in theory, but some key issues have yet to be resolved. These issues include the strain correlation between the optical fiber and the soil, the effect of temperature on the optical fiber strain and the method of laying optical fibers in the soil. Finally, some proposals are suggested in the hope that they will generate public discussion, reducing the damage caused by karst collapse.

Variations in Evaporite Karst in the Holbrook Basin, Arizona

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At least six distinct forms of evaporite karst occur in the Holbrook Basin—depending considerably on overburden and/or bedrock type. Early Permian evaporites in the 300-m-thick Corduroy Member of the Schnebly Hill Formation include halite, sylvite, and anhydrite at depths of 215-250 m. Karst features result from collapse of overlying Permian and Triassic strata into underlying salt-dissolution cavities.

Evaporite karst occurs primarily along the 100+ km-long dissolution front on the southwestern edge of the basin, and is characterized by numerous sinkholes and depressions generally coincident with the axis of the Holbrook Anticline—in reality a dissolution-collapse monocline. “The Sinks” comprise ~ 300 individual sinks up to 200 m across and 50 m deep, the main karst features along the dissolution front. Westerly along the dissolution front, fewer discrete sinkholes occur, and several breccia pipes are believed to be forming. Numerous pull-apart fissures, graben-sinks, sinkholes, and broad collapse depressions also occur.

A newly recognized subsidence/collapse area of some 16 km^2 occurs in the western part of the basin, northward from the extension of the Holbrook “anticline.” The Chimney Canyon area is some 12 km east of McCauley Sinks, a postulated breccia pipe exemplified in, and possibly manifested in at least four other closed depressions. Interferometric Synthetic Aperture Radar (InSAR) data of one depression shows active subsidence of ~4 cm/yr.

Karst formation is ongoing, as shown by repeated drainage of Dry and Twin Lakes into newly opened fissures and sinkholes. These two playa lakes were enlarged and modified in recent years into evaporation impoundments for effluent discharge from a nearby pulp mill. Four major drainage events occurred within these playa reservoirs during the past 45 years, collectively losing more than 1.23 x 107 m^3 (10,000 acre-feet) of water and playa sediment. Drainage occurs through piping into bedrock joints in Triassic Moenkopi Formation (sandstone) in the bottom and along the margins of these playas. Effluent discharge has been discontinued into these playas, although recurring precipitation can fill the basins.

Clastic Sinkhole and Pseudokarst Development in East Texas

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Pseudokarst development in East Texas is controlled primarily by a combination of suffosion and preferential flow paths, often creating small ephemeral sinkholes but occasionally persistent features develop in more indurated facies. Pseudokarst occurs in Claiborne (Eocene) strata in Angelina, Cherokee, Nacogdoches, Panola, Rusk, San Augustine and Shelby counties. Strata consist of interbedded fine- and coarse-grained clastics with variable cementation and associated permeabilities. Preferential fluid migration along fractures and bedding planes create local voids through suffosion that stope upward to create sinkholes and incised collapse valleys often associated with persistent and ephemeral springs.

GIS-based delineation of pseudokarst sinkholes is complicated in the region by low gradient fluvial systems and extensive anthropogenic overprinting regionally, which create numerous constructional closed depressions. Sinkhole densities coupled with slope analyses indicate clustered regions of pseudokarst development within Carrizo, Queen City and Sparta sandstones. Known pseudokarst caves within the region include features developed along low permeability boundaries where discharge interface features occur. Gunnels Cave is an end member product of natural suffosion processes in East Texas with more than 160 meters of surveyed passage and a collapse sinkhole covering approximately a hectare. Smaller suffosion sinkholes occur along steep gradients but generally remain associated with fracture-controlled flow paths, either forming bypass features or enlarged regions associated with spring discharge. Anthropogenic pseudokarst sinkholes are generally associated with leaky pipelines and focused groundwater recharge from impermeable surfaces and produce local geohazards. Traditionally East Texas is not known for extensive pseudokarst development; however, isolated caves and sinkholes can be locally significant and potential geohazards.

Delineation and Classification of Karst Depressions Using LiDAR: Fort Hood Military Installation, Texas

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The Fort Hood Military Installation is a karst landscape characterized by Cretaceous-age limestone plateaus and canyons in Bell and Coryell Counties, Texas. The area is located in the Lampasas Cut Plain region of the Edwards Plateau and is stratigraphically defined by exposures of the Fredericksburg Group. Spatial interpolation of 105 km^2 of the Fort Hood Military Installation provided depression data that were delineated and classified using geoanalytical methods. Most of the karst features within the study area are predominantly surficial expressions of collapse features, creating windows into karst conduits with surficial exposures of epikarst spatially limited.

The increasing capabilities of GIS (Geographic Information Systems) and accuracy of geographically referenced data has provided the basis for more detailed terrain analysis and modeling. Research on terrain-related surface features is highly dependent on terrain data collection and the generation of digital models. Traditional methods such as field surveying can yield accurate results; however, they are limited by time and physical constraints. Within the study area, dense vegetation and military land use preclude extensive traditional karst survey inventories. Airborne Light Detection and Ranging (LiDAR) provides an alternative for high-density and high-accuracy three-dimensional terrain point data collection. The availability of high density data makes it possible to represent terrain in great detail; however, high density data significantly increases data volume, which can impose challenges with respect to data storage, processing, and manipulation. Although LiDAR analysis can be a powerful tool, filter mechanisms must be employed to remove major natural and anthropogenic terrain modifications resulting from military use, road building and maintenance, and the natural influence of water bodies throughout the study area.

Challenges and Lessons Learned From Managing a Newly Developed Catastrophic Sinkhole Lake Located on Multiple-Use Managed Public Land in the Lower Pecos Valley, New Mexico

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The majority of public land managed by the Roswell Field Office Bureau of Land Management in the Pecos Valley is land that has a high potential for karst development. A newly developed catastrophic sinkhole lake located on public land has presented public-land-management challenges. This paper will describe this sinkhole lake and the monitoring techniques that are used to protect its values, while allowing for limited recreational, commercial, and educational use. Management objectives for the sinkhole will include maintaining a protective fence barrier around its perimeter, install warning signs, publish education material, maintain a monitoring program, and avoid new surface disturbance activities that may impact the sinkhole.

Locating Sinkholes in LiDAR Coverage of a Glacio-fluvial Karst, Winona County, Minnesota

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Sinkholes in Winona County, Minnesota have been mapped four times since 1985 using different techniques including field observations, topographic maps, air photos and Global Positioning System (GPS) measurements. As of early 2009, these efforts had identified and inventoried 672 sinkholes in Winona County that are recorded in the Minnesota Karst Feature Database (KFDB) (See the KFDB at: http:/ /deli.dnr.state.mn.us/). The acquisition of one-meter resolution Light Detection and Ranging (LiDAR) images has significantly increased the speed and accuracy of sinkhole mapping. One meter shaded relief LiDAR Digital Elevation Models (DEMs) for Winona County were visually scanned to compare sinkhole locations in the KFDB with the LiDAR images and to find new sinkholes in the LiDAR DEMs. The results of this method indicate that the number of actual sinkholes in Winona County could be as many as four times more sinkholes than identified by the pre-LiDAR surveys.

To automate sinkhole detection from LiDAR data at a regional scale, an algorithm was developed in Matlab based on image processing techniques. The algorithm has three steps. The first part detects potential sinkhole locations as depressions in the DEM using a morphological operation (erosion). The second part of the algorithm delineates sinkhole boundaries by automatically fitting an active contour (snake) around the potential sinkhole locations. In the last step, a pruning process and based on the relationship between depth and area of depressions, was applied to discard shallow depressions. The proposed method was evaluated on selected parts of Winona County. Evaluations of precision and recall returned positive results at 82% and 91% levels, respectively, which are sufficiently accurate to permit regional-scale, reconnaissance sinkhole mapping in complex landscapes.

Induced Sinkhole Formation Associated With Installation of a High-Pressure Natural Gas Pipeline, West-Central Florida

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Induced sinkholes are a known geologic hazard and may be associated with construction activities that cause alteration of ground water flow patterns or induce rapid loads and/or vibrations on karst-affected soils and rocks. This study describes the geophysical and geotechnical investigation of a site in northern Hillsborough County, Florida, where a large diameter underground high-pressure natural gas pipeline was installed utilizing horizontal directional drilling (HDD) methods. Objectives of the investigation were to evaluate the impacts of: 1) pipeline installation on existing ground-collapse features, 2) potential induced ground subsidence and 3) possible effects on water bodies and building structures. The site was investigated utilizing geophysical testing (electrical resistivity), standard penetration test (SPT) borings, and ground vibration monitoring during pipeline construction. In the investigation, subsurface conditions indicative of possible preexisting weakened soil and rock materials associated with incipient raveled zones in overburden soils and soil-filled conduits in limestone bedrock were found in proximity to the pipeline corridor. During the HDD boring and pipeline installation, noticeable ground vibrations occurred, along with formation of several ground settlement/collapse features. The data suggest two mechanisms of induced sinkhole formation: erosion of weak zones in overburden soils by the high pressure drilling mud and/or erosion of weak, soil-filled conduits in limestone bedrock. In addition to current settlement impacts to the property, the investigation found a potential for future ground subsidence associated with undetected eroded and raveled zones that may in the future propagate to the land surface.

Characterization of Karst Collapse Hazard Based on Groundwater Fluctuations in Qingyun Village, Guigang, Guangxi, China

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In the past decade, sinkhole collapses occurred every year at Qingyun village, Guigang, Guangxi, China. Groundwater fluctuations were thought to cause these collapses. A high resolution real-time monitoring system was established to assess sinkhole hazards in this area. Monitoring of water levels of residential and community wells indicate a water shortage in the shallow karst aquifer, which is greatly influenced by precipitation in the study area. Domestic and irrigation water usage could result in frequent and dramatic changes of water level in the shallow karst aquifer. By comparing with real-time monitoring of the groundwater level in a referenced area with no sinkhole collapsing event, a characterization process was developed to assess sinkhole hazards in the Qingyun village area. Characterization criteria include daily water level fluctuations of the karst aquifer, recovery of water level in the karst aquifer, maximum declining rate of water level in the karst aquifer, and sinkhole distribution within 500 m of water pumping activity. The characterization process was then applied to the study area to identify and prioritize areas that are most likely to be affected by human activities. This characterization process could be used by engineers and land-use planners to prioritize water usage and to prevent the development of soil voids and human-induced sinkholes in active karst areas.

Investigations of Large Scale Sinkhole Collapses, Laibin, Guangxi, China

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A series of sinkholes collapsed at Jili village and Shanbei village, Laibin Guangxi, China in June 2010. A large underground stream exists in the north-south transect of the study area and passes the collapse site. Preliminary investigations revealed that extremely heavy rainfall between May 31 and June 1 2010 may have triggered this collapse event. The precipitation, as high as 469.8 mm within one day, was a record high in the study area. A long period of drought in 2009 followed by extremely heavy rainfall along with cave roof collapse may have caused the collapse event on June 3 2010. The "water hammer" effect and collapse-triggered earthquakes caused severe ground failure and fractures in residential houses and Jili Dam. Several collapse events were caused by extreme weather conditions in Guangxi over the past few years. Further studies of the relationship between extreme weather events and sinkhole collapses will help minimize the damage or impact to human infrastructure by avoiding areas susceptible to collapse or by designing infrastructure to better withstand subsidence.

A Calibration Test of Karst Collapse Monitoring Device by Optical Time Domain Reflectometry (BOTDR) Technique

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Brillouin Optical Time Domain Reflectometry (BOTDR) is a distributed fiber optic strain sensing systems based on Brillouin scattering. This technique may potentially become a useful tool to monitor and predict karst collapse, especially for linear infrastructure such as roads, highways, and railways. This paper introduces a calibration device which is used to establish the relationship between fiber deformation and underlain soil -cave dimension. Based on the deformation characteristics of the sinkhole collapse, the mechanical relation between soil body and sensing fiber is analyzed, and a simplified model of collapse is proposed for testing design. The experimental tests are carried out through the designed equipment to investigate the effect of the sinkhole's size and the overburden stratum's thickness on embedded optical fibers. Firstly, the sinkhole formation process was stimulated with the orderly changes in load on the optical fiber. Secondly, the impact of the changes of sinkhole size on the sensing fiber monitoring was analyzed. It shows from the experiment results that the strain change in the sinkhole formation process can be monitored by distributed optical fiber sensing technology and the sinkhole size can be reflected through the optical fiber strain range. Besides, the sensibility of coated optical fiber in sinkhole collapse monitoring tests varies between different types of optical fibers. Due to the effective response of the distributed optical fiber sensing technology to sinkhole forming and evolving, it can be adopted in the monitoring for potential sinkhole collapse.

Thursday May 9
9:00am-11:00am
Geophysical Exploration in Karst Terrane

Geophysical Investigations of the Edwards-Trinity Aquifer System at Multiple Scales: Interpreting Airborne and Direct-Current Resistivity in Karst

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Electrical and electromagnetic geophysical characterization is a proven tool for delineating obscured subterranean karstic features, such as caves, sinkholes, and solution enlarged fissures. Geophysical characterizations allow a wide range of deployment scales; airborne methods can accommodate a regional view on the order of kilometers, and ground-based methods can follow up with focused data on the order of meters. A helicopter frequency domain electro-magnetic (HFDEM) survey and ground-based direct-current electrical resistivity imaging (DC-ERI) geophysical studies at the Camp Bullis Military Training Site (Camp Bullis) in central Texas have been used to characterize permeability properties of the Edwards and Trinity Aquifers in the area. Results of three separate investigations identified zones of high density karst features and characterized specific karstic voids, including caves. In 2003, the USGS completed an HFDEM survey of Camp Bullis and nearby areas to map and image subsurface features related to the groundwater resources. The survey refined locations of mapped and previously unmapped faults and characterized the heterogeneity of the subsurface electrical signature. Karst mapping at Camp Bullis identified over 1500 features, and high density zones of features correspond with areas of high resistivity from the HEM data. DC-ERI surveys at several locations were used to infer and characterize known and hypothesized karst features. Site 8 suggests an inferred fault and dissolution feature. Two other sites were surveyed near major caves that directly recharge the Trinity Aquifer (indirectly to Edwards Aquifer) along Cibolo Creek. Integration of multi-scale geophysical datasets could be used to augment aquifer-wide recharge characterization and quantification.

Subbottom Profiling (SBP) Investigation of Sinkhole Lake Structure in Bay & Washington Counties, Florida

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The sandhill lakes of Bay and Washington Counties, Florida, are deep, pristine environments which owe their existence to sinkhole activity as observed in limited bathymetric maps and in the appearance of small circular depressions around their perimeters ("string of pearls") observed on aerial photography especially during low water level periods. However, little investigative information exists that shows the internal, deep structure of these lakes and how that structure might affect interaction with groundwater flow and lake levels.

High resolution seismic reflection surveying with a marine subbottom profiler (SBP) was applied over reconnaissance profile lines on a series of these sandhill lakes in order to investigate the deep structures of the lakes for purposes of determining the mode of sinkhole development within each lake and their relationships with subjacent aquifers, specifically the Floridan aquifer system (FAS). The SBP provided mapping of the bathymetry (maximum 15 - 32 m water depth) and subbottom structure up to an additional 18 - 24 m below the bottom, all with a theoretical resolution of approximately 0.10 m bed thickness.

The resulting SBP profiles showed that a) the lakes form through the coalescence of numerous small sinkhole features, b) the sinkhole features penetrate the uppermost FAS, disrupting the overlying sediments, and c) multiple stages of sinkhole development and sediment movement are exhibited in the subbottom strata.

Improved Imaging of Covered Karst with the Multi-Electrode Resistivity Implant Technique

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Electrical resistivity tomography (ERT, also called ERI) is commonly used to identify geologic features associated with sinkhole formation. In covered karst terrain, however, it can

be difficult to resolve the depth to top of limestone with this method. This is due to the fact that the sediments mantling the limestone are often clay-rich and highly conductive. The resistivity method has limited sensitivity to resistive zones beneath conductive zones. This sensitivity can be improved significantly with electrodes implanted at depths near the top of limestone, in addition to readings at the surface. Deep electrodes are installed with direct push technology, placing an ERT array in the clay-rich karst cover near the top limestone surface contact. This method, which we are calling Multi-Electrode Resistivity Implant Technique (MERIT), offers the promise of significantly improved resolution of epikarst and cover collapse development zones at the limestone surface sediment interface in heterogeneous karst environments. The technique could also help reduce the effects of cultural features typically encountered by surface electrical resistivity surveys in urban environment.

The results of a case study sinkhole investigation in west-central Florida show the applicability of MERIT. At this site the resistivity array length is restricted to 60 meters. The depth to the top of the limestone lies at ~15 meters. Electrodes were implanted both at the surface and at 10 meters depth every 3.3 meters along a profile 50 meters long. The combination of both surface and deep measurements improves the resolution of the sediment-limestone interface over that from surface measurements alone.

Reconnaissance Evaluation of a Potential Future Sinkhole Using Integrated Simple Surface Geophysics and Surface Monitoring Points

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The Arizona Department of Water Resources (ADWR), using satellite-based Interferometric Synthetic Aperture Radar (InSAR) to assess subsidence in parts of Arizona, has identified several subsidence features consistent with potential future sinkholes in an area with several hundred natural evaporite karst depressions or sinkholes. An initial reconnaissance geophysical subsurface evaluation at the most significant of these features was performed in September 2012. Subsurface geo-material strength profiles to depths commonly in excess of 100 meters can be obtained using relatively simple, unobtrusive and inexpensive seismic surface wave (s-wave) geophysical methods such as Refraction Microtremor (ReMi). ReMi can utilize ambient ground vibrations from natural sources or deliberate sources such as vehicle traffic or construction equipment. Shallow ReMi has been applied in conjunction with seismic refraction to characterize shallow subsurface material strength as part of assessing the potential for collapse of an evaporate brine cavern into a large sinkhole in southeast New Mexico, but had not been specifically applied to assessing subsurface conditions in the deeper subsurface above and in the vicinity of a possible impending sinkhole.

Two deep ReMi surface wave soundings and two resistivity soundings using the Wenner array method were performed, one each within and outside of the extent of current subsidence as derived from the InSAR. Surface wave velocity profiles indicated relatively low velocity materials extending to depths of 36 to 50 meters; surface wave velocities within the subsidence zone were lower (weaker material) than surface wave velocities outside the zone. The underlying horizon had high surface wave velocities indicating relatively competent rock. Deep resistivity soundings indicated possible lithologic change at depths of roughly 120 to 150 meters. Results of this work, including interpretations and assessments of knowledge gained, practical additional assessment work that could be performed, and some as yet unanswered questions are presented.

Ground-Penetrating Radar, Resistivity and Spontaneous Potential Investigations of a Karst Aquifer near Cancún, Mexico

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Geophysical surveys were made over portions of the Cancún municipal well field in the Yucatán Peninsula of Mexico, approximately 20 km southwest of the city of Cancún, in order to identify karst conduits that channel contaminated surface waters into the main aquifer. Specifically, ground-penetrating radar (GPR), vertical electrical soundings (VES) and spontaneous potential (SP) surveys were employed to identify these conduits and detect water movement through them.

Cancún's municipal water supply has frequently been affected by fecal coliform bacteria and other contaminants. Water supplies are largely derived from highly permeable fractured karst limestone aquifers characterized by rapid transport of microbial and chemical contaminants from the surface to subsurface unconfined and confined aquifers. Quaternary and Tertiary limestone bedrock outcrops across this entire area, which exhibits less than 3 m of local relief.

Schlumberger array VES were made at two locations. One sounding revealed a 3-layered structure consisting of a 177 ohm-m layer 2.1 m thick, (probably weathered limestone), overlying a high resistivity layer 8.2 m thick (massive limestone with some small caves), overlying saturated limestone (45 ohm-m). The other sounding could not be successfully inverted due to lateral resistivity variations. Twenty-one GPR profiles were also made with 50- and 100-MHz antennas along roads passing through the well field. In the upper 5 m these profiles reveal cut-and-fill structures and a myriad of diffractions that may represent collapsed and filled sinkholes or solution-enlarged fractures. A major interface delineated by GPR at about 6-8 m depth probably represents the water table. An unusual transparent zone (absence of GPR reflections) was also visible in one GPR profile made near a surface conduit. This transparent zone was at least 1.5 m wide and extended over several meters depth. SP measurements near this conduit during a rainstorm revealed a peak-to-peak variation of 16 mV, suggesting SP may also be a viable method for mapping subsurface water movement in this well field. The overall implication of this work is that geophysical methods are valuable in delineating recharge points and shallow contaminant pathways, and should be used more extensively in this part of the Yucatán Peninsula to support groundwater investigations.

Thursday May 9 11:00am-12:00pm Formation Processes of Karst and Sinkholes Part 1

Examples of Anthropogenic Sinkholes in Sicily and Comparison with Similar Phenomena in Southern Italy

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Anthropogenic sinkholes affect several built-up areas of Sicily (southern Italy) representing a great risk to people, buildings, and infrastructures. These phenomena are generally associated with the presence of ancient underground quarries for the extraction of calcarenite rock, used for building or ornamental materials. These quarries were poorly constructed and abandoned throughout history.

Field surveys, structural analysis of the fissure networks in the rock mass, and numerical modeling were carried out in order to understand the most significant factors responsible of the instability processes of underground quarries. The genetic mechanisms of anthropogenic sinkholes have also been investigated. Jointing and saturation conditions of the calcarenite, along with indiscriminate enlargement of voids, can reduce the available strength. This strength is needed to maintain the stability of the rock mass above the underground quarry, the lack of which can cause the sinkholes formation.

Finally, a comparison between the cases of Sicily and Apulia regions, where similar anthropogenic sinkholes are widespread, was carried.

Development of Sinkholes in a Thickly Covered Karst Terrane

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A cluster of aquifer drawdown-induced sinkholes developed in eastern Hillsborough County, Florida (west-central Florida), during two major freeze events in 2010. The sinkholes resulted in millions of dollars in losses and caused us to revise our thinking about how sinkholes form in a terrain normally considered to have low sinkhole risk owing to thick, clay-rich cover.

The cover material consists of the Miocene Hawthorn Group, which includes up to 120 m of interfingering expansive clay, sand and sandy clay, and carbonate strata. The lower Hawthorn Group Arcadia Formation is primarily carbonate and is up to 90 m thick. The upper Hawthorn Group Peace River Formation contains more clay and sand with minor amounts of carbonate and is up to 30 m thick. The Hawthorn Group constitutes an effective aquitard for the underlying upper Floridan aquifer (UFA), which is composed of karstic, Oligocene and Eocene limestone and dolostone.

A rapid drawdown of up to 20 m in the potentiometric surface of the underlying UFA resulted in mobilization of water-saturated clays and clayey sands within the Hawthorn

Group. Subsidence and possible clay consolidation resulting from dewatering and loss of support/buoyancy caused development of new sinkholes and reactivation of clay-filled sinkholes that had developed as early as the Miocene Epoch. Stable, clay-filled, relict sinkholes of apparent Miocene age discovered in an earlier investigation in the same area in 1998-1999 support the presence of clay-filled, relict sinkholes in the area. Combining information gathered from study of these modern and relict sinkholes presents evidence of sinkhole development mechanisms in the thickly covered karst of west-central Florida.

Paleokarst Crust of Ordovician Limestone and its Capability in Resisting Water Inrushes in Coalmines of North China

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With increase in mining depth of the Carboniferous-Permian coal seams in North China, it is particularly important to study the heterogeneity of karst development in the underlying Middle Ordovician limestone and determine any impermeable strata that may prevent the pressurized karst water from bursting into coalmines. Detailed analysis of the exploratory borehole data suggests presence of a paleokarst crust at the top of Middle Ordovician Fengfeng Formation. Because of its mechanical strength and low permeability to water, the paleokarst crust can function as an additional water-resisting layer. This paper takes Sihe Mine of Shanxi Province as an example to study the geotechnical and hydrogeological characteristics of the paleokarst crust. Incorporation of this additional hydrological barrier led to more minable coal seams in the coalmine.

Thursday May 9 1:30-2:30pm Formation Processes of Karst and Sinkholes Part 2

Deep Time Origins of Sinkhole Collapse Failures in Sewage Lagoons in Southeast Minnesota Karst

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Three of the approximately twenty-three municipal wastewater treatment lagoons constructed in the 1970s and 1980s in southeastern Minnesota's karst region have failed through sinkhole collapse. Those collapses occurred between 1974 and 1992. All three failures occurred at almost exactly the same stratigraphic position. That stratigraphic interval, just above the unconformable contact between the Shakopee and Oneota Formations of the Ordovician Prairie du Chien Group is now recognized as one of the most ubiquitous, regional-scale, karst hydraulic high-transmissivity zones in the Paleozoic hydrostratigraphy of southeastern Minnesota.

These karst aquifers have been developing multi-porosity conduit flow systems since the initial deposition of the carbonates about 480 million years ago. The existence of syndepositional interstratal karst unconformities between the Oneota and Shakopee Formations and between the Shakopee and St. Peter Formations, were recognized in the 1800s. About 270 million years ago galena, sphalerite and iron sulfides were deposited in pre-existing solution enlarged joints, bedding planes and caves. The region has been above sea level since the Cretaceous and huge volumes of fresh water have flowed through these rocks. The regional flow systems have changed from east-to-west in the Cenozoic, to north-to-south in or before the Pleistocene. The incision of the Mississippi River and its tributaries has and is profoundly rearranging the ground water flow systems as it varies the regional base levels during glacial cycles. The Pleistocene glacial cycles have removed many of the surficial karst features and buried even more of them under glacial sediments. High erosion rates from row crop agriculture between the 1850s and 1930s filled many of the conduit systems with soil. Over eighty years of soil

conservation efforts have significantly reduced the flux of mobilized soil into the conduits. Those conduits are currently flushing much of those stored soils out of their spring outlets. Finally, the increased frequency and intensity of major storm events is reactivating conduit segments that have been clogged and inactive for millions of years.

The karst solution voids into which the lagoons collapsed have formed over 480 million years. The recognition and mapping of this major karst zone will allow much more accurate karst hazard maps to be constructed and used in sustainable resource management decisions.

Emergency Investigation of Extremely Large Sinkholes, Maohe, Guangxi, China

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A series of sinkholes collapsed at Maohe Village, Liuzhou, Guangxi, China. The collapsing event formed 41 sinkholes, 11 donut-shape subsidence areas and 68 fractures in May of 2012. Many ground failures and fractures formed and an area of 40000 m^2 was impacted by the collapsing event. The collapsing event was caused by large scale soil piping and soil void collapses. Preliminary investigations revealed that drastic fluctuations of karst water level caused this collapsing event. Heavy precipitation along with bedrock roof collapse of underground streams may trigger a “water hammer” effect in the karst conduits. The “water hammer” effect caused severe soil damage and subsequent collapses in Maohe Village. Soil disturbance may cause a change in hydraulic gradient, causing water level fluctuations that eventually resulted in sinkhole collapses. By monitoring pressure changes of karst water, turbidity of groundwater, locating soil voids and soil disturbances using ground penetrating radar (GPR), it is possible to predict future sinkhole collapses.

Karst Landforms in the Saraburi Group Limestones, Thailand

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Agricultural development in the Saraburi Province of Central Thailand has increased the demand for groundwater resources. Hydrogeological investigations have been undertaken by Department of Groundwater Resources (DGR) to identify potential zones of groundwater in the karstified limestone of the Saraburi group.

The area is located 120 km North of Bangkok between the cities of Saraburi and Pak Chong in the south, Lopburi to the west, Chai Badan and Nong Pong to the north, and Nakhon Ratchasima to the east. It covers the following districts: Amphoe Pack Chong, Nakhon Ratchasima Province; Amphoe Muang Muak Lek, Khangnoi, Phaputabat, Wong Muang and Chalormphrakiat in Saraburi Province; and Amphoe Moung, Lamsonthi, Phatananikom, Thaluang and Chaibadan in Lopburi Province.

The topography is characterized by mountain ranges, karstic plateaus, and rolling hills of low to medium relief, with low lands in between. The mountainous ridge elevation reaches over 800 m above sea level (ASL), karstic plateaus are developed between 300 and 500 m ASL, and the low lands are at about 100 m ASL. In the karstic plateaus and mountains areas, springs, caves, and dry stream beds exist. In dry periods, some streams in low land areas are dry, but the large rivers continue flowing.

Tropical climate (Monsoon type) with two distinct seasons is characteristic of this area. The dry season begins in October and ends in May, followed by a monsoon season between June and September. Annual rainfall ranges between 1,500 and 2,000 mm and temperature ranges between 20.0^{o}C and 40.7^{o}C.

The area is underlain by the limestone of the Saraburi Group of Permian age. The limestone is exposed as a chain of hills, ridges, and occasionally as mounds which create classic 'tower karst' scenery.

The rainforests, excessive rainfall and widely variable climatic conditions caused karst landscape and cave-forming environment to develop, with streams draining into the limestones from mountain catchments. In this area, the matured karst is locally fringed by tall cliffs that overlook valleys and closed basins. The area underlain by limestone is extensive and rainfall is abundant. Therefore karstification potential exceeds 200 m vertically. Exokarst landforms are well represented. Various types of karrens, tsingi, small- to medium- sized sinkholes, sinking streams, and closed depressions were identified, during site investigation.

A dye study performed in October 2012 indicated the hydraulic connection between a sinking stream and Tham Lumphini Suan Hin Spring, and a water supply well (Well 114) located 300 meters southwest of the spring. Based on dye study, the protection area for the Well 114 and the spring also includes the closed depressions.

Thursday May 9
2:50pm-4:30pm
Hydrological Aspects of Karst

Mapping Flood Related Hazards in Karst Using KARSYS Approach: Application to the Beuchire-Creugenat Karst System (JU, Switzerland)

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The city of Porrentruy (JU, Switzerland) is vulnerable to flooding from karst water draining the system of the Beuchire-Creugenat. Major flood events in 1804 and 1901 led to heavy damage throughout the city and its vicinity. Furthermore small-scale flood events have been recorded five times in the last 30 years - each resulting in substantial costs.

The Beuchire-Creugenat karst system is characterized by a perennial outlet (the Beuchire spring) and several overflow outlets (among which the Creugenat temporary outflow is the most significant one) where the discharge rate often exceeds 15 m^3/s. The ratio between rainfall intensity and discharge rate of the overflow springs is not closely correlated. Therefore, the discharge rates and the conditions at which a certain overflow becomes active could not be assessed without a comprehensive understanding of the karst system behavior. Thus, the establishment of effective flood risk management measures remains significant challenge.

In order to assess similar flood events and to determine the most flooding vulnerable areas, the KARSYS approach has been applied to the Beuchire-Creugenat karst system. A detailed geological 3D model of the study area has been built in order to reproduce the aquifer base geometry, the extension of its expected saturated part(s) and the position of the main vadose flowpaths “drainage axes”. This approach enabled the catchment area delineation by combination of subterraneous drainage axes. The comparison of the discharge time series of the main springs and the relevant rainfalls (~10-year series) provides sufficient implications for understanding and consequent reproducing of threshold functionality of the karst system exposed to flooding due to rainfall events. A relationship could be established between rainfall intensity/frequency (return period) and the corresponding elevation of the groundwater level within the karst conduits (or respectively, the relevant spring discharge rates). The known overflow springs have been added in the 3D model. The areas where (and when) karst groundwater is expected to reach the ground surface during extreme high-water events could be identified as potential overflow springs. Such draining sensitive areas have been delineated and mapped according to the calculated return period of multiannual, 30- and 300- years flood events and the relevant maximum discharge rates at the main outlets have been assessed.

Conceptualization of Groundwater Flow in the Edwards Aquifer through the Knippa Gap Hydrogeologic Constriction, Uvalde County, Texas

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The Balcones Fault Zone Edwards aquifer (Edwards aquifer) is one of the major regional karst aquifers in the United States, with an average withdrawal of 950 million liters per day (L/d). This study focuses on the connection between the Uvalde pool and the San Antonio pool of the Edwards aquifer, west of the San Antonio metropolitan area in Uvalde County, Texas. This area is known as the Knippa Gap and is located north of the community of Knippa. The Knippa Gap is a major zone controlling the flow from the Uvalde pool to the San Antonio pool. The San Antonio pool is the primary source of water for the greater San Antonio water supply. The Knippa Gap is a restriction where the aquifer narrows to a width estimated to be approximately 4 km, is bounded by northeast trending faults of the Balcones Fault Zone on the north, and uplift from the Uvalde salient and igneous intrusive plugs to the south (Green et al, 2006). The hydrogeology in the Knippa Gap have been a topic of major interest among researchers in this area for numerous years, yet the exact location, nature of boundaries, and karst hydrogeology are not well defined, and the flow through this area is in need of refinement to improve the aquifer water balance.

This study integrates recent research by other scientists with field studies conducted during the summer of 2012 as part of an M.S. thesis. This paper is limited to a discussion of the water quality as it relates to the southern flow boundary of the Knippa Gap near the Devils River Trend of the Uvalde salient. Water-quality data constrain a revised conceptual model of the flow and karstification in this critical area of recharge to the San Antonio pool, and provide specific lateral boundaries and vertical karstification zones which are being tested in the more comprehensive M.S. thesis. Although current interpretations are tentative, it appears this conceptual model will be readily convertible into a digital model that can test hypotheses relating a much broader suite of calibration data, including water levels, water budgets, and spring discharges.

Delineating Source Areas to Cave Drips and Cave Streams in Austin, Texas, USA

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Delineating the source area of cave drips and streams (subsurface infiltration catchment area) is important for maintaining high-quality water sources critical for healthy cave ecosystems. In order to focus protection for cave ecosystems, particularly those containing federally listed species, it is necessary to accurately delineate the potential contributing infiltration area with high confidence.

Various methods are used in conjunction to delineate subsurface infiltration catchment areas in four Balcones Escarpment sites (Buttercup Creek, Barker Ranch #1 Cave, McNeil Drive, and Davis Lane). The methods consists of 1) observation and flow measurement of drips, speleothems, pools, and streams under wet and dry conditions to characterize drips as discrete or seepage, 2) cave mapping surveys to determine spatial relations and elevation of drips, speleothems, pools and streams, 3) hydrostratigraphic characterization (dip of beds, faulting, and the rock tendency to perch vadose groundwater downward at a minimum hydraulic gradient), 4) water-quality characterization and comparison with potential sources and 5) dye and chemical tracing. Steps 4 and 5 provide the most direct delineation of source areas based on the detection (or non-detection) of tracers and injection locations. Not all of the methods were applied at all four study sites and some catchment areas are so large that they were not completely delineated without additional investigation.

Mapping the highest elevation of a drip source in a cave limits the surface extent of any infiltration source area. A non-persistent, seepage drip is more likely to originate from soil-moisture drainage close to the cave footprint. Direct tracing of vadose groundwater illuminates the influence played by dip and lower permeable hydrostratigraphic units in perching groundwater and directing vadose flows long distances to drips and cave streams. Injected tracers measured minimum hydraulic gradients of 0.4 to 3% across lower permeable hydrostratigraphic units and minimum hydraulic gradients of 12% across higher permeable units. The updip outcrop of the top of a perching lower permeable unit, as well as caves that breach the lower permeable unit, may be used to define the extent of a subsurface catchment area. Through deeper investigation of the caves using various methods together, the mapped subsurface catchment areas are refined to a focused source area. Where insufficient data are available to constrain the boundaries, the subsurface catchment area should always be conservatively overestimated.

Use of Physical and Chemical Response in Cave Drips to Characterize Upland Recharge in the Barton Springs Segment of the Edwards Aquifer, Central Texas, USA

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Cave drips are useful for characterizing recharge and transport through soils, particularly in upland karst settings. Estimation of upland recharge is important for the Barton Springs Segment (BSS) of the Edwards Aquifer, but discrepancies between previous and recent studies indicate how little is known about it in the BSS. We outline a methodology for using cave drips to characterize upland recharge and present initial findings from a study of drips in four BSS caves.

Soils in the BSS are heterogeneous, making it difficult to characterize their hydraulic properties over larger areas, particularly with methods that only yield information about a discrete location (i.e., infiltration tests, moisture sensors). This is particularly true in the BSS where thin, clay-rich, soils often contain macropores (i.e., desiccation cracks, roots, burrows) that act as preferential flowpaths for rapid recharge through the soil zone. Cave drips are well suited for characterizing recharge in upland areas as they often have large source areas.

Drip responses to storm events were monitored at drips in three BSS caves. Hydrograph separation and chemical analyses allowed distinction of fast flow, through macropores and conduits, from slow flow drainage primarily from the soil column. Natural and artificial soil tracers indicate that surface water reaches many of the drips within a few hours of the onset of storm events, even though reported soil K_{sat} values of

0.06-0.57 in/hr are relatively low, and no discrete recharge was observed within the subsurface drainage basin of three of the caves. These results indicate that upland recharge may contribute a greater portion of total recharge in the BSS than previously estimated, and that rapid recharge can occur in the absence or discrete recharge features likely via macropore flow.

The Need for Presumptive Habitat Considerations in Working with Subterranean Aquatic Species of Concern: Three Ozark Region Case Histories, USA

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Delineating habitats for aquatic species of concern present in groundwater systems, and especially those in karst groundwater systems, presents challenges. It is not reasonable to limit the delineated habitat to those portions of a groundwater system that can be directly observed. How then do we make reasonable delineations? Three case histories in the Ozarks region of the central USA illustrate differing approaches for identifying presumptive habitat in recharge area delineations for subterranean species of concern. The first case study of the Tumbling Creek Cavesnail explores the reasoning for designating presumptive habitat downgradient of observed habitat in a cave stream. The second case study of Ozark Cavefish illustrates reasonable designation of presumptive habitat in a complex distributary spring system that discharges water from a well-developed saturated epikarstic area. The final case history illustrates the case for expanding the presumptive habitat in both upgradient and downgradient areas for a Hell Creek Cave Crayfish site in northern Arkansas.

Friday May 10
8:20am-11:20am
Mapping and Management of Karst Regions

Populating a Chronological Catalogue of Sinkholes in Italy: The First Step for Assessing the Sinkhole Hazard

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Among the many different types of geological hazards affecting the Italian territory, sinkholes have often been underestimated (if not neglected entirely), and only in some sectors of the country they have been effectively considered in hazard and risk analysis. Nevertheless, sinkholes affect large parts of Italy, covering the whole territory with a variety of typologies, and showing both natural and anthropogenic origin. The latter clearly derives from the long history of Italy, with the complex historical vicissitudes that have characterized this territory, during which different types of artificial cavities have been realized underground for different purposes in different epochs. Over time, many of these cavities have been abandoned, and the consequent loss of memory resulted in their inclusion in newly developed parts of towns, thus creating a serious risk to the built-up environment above.

Starting from these considerations, an archival research was started to collect information about the occurrence of sinkholes in Italy, with particular attention to their precise site and date of occurrence, in order to make an effort in assessing, respectively, the susceptibility and the hazard related to the particular phenomenon under study. As concerns date of occurrence, the accuracy of the information is provided (depending upon the amount of available data), with the highest quality when hour, day, month and year of occurrence are indicated, and a decrease in quality when one or more of these data are lacking. For being included in the database, at least a temporal reference (even though generic) of the sinkhole has to be known.

The present article illustrates the first results of this study, describing the catalogue obtained so far which consists of more than 650 sinkhole events for which at least some information about temporal occurrence of the event have been found. The data, even though not definitive, represent a good starting point for analysis of the sinkhole hazard at a national scale, aimed at increasing the level of attention by scientists, practitioners and authorities on this subtle hazard.

Lessons Learned from Occurrence of Sinkholes Related to Man-made Cavities in a Town of Southern Italy

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The presence of man-made cavities below the historical parts of towns is a common feature in large portions of Italy. Different typologies of anthropogenic cavities have been excavated in different epochs for many purposes, including research and collection of potable water, establishment of underground working sites for olive oil production, worship sites, etc. Underground quarries are probably the most diffuse typology of subterranean cavities, especially the largest ones. Originally located at the outskirts of towns, quarries are increasingly found in built up areas due to urban expansion that has characterized the last century.

This paper describes the recent occurrence of sinkholes related to underground quarries in the town of Altamura, in the Murge plateau of inland Apulia, where since 2006 a number of sinkholes have formed above subterranean calcarenite quarries, the local rock mostly used for building purposes. These quarries developed below ground because the calcarenite is generally located covered by clays (ranging in thickness from a few to 15 meters). Their abandonment, and the progressive weathering of the rock, has caused failures in the underground quarries. Eventually, such instabilities propagated upward until reaching the surface, and producing sinkholes.

Many sinkholes in Altamura have occurred within the urban area, and/or in areas of recent or proposed future constructions. As a result, in 2008 the local Authority established a new building code, requiring detailed geological studies in areas determined to be at risk in order to verify and mitigate any hazardous situations. A great amount of data has been collected in these studies in recent years, which has been organized and managed in a dedicated geo-database.

All activities used to identify the underground quarries, recognize the corresponding sinkhole-prone areas at the surface, survey the cavities, produce detailed maps, and reclaim the sites in order to allow future development, are described in this paper, as an example of how to properly manage a territory characterized by sinkhole problems.

Restoring Land and Managing Karst to Protect Water Quality and Quantity at Barton Springs, Austin, Texas

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The Water Quality Protection Lands program was established in 1998 based on a bond proposal passed to protect Barton Springs in the heart of Austin, Texas. Barton Springs is a popular swimming area for citizens and is also home to at least one federally endangered species of salamander. The initial bond called for 6,070 hectares of land to be protected. Land acquisition has benefitted from additional bonds since then as well the use of grants to raise the total acreage to over 10,731 hectares at present. Additional cost saving measures such as the use of conservation easements have allowed these dollars to be stretched further. Science has helped guide the acquisition of land into more productive geographic areas (based on recharge) and helped direct the management of these lands to further benefit water quality and quantity. Land management focuses on ecological restoration of vegetation back to native prairie and savanna ecosystems which provide optimal water yield from the land based upon the inverse relationship between woody cover and water yield. These restoration actions combined with proper karst management protects both water quality and water quantity recharging through these lands.

The Use of Drought-Induced “Crop Lines” as a Tool for Characterization of Karst Terrain

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The persistent drought of the summer of 2012 in the Midwestern US impacted the health and vigor of Illinois’ crops. Serendipitously, it provided a rare opportunity to examine and characterize the bedrock surface and underlying karst aquifer within the Driftless Area of northwestern Illinois. Complex networks of vegetated lines, herein referred to as crop lines, and polygonal patterns crisscrossed the dry summer landscape of Jo Daviess County. Initially, the crop lines were examined and photographed on the ground using a hand-held digital camera on the ground and from a small, high-wing aircraft at an elevation of 300 m. The orientations, widths and horizontal separations of the lines were measured. Crop lines and their patterns and orientations were compared with those of crevices in outcrops, road cuts and quarries, and with lineaments seen in LiDAR imagery of Jo Daviess County.

Primarily confined to fields of alfalfa and, to a lesser extent, soybeans and corn, the crop lines are the result of a combination of extremely dry conditions, and a thin soil zone overlying fractured and creviced Galena Dolomite bedrock. The plants forming the lines tend to grow denser, taller (0.5 m vs 0.15 m) and darker/greener than those in adjacent areas. Alfalfa taproots are the deepest of the aforementioned crops extending up to 7 m below the surface. Groundwater and associated soil moisture within the vadose zone present within bedrock fractures and crevices provide the necessary moisture to sustain the overlying healthy plants, while the remaining area of the field exhibits stunted and sparse plant growth.

Overall, the crop lines are a reflection of the creviced pattern of the underlying karst bedrock and associated karst aquifer, and reveal the degree and extent of karstification in eastern Jo Daviess County. The crop lines were consistent with the angular lines of adjacent streams that show a trellised drainage pattern. Stream patterns like these are well known and are due to drainage controlled by crevice/fracture patterns in the top of bedrock. The lines appeared to have been formed by two sets of fractures trending roughly north-south and east-west with occasional cross-cutting fractures/crevices. The east-west trending lines are consistent with tension joints, and the north-south lines are consistent with the shear joints identified by earlier researchers. The trends of the crop lines, tension and shear joints are similar to those of lineaments identified from LiDAR imagery in the same area (N 20° W, and N 70° W and N 70° E) and coincide with the occurrence of karst features throughout eastern Jo Daviess County.

The pattern observed in the crop lines closely mimics the fracture/crevice patterns of the bedrock surface. The widths and extent of the lines may be used as a proxy for the karst features present on the bedrock surfaces. Crop lines, coupled with solution-enlarged crevices seen in bedrock exposures, yield a three dimensional view of the bedrock crevice-fracture system, and ultimately could provide a more complete and accurate model of the karst aquifer in the study area and similar karst areas in the Midwestern US and perhaps in other karst regions of the world.

Mapping Surface and Subsurface Karst Geohazards for Highway Projects: SR 71 South Knoxville Blvd. Extension, Knox County, Tennessee

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The proposed extension of SR 71 (South Knoxville Boulevard) located in Knoxville, Tennessee necessitated a preliminary geologic evaluation of the corridor which was under consideration by the Tennessee Department of Transportation. A geohazards review disclosed the presence of extensive karst terrain located within the corridor being considered. A number of caves were also found during the investigation. The proposed routes within the study corridor were found to cross a series of very large multiple hectare (acre) sinkholes. In addition, a biological investigation of the route revealed the presence of a rare and endangered species of cave salamander called the Berry Cave Salamander.

The geologic and geotechnical investigation resulted in the development of a surface karst map of the study corridor. Sinkholes and cave entrances were located and a generalized karst boundary was established. In addition, a survey map of the Meades Quarry Cave was made which provided supporting quantitative data in connecting surface sinkholes and the cave containing the endangered Berry Cave Salamander. A recommendation of the study was a dye tracing of the suspect sinkholes. If this highway project is constructed, then measures will be required to mitigate the effects of the highway runoff in the karst terrain affecting the Berry Cave Salamander.

Government Canyon State Natural Area: An Emerging Model for Karst Management

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Government Canyon State Natural Area (GCSNA) is located on the northwest edge of San Antonio, Texas, USA. Ninety percent of the 47.04 km^2 property is located on the recharge zone of the karstic Edwards (Balcones Fault Zone) Aquifer. Urban development is encroaching onto the Edwards Aquifer karst and threatening groundwater quality and karst ecosystems. GCSNA has served as a model for karst management by:

- defining existing resources;
- restoring impacted resources;
- monitoring and protecting groundwater quality and quantity by encompassing 62% of the 30.46 km^2 Government Canyon watershed on the Edwards Aquifer recharge and contributing zones, and over 23 km^2 of adjacent karst watersheds;
- preserving the unique cave fauna;
- limiting all development to non-karst areas;
- using state-of-the-art construction techniques and infrastructure to minimize water and ecological impacts;
- monitoring land use conditions for an adaptive resource management plan; and
- establishing contiguous buffers around the core resource area.

This approach was made possible by designating GCSNA as a karst preserve in order to most effectively manage all of its resources. Karst attributes of GCSNA predominantly determine the location, type, magnitude, and management of its most significant natural and cultural resources. Federally listed endangered invertebrate species and the county's largest known bat population occur in its caves. Springs and deep canyons provide habitat for a diverse flora and fauna, including the endangered Golden-cheeked warbler. These springs and species, along with chert deposits and natural trails through rugged terrain, have supported human occupation since prehistoric times. Springflow and streamflow rapidly recharge the Edwards Aquifer to maintain this sole source system as a sustainable regional water supply. Partnerships with multiple agencies and volunteers have minimized individual costs, provided more thorough and complete assessment of karst resource issues, and developed public educational programs on the values of karst.

Combining LiDAR, Aerial Photography, and Pictometric Tools for Karst Features Database Management

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The mapping of karst features has taken on increasing importance in land use planning and zoning regulations across south east and east central Minnesota. The delineation of sinkholes, springs, and other features has traditionally depended on extensive field work, using topographic maps, and intensive networking with local landowners. The luck of the observer has also been critical as many sinkholes are rapidly refilled by landowners, concealed within extensive row crops, or hidden under tree canopies.

The application of aerial tools allows mapping across large areas. Potential karst features can be identified, and indistinct or otherwise suspicious points targeted for field verification. LiDAR mapping across Minnesota now allows high-resolution imaging (1.5 m horizontal and <15 cm vertical) of small depressions in karst landscapes without interference from vegetation. These features can be visually compared to aerial photography, both visible and infrared, flown periodically by the U.S. Department of Agriculture (USDA) to verify persistence and/or reappearance of features through time. Additionally, low angle, high-resolution pictometric imagery allows overhead views from several angles to further identify and verify the genesis of a given depression. In areas with previously mapped karst features, precise locations can be compared to earlier estimates of location, which is particularly useful in applications like nearest neighbor analysis.

The improved elevation mapping resulting from LiDAR work has greatly improved geologic mapping efforts based on well driller's logs. This improvement in geologic mapping allows much better correlation of karst features within stratigraphic units as well as identifying structural controls. The geologic mapping efforts are beyond the scope of this paper.

While field verification is the ultimate standard, many obvious sinkholes can be identified, and numerous non-sinkhole depressions eliminated from consideration, helping focus valuable field time.

An Evaluation of Automated GIS Tools for Delineating Karst Sinkholes and Closed Depressions from 1-Meter Lidar-Derived Digital Elevation Data

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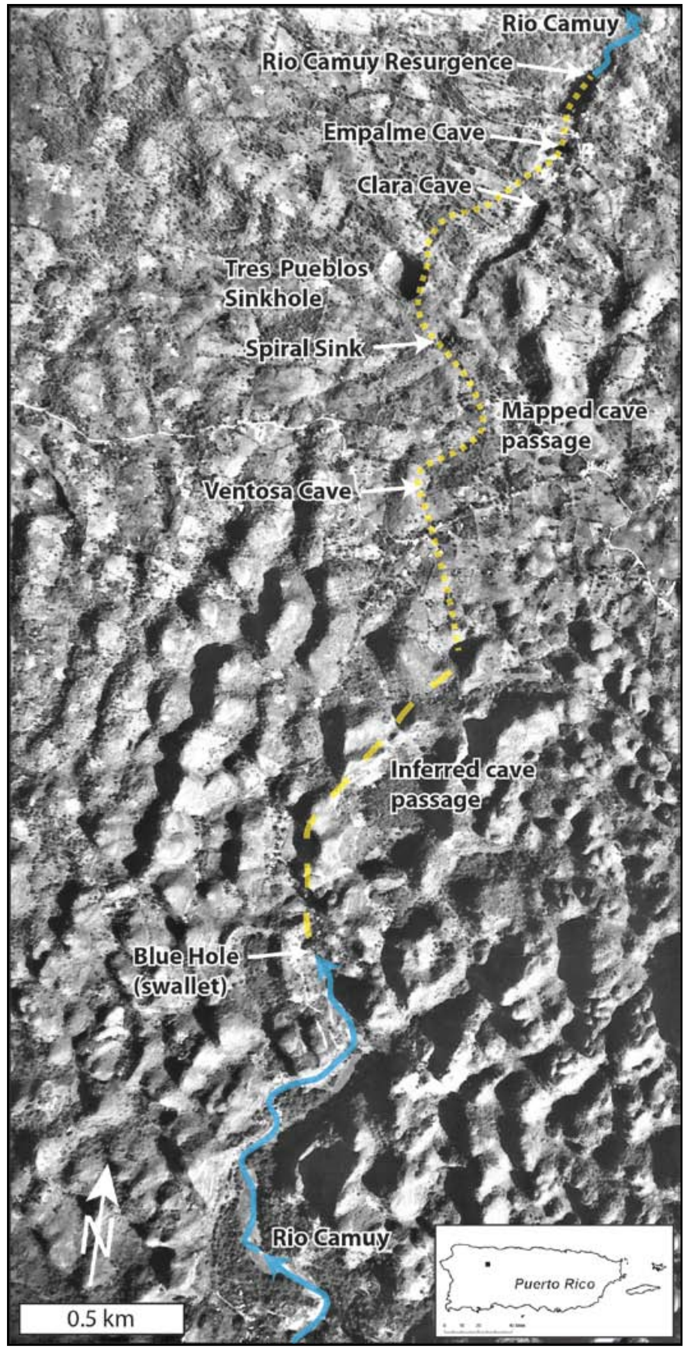
LiDAR (Light Detection and Ranging) surveys of karst terrains provide high-resolution digital elevation models (DEMs) that are particularly useful for mapping sinkholes. In this study, we used automated processing tools within ArcGIS (v. 10.0) operating on a 1.0 m resolution LiDAR DEM in order to delineate sinkholes and closed depressions in the Boyce 7.5 minute quadrangle located in the northern Shenandoah Valley of Virginia. The results derived from the use of the automated tools were then compared with depressions manually delineated by a geologist. Manual delineation of closed depressions was conducted using a combination of 1.0 m DEM hillshade, slopeshade, aerial imagery, and Topographic Position Index (TPI) rasters. The most effective means of visualizing depressions in the GIS was using an overlay of the partially transparent TPI raster atop the slopeshade raster at 1.0 m resolution. Manually identified depressions were subsequently checked using aerial imagery to screen for false positives, and targeted ground-truthing was undertaken in the field. The automated tools that were utilized include the routines in ArcHydro Tools (v. 2.0) for prescreening, evaluating, and selecting sinks and depressions as well as thresholding, grouping, and assessing depressions from the TPI raster. Results showed that the automated delineation of sinks and depressions within the ArcHydro tools was highly dependent upon pre-conditioning of the DEM to produce "hydrologically correct" surface flow routes. Using stream vectors obtained from the National Hydrologic Dataset alone to condition the flow routing was not sufficient to produce a suitable drainage network, and numerous artificial depressions were generated where roads, railways, or other manmade structures acted as flow barriers in the elevation model. Additional conditioning of the DEM with drainage paths across these barriers was required prior to automated delineation of sinks and depressions. In regions where the DEM had been properly conditioned, the tools for automated delineation performed reasonably well as compared to the manually delineated depressions, but generally overestimated the number of depressions thus necessitating manual filtering of the final results. Results from the TPI thresholding analysis were not dependent on DEM pre-conditioning, but the ability to extract meaningful depressions depended on careful assessment of analysis scale and TPI thresholding.

The Rio Camuy can be seen flowing across the large Tres Pueblos Sinkhole. The sinkhole is about 600 ft across and about 400 ft deep. Image courtesy of United States Geological Survey; Image source: Earth Science World Image Bank http://www.earthscienceworld.org/images

Clara Cave (Cueva Clara) is one of the entrances to the Rio Camuy Cave System. The Department of Natural Resources of Puerto Rico developed a portion of the cave system into a park that opened to the public in 1986. Photo courtesy of Wikipedia Commons.



The Rio Camuy Cave System is a large underground river located in the north coast limestone belt of Puerto Rico. The Rio Camuy flows north from the swallet where it goes underground at Blue Hole and surfaces again at the Rio Camuy Resurgence after flowing about 4 miles underground. The endergound river can be seen at or near the entrances to Ventosa Cave, Spiral Sink, Tres Pueblos Sinkhole, and Empalme Cave.

Pump jack in sinkhole in Dagger Draw oil field, Eddy Co., NM., photo compliments of the US Bureau of Land Management.

Sinkhole collapse along a stormwater line. Photo by Joe Fischer.

Photo by Marco Vattano.

Dye tracing performed in a sinkhole collapsed within a storm water retention pond on the Edwards Aquifer of central Texas. Photo by Brian Hunt (BSEACD).

Aerial view of Jim's Water Service Sinkhole, northern Eddy County, New Mexico about six weeks after initial collapse. Photo by NCKRI.

Mirror Lake at Bottomless Lakes State Park, New Mexico. Photo by NCKRI.