CARBONATE CRITICAL ZONE – RESEARCH COORDINATION NETWORK

**Workshop 2 Field Trip Guide**

# A Brief Introduction to the Geology, Hydrology, and Natural History of North Central Florida

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**On the cover:** Looking downstream at the Rice Marsh of Ichetucknee River. This wide spot in the river is a few hundred meters below Had, Blue Hole, and Devil's Eye springs. A few additional large springs discharge directly to the Rice Marsh, but springs are uncommon below the Rise Marsh. The location is about ~ 6 km upstream from the confluence with the Santa Fe River and this confluence is ~10 km upstream of the confluence of the Santa Fe and Suwannee rivers. Because the Ichetucknee River is essentially a long spring run, it rarely has tannic stained water unlike most Florida rivers and instead is usually clear with Secchi disk measurements that can be many tens of meters "deep". Because the river has an average depth of < 2 m deep, the Secchi disk values are measured horizontally. The rare times when the Ichetucknee River becomes tannic occur when flooding of the Suwannee river backs tannic water into the Santa Fe and Ichetucknee rivers.

**Land Acknowledgment**

During our field trip today, we will travel through the original homeland of the Muscogee, Timucua, and Seminole peoples, and other Nations that traded and migrated through the area. The University of Florida main campus in Gainesville sits on the original lands of the Potano people, a Timucua-speaking society who were victimized by colonial disease and violence. The Seminole Tribe of Florida, the Miccosukee Tribe of Indians of Florida, and other Nations, continue stewardship of these places, for which we are grateful.

**Acknowledgments**

We thank staff at Santa Fe Community College, Ichetucknee Springs State Park, and O'Leno State Park for access to the field trip stops. We also thank Dr. Anita Marshall, University of Florida, for demonstrations of best practices to make field trips accessible and Dr. Ángel Garcia, James Madison University, for demonstrations of LIDAR cave mapping techniques. We thank Tom Morris, Dr. Matt Cohen, Dr. Andrew Luhmann, and Dr. Madison Flint for sharing results of their work in the carbonate critical zone of north Florida.

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## INTRODUCTION

Today's field trip includes visits to three sites in north-central Florida that represent key geomorphic, geologic, and hydrologic characteristics of the region (Fig. 1 and Appendix A). Each site reveals influences on the carbonate critical zones (e.g., Martin et al., 2021) of a major topographic feature - at least for Florida - called the Cody Scarp. Describing this feature as a "scarp" is perhaps a misnomer. It is barely noticeable in the landscape, although it provides the greatest topographic relief in Florida, with a slope that averages ~2.5 m/km over a distance of approximately 10 km (Puri and Vernon, 1964). The primary features to suggest the presence of a scarp are the small rolling hills pockmarked by sinkholes that we will drive through between Stops 2 and 3. This hilly zone, which Gainesville also sits on, separates two major flat-lying geomorphic provinces. To the southwest of the scarp, the Gulf Coast Lowland Province has elevations that range from sea level to ~20 m above sea level. To the northeast of the scarp is the Northern Highlands Province with elevations that range between ~40 to 50 m above sea level (Puri and Vernon, 1964). We will start the trip by driving west into the Gulf Coast Lowlands to the first site and end the trip at two sites on the southwestern edge of the Cody Scarp.

### Stratigraphy and Geologic History of North-Central Florida

The hills and sinkholes that mark the Cody Scarp were formed by erosion of Miocene and younger siliciclastic rocks and sediments that blanket most of peninsular Florida (Fig. 2). The Miocene rocks form the Hawthorn Group (Groszos et al., 1992; Scott, 1988; Scott, 1992), which can reach thickness >700 m in South Florida. To the northeast of the scarp, the Hawthorn Group has a maximum thickness of ~100 m. The Hawthorn Group is capped by several thin Pliocene units as well as a veneer of undifferentiated and unconsolidated Pleistocene and Holocene quartz sands. Underlying the Hawthorn Group are Oligocene and Eocene carbonate rocks (mixed limestone and dolomite) that make up the Suwannee and Ocala limestones and Avon Park and Oldsmar formations. The carbonate rocks also contain minor amounts of siliciclastic and evaporite minerals, which are mostly confined to the Avon Park Formation.

Most carbonate minerals exposed in north-central Florida are mapped as the Eocene Ocala Limestone, although the Oligocene Suwannee Limestone sporadically crops out where it has not been removed by erosion. These

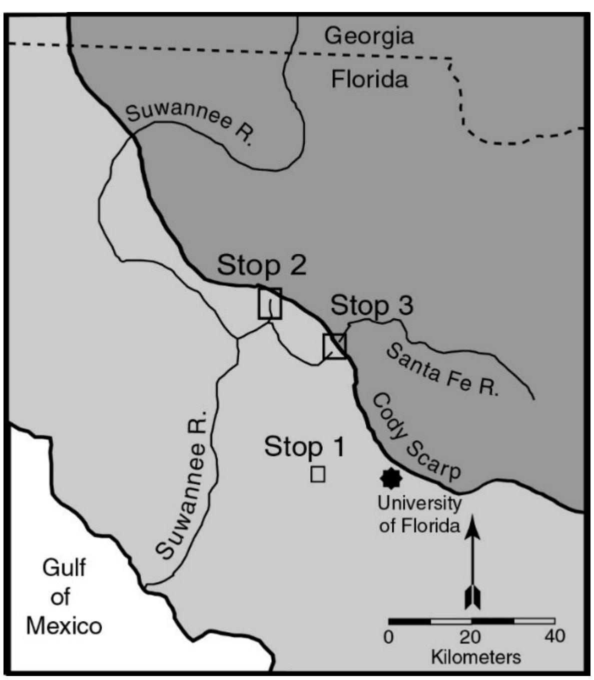


**Figure 1.** Sketch map of north-central Florida showing approximate locations of the field trip stops and the relationships between the Suwannee, Santa Fe and Ichetucknee river drainages. The darker shaded region marks the presence of Hawthorn Group rocks where the Floridan aquifer is confined. In the lighter shaded region, the Hawthorn Group is missing and the Floridan aquifer is unconfined. The boundary between confined and unconfined Floridan aquifer is the Cody Scarp. Modified from Martin and Dean (2001).

| System | Series | Hydrostratigraphic Unit | Lithostratigraphic Unit | Lithologic Descriptions | |
|---|---|---|---|---|---|
| Quaternary | Holocene | Surficial Aquifer System | Undifferentiated Pleistocene-Holocene Sediments | Fine to coarse grained poorly indurated quartz sands with minor amounts of clay. Peat and fresh water carbonates are present in places. | Mostly siliciclastic rocks |
| | Pleistocene | | | | |
| Tertiary | Pliocene | | Miccosukee Fm<br>Cypresshead Fm<br>Nashua Fm | Interbedded clay, silt, sand, and gravel siliciclastics with carbonate content increasing upward. | |
| | Miocene | Confining Unit, contains lenses of the Intermediate Aquifer | Hawthorn Group<br>Statenville Fm<br>Coosaqhatchie Fm<br>Markshead Fm<br>Penny Farms Fm<br>St. Marks Fm | Fine to coarse grained quartz sand, silt and clay minerals with occational phosphate mineral-rich units. The intermediate aquifer is confined to four distinct dolostone units. | |
| | Oligocene | Floridan Aquifer System | Suwannee Limestone | Variable vuggy and muddy limestone. | Mostly carbonate rocks |
| | Eocene | | Ocala Limestone<br>Avon Park Fm<br>Oldsmar Fm | Fossiliferous limestone interbedded with vuggy dolostone. Avon Park acts as a confining unit in places. | |
| | Paleocene | Sub-Floridan Confining Unit | Cedar Keys Fm | Coarsely crystalline, porous dolostone w/ minor limestone and evaporites. | |
| Cretaceous and older | | | Undifferentiated | | |

**Figure 2.** Lithostratigraphic and hydrostratigraphic units of north-central Florida. Modified from Scott (1988; 1992) and Groszos et al. (1992).

carbonate rocks, along with the Avon Park and Oldsmar formations, comprise the Floridan aquifer system, which is one of the most productive aquifers in the world. The Avon Park Formation acts as a discontinuous intermediate confining unit that separates the upper and lower Floridan aquifers. The Floridan aquifer has never been deeply buried or recrystallized and thus retains primary porosity that can be as high as 20%, supporting its ability to produce large volumes of water. The primary diagenetic alteration to the Floridan aquifer is extensive dissolution forming many air and water-filled caves that enhance the permeability of the rocks. The combination of high primary porosity and extensive dissolution features makes the Ocala Limestone a great example of eogenetic karst (Vacher and Mylroie, 2002). Eogenetic karst contrast with telogenetic karst, which has been recrystallized during deep burial, a process that occludes its primary porosity and forms secondary porosity through fracturing and dissolution.

The shift from carbonate deposition during the Eocene and Oligocene to siliciclastic deposition during and post Miocene reflects the presence and subsequent closing of the Suwannee Channel (also known as the Georgia Seaway, Fig. 3). This channel was located around the current Florida-Georgia border and separated the Florida carbonate platform from the mainland of North America during the Early Tertiary. The channel allowed an ocean current (the proto-Gulf Stream, Pinet et al., 1981) to flow from the Gulf of Mexico to the Atlantic and prevented siliciclastic sediments that had been eroded from the Appalachian Mountains from being deposited on the carbonate platform to the south. Instead, the sediment was swept to the east and deposited on the continental slope to form bathymetric features including the Charleston Bump and Blake Spur in the South Atlantic Bight. Limited siliciclastic deposition on the Florida carbonate platform allowed extensive carbonate mineral production (i.e., the carbonate factory) during the Eocene. The Florida carbonate platform was thus similar to and, in fact, the northern extension of the carbonate platforms that make up the modern Bahamian archipelago.

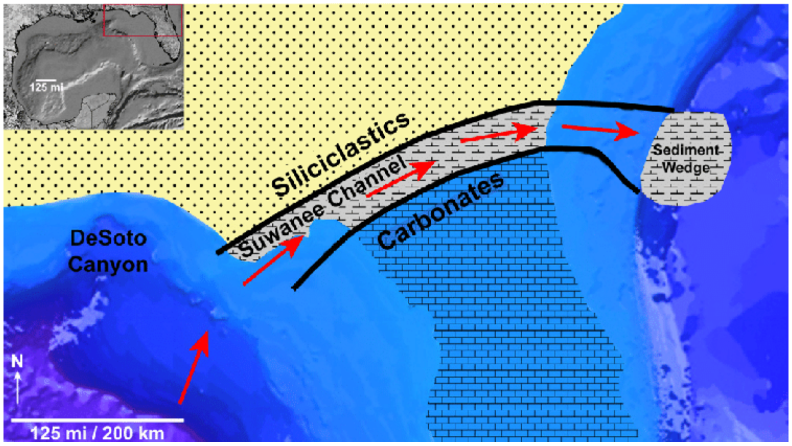


**Figure 3.** Schematic diagram of the location of the Suwannee Channel. The channel isolated the Florida carbonate platform from siliciclastic sediments shed off of the Appalachian mountains during the Eocene and Oligocene. Sediments were deposited on the Atlantic continental slope in the south Atlantic Bight to form various bathymetric features represented here as a "sediment wedge".

Depositional patterns changed at the start of the Miocene when the Suwannee Channel filled with siliciclastic sediments from the eroding Appalachian Mountains and forced the Gulf Stream to flow farther to the south. Once filled, siliciclastic sediments were distributed across the entire carbonate platform, which shut off carbonate mineral production. These marine siliciclastic sediments formed the Hawthorn Group and younger rocks, which were deposited under upwelling currents supporting large amounts of marine primary productivity. Consequently, the rocks are organic matter rich and contain large deposits of diagenetic apatite. The apatite is mined extensively for its phosphorous content, which contributes to Florida's third major industry – mining – after agriculture and tourism. The Hawthorn Group also contains fossils of many marine organisms and shark tooth collecting is a favorite pastime in the creeks around Gainesville.

During the Pleistocene, the land surface was near sea level and marine erosion removed the Hawthorn Group from the Big Bend region of northwest Florida to form the Cody Scarp. During this time, marine beach ridges were deposited down the center of the state. These ridges are rich in ilmenite and rutile, which is also extensively mined as a base for paint, varnish and lacquers. Although formed at sea level, the beach ridges are now at elevations of 40 to 70 m above sea level and the Cody Scarp, also formed by marine processes, ranges in elevation from ~20 to 40 m above sea level. These elevations are higher than any sea level during the Pleistocene. The conundrum of marine geomorphic features at elevations above past sea level led Opdyke et al. (1984), Adams et al. (2010), and Woo et al. (2017) to propose that dissolution of the Ocala Group rocks reduced the density of the carbonate platform and allowed isostatic uplift to raise north central Florida to its current elevations (Fig. 4).

## A brief introduction to north Florida hydrology

The removal of the Hawthorn Group and resulting distribution of exposed, semi-confined, and confined Floridan aquifer across north-central Florida provide important controls on hydrology and hydrogeology of the region. Semi-confinement of the Floridan aquifer is defined to be where the Hawthorn Group is between 0 and 30 m thick. This semi-confined zone creates the Cody Scarp and represents a zone of extensive interactions of surface water and groundwater. Where the Floridan aquifer is fully confined in the northern highlands, surface water is abundant in the form of numerous wetlands, lakes, and streams. In contrast, in the Gulf Coast Lowlands, surface water is mostly restricted to the Suwannee River and Santa Fe River,

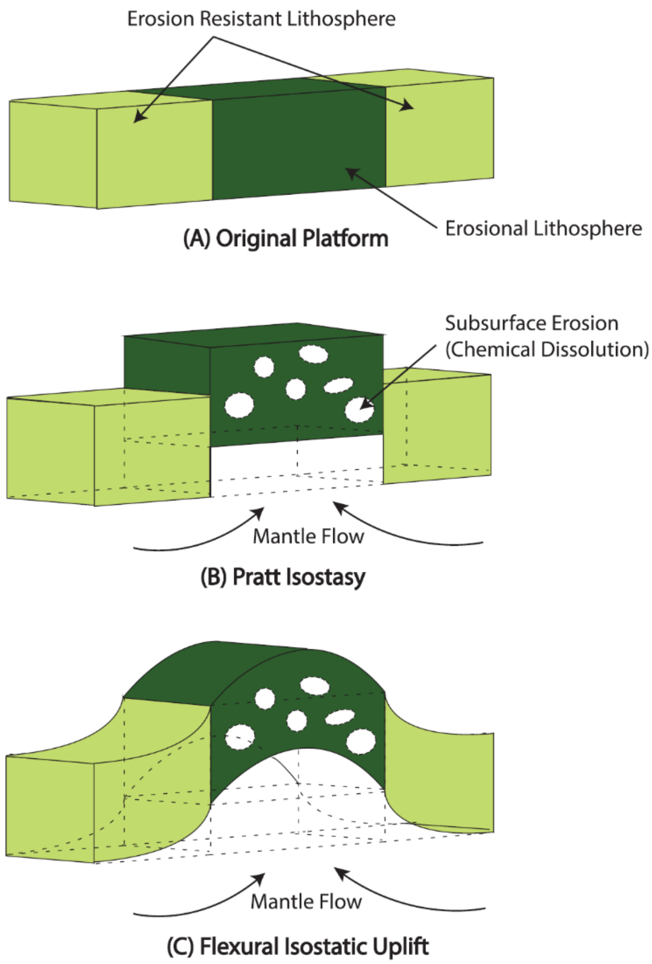


**Figure 4.** Lithospheric deformation resulting from isostatic uplift and flexure caused by changes in crustal density during dissolution of the carbonate rocks of the Floridan aquifer. **A.** Distribution of lithosphere rocks prior to dissolution following dissolution. **B.** Deformation derived from pure isostatic uplift of the lower density lithosphere. **C.** Flexural isostatic uplift where the uplifted lithosphere is pinned to lithosphere with limited amount of dissolution. From Woo et al., 2017

which is the primary tributary to the Suwannee River below the Cody Scarp (Fig. 1). (The Suwannee River is of the famed song by Stephen Foster, who never saw the river or visited Florida and chose the name simply to fit the poetic meter). Surface water in the Gulf Coast Lowlands also occurs in wetlands of Waccassassa Flats near the coast, which is underlain by a small outlying remnant of the Hawthorn Group.

The Suwannee and Santa Fe rivers have median discharges of ~230 and 17 $m^3$/sec, respectively, where they cross the Cody Scarp. Their minimum and maximum discharges are 23 and 1500 $m^3$/sec and 5.6 to 27 $m^3$/sec for the Suwannee and Santa Fe rivers, respectively. The range of discharge is large because of rapid drainage off of the Hawthorn Group in the Northeastern Highlands. At the Cody Scarp, the Suwannee River becomes a losing stream (Spellman et al., 2019) and at times other than at extreme flow events, the Santa Fe River is completely captured by a sinkhole and reemerges about 7 km away from a first magnitude spring (Martin and Dean, 2001). All other streams draining off the Northern Highlands sink into the subsurface as they cross the Cody Scarp and recharge the Floridan aquifer without having defined resurgences to the surface. Instead, the Floridan aquifer discharges at numerous springs discharging Floridan aquifer water with little recharged surface water than can be linked directly to the springs. Most of these springs discharge directly to the Suwannee and Santa Fe rivers or into short spring runs that act as tributaries to these two rivers. The springs of north Florida represent the world's densest clustering of first magnitude springs, which are defined as having discharge > 100 $ft^3$/sec (> ~2.5 $m^3$/sec, Meinzer, 1927). The Floridan aquifer is the primary source of potable water across the region, and the many discrete recharge locations make this critical water resource vulnerable to contamination. During the three stops on today's field trip, we will observe the role of variable confinement on the connections between surface water and groundwater of the Floridan aquifer.

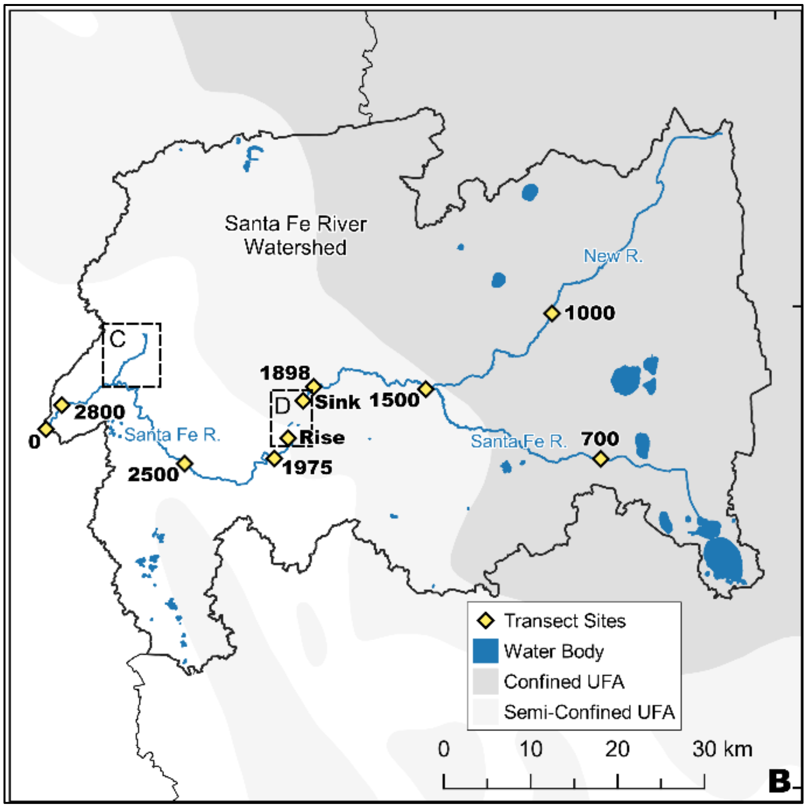


**Figure 5.** Santa Fe River watershed showing locations of USGS gauging stations (watershed 0232, gauge identifiers 0700, 1000, 1500, 1895, 1975, 2500, 2800). Dark grey area in the northeast is where Floridan aquifer is fully confined and the light grey areas is where the Floridan aquifer is semi-confined and represents the location of the Cody Scarp. The Floridan aquifer is unconfined in the remainder of the mapped area. Lake Santa Fe is located in the southeast corner of the watershed. The box marked C is the location of the Ichetucknee springs group and roughly the outline of Figure 7. The box marked D is the location of the Sink Rise system showing locations of River Sink and River Rise (Fig. 9).

## FIELD TRIP STOPS

Today's trip includes three sites starting in Gainesville, which derives its small hills (along with many sinkholes and architectural characteristics such as cracked foundations and high radon concentrations in many houses) from its location on the Cody Scarp and common occurrence of smectitic swell clays that are widely distributed in the shallow subsurface throughout the Hawthorn Group. Our first stop will be in the Gulf Coast lowlands southwest of the Cody Scarp and from there we will travel generally northeastward towards the scarp where we will be in the Santa Fe River watershed for the remainder of the trip (Fig. 5). Our return to Gainesville will roughly parallel the scarp (see Appendix A for a Google Maps road map of the trip). **Stop 1** will be Bat Cave near the town of Newberry. During this stop we will have time to explore the cave and will have demonstrations of the use of LIDAR to map caves and methods to make field trips accessible for people with disabilities. From Bat Cave we will drive north ~50 km to **Stop 2** at Ichetucknee Springs State Park near the town of Fort White where we will have a picnic lunch (provided) and time to look around some of the springs. Two of the springs near our lunch site (Head Spring near the parking lot, and Blue Hole Spring about a quarter mile walk from the parking lot) are open for swimming. Changing rooms are available. From Ichetucknee springs, we will travel east to **Stop 3** at O'Leno State Park near the town of High Springs. At this location we will see where the upper Santa Fe River flows into water filled caves at River Sink and then resurges at River Rise to form the headwaters of the lower Santa Fe River. At the end of the day, we will return to the hotel where you will have time to change out of field clothes before enjoying a catered dinner at Cypress and Grove Brew Pub. This facility was built to serve as Gainesville's ice plant with an on-site well producing Floridan aquifer water. That well now provides the water to create various libations, including beer and non-alcoholic drinks that we will have an opportunity to sample with dinner.

**STOP 1: Bat Cave (28200 NW 46th Ave. Newberry FL)**

Bat Cave is a dissolution cave that formed in the Ocala Limestone (Fig. 6). It is located in the Gulf Coast Lowlands with Ocala Limestone exposed at the surface and in the cave walls. The only remaining traces of the Hawthorn Group is a veneer of reworked and undifferentiated Pleistocene quartz sands, which also comprise much of the sediment on the cave floor along with organic matter such as bat guano. The lack of a confining unit over the cave allows diffuse recharge of water to the Floridan aquifer through the overlying soils and sands. As we will see in the cave, the wall rock retains intergranular porosity typical of eogenetic karst. Unconfined conditions and high primary porosity allow dissolution where groundwater may become undersaturated with respect to calcite and tend to form spongework caves in the cave classification scheme proposed by Palmer (1991). Bat Cave provides a nice example of this type of cave.

Although Bat Cave is far from the coast, its formation may be related to past sea level considering the periodic ~130 m variation in sea level during the Pleistocene and that elevations of many caves in the region correspond to past sea level still stands (Florea et al., 2007; Gulley and Florea, 2016). Dissolution of a particular type of coastal cave (termed Flank Margin Caves, Mylroie and Carew, 1990) has been proposed to relate in part to mixing of fresh and salt water of carbonate islands. However, mixing does not create sufficient amounts of undersaturation with respect to carbonate minerals to form the volumes of caves observed in these systems (Gulley et al., 2013). In addition, carbonate dissolution reaction rates generated by mixing of fresh and sea water are too slow to form the caves during the 10,000 yr long interglacial periods when sea level was sufficiently high to form the caves at their current elevation (Moore et al., 2009). Instead, most dissolution of these spongework caves results from production of carbonic acid as $CO_2$ is formed by organic matter remineralization in the subsurface. Delivery of surface organic matter to the subsurface is controlled by variations in vertical permeability that create localized environments where dissolution may occur (Gulley et al., 2016). In addition, some chemolithoautotrophy may produce organic matter in the subsurface that is ultimately remineralized, particularly where dissolved oxygen increases with surface water-groundwater interactions (Jin et al., 2014).

A good description of the flora and fauna surrounding Bat Cave can be found at https://www.sfcollege.edu/batcave/life and that information is reviewed briefly here. The original forest surrounding Bat Cave was composed of hardwoods including oak and hickory. Those forests have been logged to allow for farming and sylviculture of slash pine (*Pinus palustris*) with an understory of native species such saw palmetto (*Serenoa repens*) and various ferns. Sylviculture was restricted around the cave openings because of danger to large equipment used to fell trees, which has allowed hardwoods including live oak (*Quercus virginiana*) and wild cherry (*Prunus serotina*) to reestablish the site. Several organisms occur in the cave including transients such as bats, occasional owls, and people. At least 13 species of crayfish live in the cave along with crickets.

Florida usually experiences dry winters with much of its rainfall occurring during the summer months with convective thunderstorms and occasional tropical storms. However, because of extensive evapotranspiration in the summer, paradoxically, much recharge to the

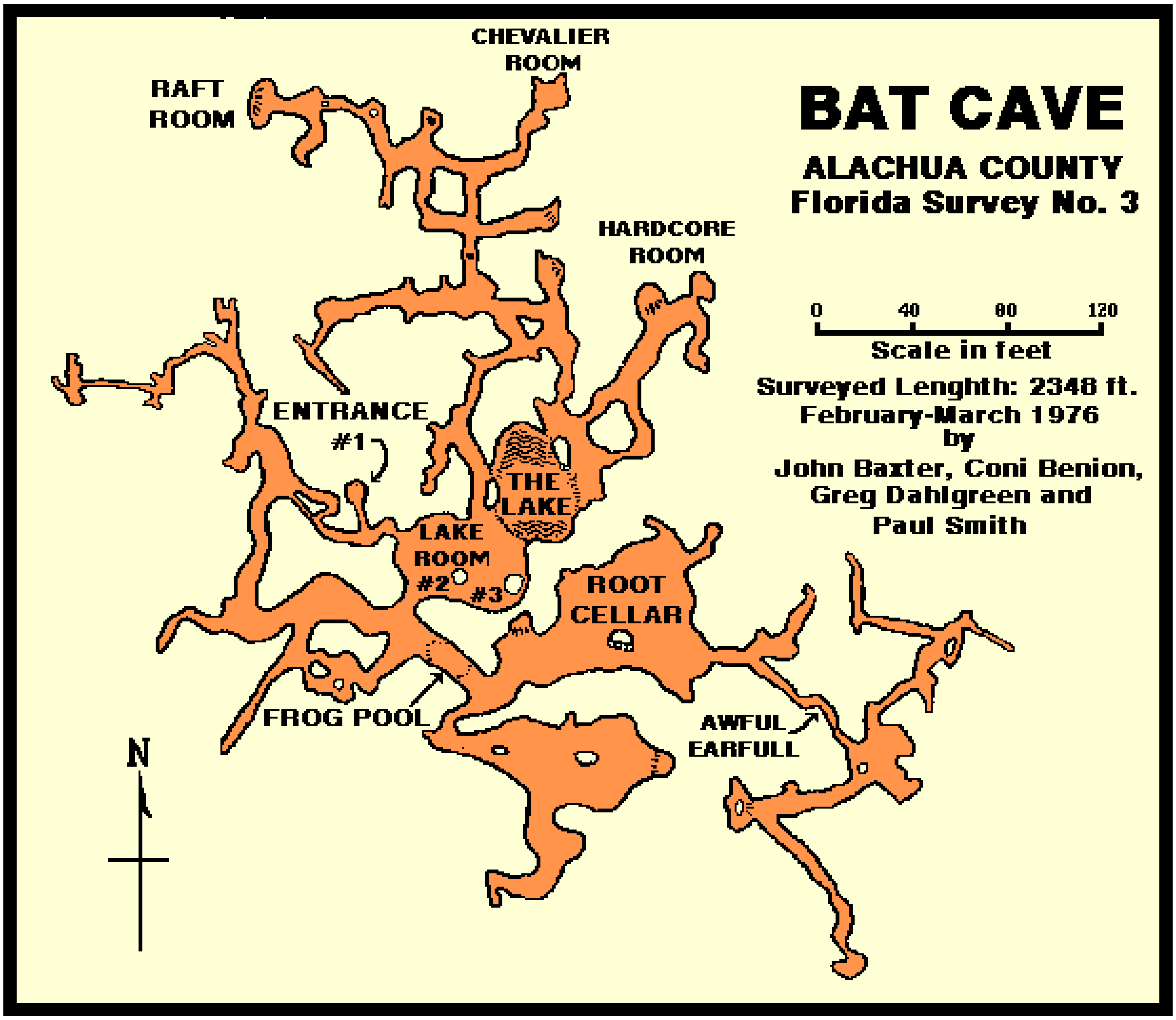


**Figure 6.** Map of Bat Cave. If the water level is sufficiently low all passages will be accessible without wading through water. Please stay on walkways while on the surface.

Floridan aquifer occurs during the winter dry season except during large precipitation events such as tropical storms. Although recharge in these events may be rapid, the response of the Floridan aquifer to them, including rate of change of the water table and variations in spring discharge, is slow and occurs over many weeks to months in contrast with “flashy” telogenetic karst aquifers (Florea and Vacher, 2006). The slow response reflects the high porosity and bulk permeability of eogenetic karst relative to telogenetic karst aquifers.

How much of the cave we will be able to explore depends on the water table elevation of the Floridan aquifer at the time of the field trip. The water table elevation is shown by the water surface in the cave pools, which are connected to the Floridan aquifer. Thus, the few meters we will descend to enter the cave represents the relatively thin vadose zone found across north-central Florida and the upper portion of the carbonate critical zone. This thin vadose zone and lack of confinement should provide a sense of the vulnerability of the Floridan aquifer to contamination from land-use practices. Hopefully, a visit in early April will provide a sufficiently low water table to allow us to explore most of the passages of the cave. If the water table is high, however, we may be confined to the main room without walking through water that may be waist high. That decision can be made once we are on site.

Bat Cave is located on land that was owned by a timber company until the early 2000s. Other than trespass laws, no restrictions were in place to limit access by the public and it became a favorite hangout for students from nearby high schools and the University of Florida. Parties were common, trash and other refuse built up, and campfires in the cave blackened its walls with soot. Partying led to numerous accidents that severely injured people and the timber company decided its liability was too great to continue owning the property. At that time the cave was donated to Santa Fe Community College (now Santa Fe College) and cave management was taken over by the Natural Sciences Department at the College. Once ownership transfer was completed, volunteers cleared the cave of trash and scrubbed much of the soot from the cave walls. The accumulated trash filled five tractor trailers and included an old school bus chassis that was used to enter the cave at a second now gated entrance. The College built the current facilities and fenced the area, restricting access, and providing the nicely restored condition we will experience today. We will enter the main room of the cave using a circular ladder that was installed after the College began to manage the cave.

Access to the cave is provided for educational purposes only. All visitors will be required to sign a liability waiver form and are expected to abide by the following rules of behavior while in and around the cave:

- **Clothing:** Wear long pants and closed toe shoes. They will get dirty.
- **Headgear:** We will provide helmets, but if you have a favorite you are welcome to bring it. Protective head gear should be worn at all times in the cave.
- **No alcohol or drugs:** Enough said.
- **Lights:** Some flashlights may be available, but there will not likely be enough working lights to go around. It will be best for everyone to have their own light, but you may partner with someone else with a light.
- **Do not explore alone:** We are a large group and the cave will be crowded if we stay together. If you split from the group, be sure to explore with a partner in case one of you is injured.
- **No running:** Like all caves, many places have low ceilings and uneven floors. Be particularly careful not to trip/fall.
- **While on the surface, stay on the boardwalks:** The natural ground cover has been stripped away from previous timbering operations and the College is trying to support reestablishment of the native vegetation.

**STOP 2: Ichetucknee Springs (8294 SW Elim Church Road)**

The Ichetucknee springs make up a group of nine named second-magnitude springs, which are defined as having discharge of 10 to 100 $ft^3$/sec, or ~0.25 to 2.5 $m^3$/sec (Meinzer, 1927) and hundreds of smaller unnamed springs and seeps (Scott et al., 2004). These springs and seeps source the 8 km long Ichetucknee River (Fig. 7). Most of the springs occur along the upper 1 to 2 km of the river, making it the longest spring run and the largest tributary to the lower Santa Fe River (see cover photo). Although discharge was monitored from some of the springs for a few years in the early 2000's, loss of funding closed those gauging stations and since then few springs have been regularly monitored. The USGS gauging station 02322700, located at the Highway 27 bridge about three quarters of the distance between the springs and the

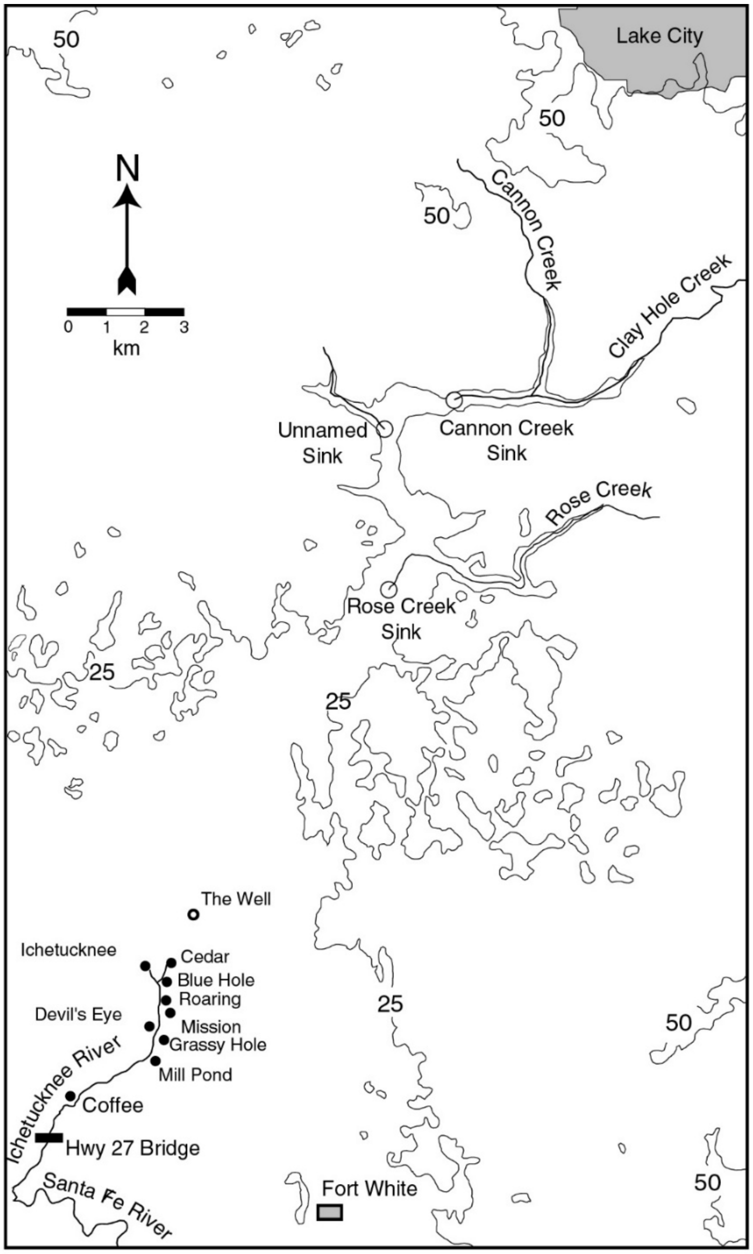


**Figure 7.** Topographic map of region surrounding the Ichetucknee springs. The 25 m contour marks the approximate boundary of the semi-confined and unconfined Floridan aquifer and the southwestern edge of the Cody Scarp. If time, we may visit Rose Creek Sink, but our main stop will be at the head springs. Modified from Martin and Gordon (2000).

confluence with the Santa Fe River shows a mean discharge of 8.5 $m^3$/sec over the past 19 years. Because the river is spring feed, discharge shows little variation with a range from 5.2 to 12 $m^3$/sec.

The springs and upper half of the river are now protected by Ichetucknee Springs State Park, which is considered the "crown jewel" of Florida's park system. Along with small variations in discharge, the Ichetucknee springs are renowned for constant chemical compositions and temperatures. These characteristics result from the 10 to 15 km distance that separates the springs from recharge points along the Cody Scarp, where several small ephemeral streams flow into the subsurface at sinkholes (Fig. 7). This distance allows homogenization and dilution of potential variations in chemical compositions caused by periodic point recharge from sinking streams as they cross the Cody Scarp. One sinkhole, called Rose Creek Sink, was purchased by the state in an effort to protect the Ichetucknee springs, and is now part of the Florida Park system. We may visit this site if we have time. This sink and several others nearby are located at the northern end of the Ichetucknee trace, which is presumed to represent an early channel for the Ichetucknee River as the Cody Scarp retreated to the northeast and may have connected the Ichetucknee springs with the small streams in the past. Cave diving exploration has revealed extensive water filled caves (e.g., "conduits") connected to these sinkholes that are oriented toward the south and the Ichetucknee springs.

Several dye trace studies have been attempted in the region to identify potential surface water sources to the Ichetucknee springs. The first dye trace was carried out in the early 1990s and used the gas $SF_6$ as a tracer, but the trace yielded equivocal results (Hirth, 1995). The dye

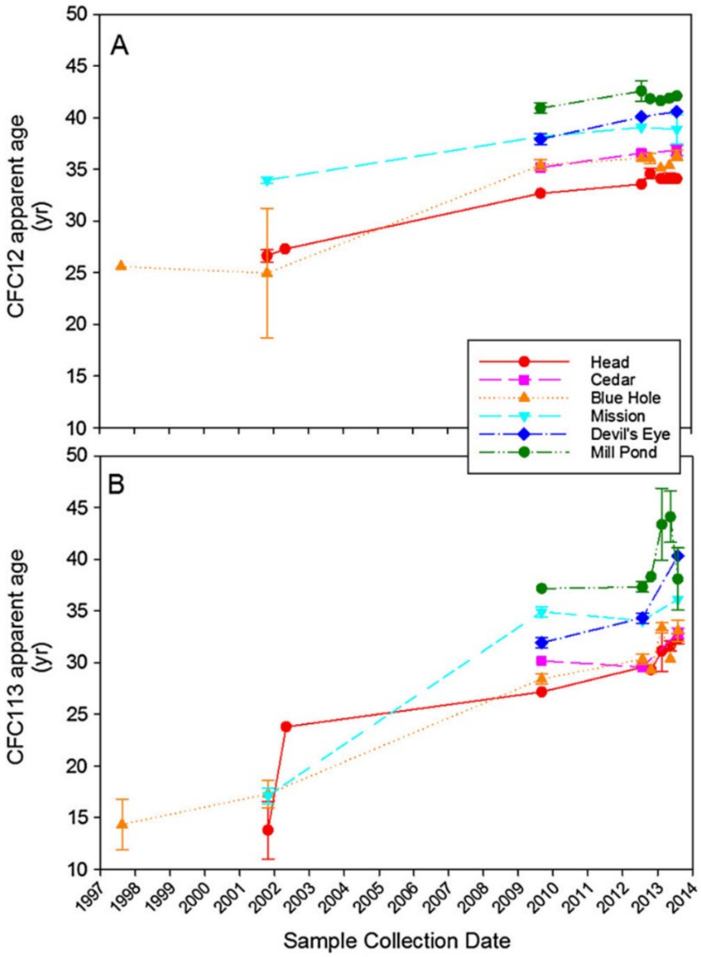


**Figure 8**. The average apparent age of water based on A. CFC-12 and B. CFC-113 versus the time of collection. The warm colors represent the Group 1 springs and the cool colors represent the Group 2 springs. The increase in apparent age with time is interpreted to reflect decreasing precipitation and recharge starting around 1980 caused by shifts in the AMO and ENSO. From Martin et al., 2016.

trace also contaminated the aquifer with $SF_6$, limiting its use as a water dating method. A second study was completed a few years later, and used 9.1 kg of fluorescein dye. The dye was injected by cave divers at a location ~40 m below the water table and ~200 m into a conduit that is connected to Rose Creek Sink (Butt et al., 2000). Small amounts of dye were detected at six of 14 monitoring points in the Ichetucknee springs and river. The breakthrough curve indicated flow rates of 1.5 km/day, suggesting the possibility of conduit flow from Rose Creek Sink to at least some of the Ichetucknee springs. However, the lack of return at several of the springs indicates that different groups of the Ichetucknee springs may have distinct sources.

Two groups have been recognized among the Ichetucknee springs based on their average chemical compositions, absolute temperatures, and seasonal variations in temperature (Martin and Gordon, 2000). One of the two spring groups (Group 1 springs: Ichetucknee Head, Cedar, and Coffee springs) had no dye return and is characterized by higher dissolved oxygen and $NO_3$ concentrations, lower Cl and $SO_4$ and Mg concentrations, and slightly lower (~0.2° C) and greater seasonal variations in temperature, with winter-summer variations of ~0.2° C compared with the second group of springs. The second group of springs (Group 2: Mission, Devil's Eye, and Mill Pond springs), received detectable amounts of dye and is characterized by dissolved oxygen concentrations near the detection limit, , with winter-summer variations < 0.1° C, and elevated Mg and $SO_4$ concentrations compared with the Group 1 springs. These characteristics are consistent with deep sources that have reacted at depths of a few hundred meters below the surface with evaporite minerals of the Avon Park Formation (Moore et al., 2009). Putative deep flow would also be consistent with slightly higher temperatures and less seasonal variability. The depth of flow suggests the water has long subsurface flow paths, as suggested by dye return from Rose Creek Sink, which would also cause low dissolved oxygen concentrations during organic matter remineralization in the aquifer.

Long flow paths are supported by chlorofluorocarbon age dating of the water discharging from the Ichetucknee springs, which indicates the water has long residence times in the aquifer (i.e., the average time since recharge) that are on the order of several decades (Martin et al., 2016). Estimated water ages show that the Group 2 springs (with low dissolved oxygen and elevated temperatures) have average residence times on the order of 30 to 40 years, while Group 1 springs have average residence times on the order of 10 to 20 years. The residence times have increased by about a decade between the first time the spring water ages were measured in 1997 (Happell et al., 2006; Katz, 2004; Katz et al., 2001) through the final dating in 2014 (Fig. 8). The increase in residence time follows a period of decreased regional precipitation and thus recharge to the Floridan aquifer starting around 1980. The change in precipitation corresponds with decadal long swings in oceanographic and climate patterns including the El Nino Southern Oscillation (ENSO) and a shift to the cool period of the Atlantic Multi-decadal Oscillation (AMO). These global climate patterns alter the location of much of the summer rainfall from northern to southern peninsular Florida and the shift in potential recharge to the aquifer (Goly and Teegavarapu, 2014). However, some of the increase in water ages may also reflect increased reliance on groundwater withdrawals for agriculture as cumulative precipitation decreased over the past couple decades.

Until the early 2000s a limestone quarry was active in the Ichetucknee trace midway between sinkholes and caves at the Cody Scarp and the Ichetucknee springs. The mining operations created concerns about degradation of water quality from contaminants, mostly silt that would cloud the clear spring waters. The dye trace connection between the sinkholes at the Cody Scarp and the Ichetucknee springs contributed to concerns about degradation of water quality, and led the state to negotiate an agreement with the quarry owner to purchase the mine. In exchange for the purchase agreement, however, the owner required that the state issue a building permit to construct a cement kiln. The kiln is located approximately 3 km southwest of the Ichetucknee River, about midway between the Ichetucknee and Santa Fe rivers. The exchange of the mine for a cement kiln was viewed by many local and national conservation organizations as unreasonable, and led to numerous failed attempts to block permitting and construction of the kiln through the courts. The concern was that noise, water, and air pollution from the kiln would exceed that of the mine and could cause serious environmental damage to the ecosystems and spring water, in the surrounding area. The kiln is fueled with coal and used tires, potentially introducing large volumes of sulfur dioxide, nitrous oxides, carbon monoxide, and mercury into the atmosphere and water.

Much of the concern about contamination of the springs reflects the importance of Ichetucknee River to the local economy, with over 400,000 visitors passing through the park each year. Most visitors come during the summer months to escape the Florida heat and humidity by tubing and canoeing in the perennial 22º C water. Prior to the establishment of the Ichetucknee Springs State Park in 1970, the Ichetucknee River had been severely degraded by extensive and unrestricted recreational use. Much of the subaquatic macrophyte communities on the bottom of the river had been destroyed by people walking on the river bed and the banks were extensively eroded. Additionally, the owner of the land surrounding the Ichetucknee Head Spring had attempted to stop its flow by dumping tons of concrete into the throat of the spring in an attempt to prevent cave divers from entering the conduit system. The establishment of the park led to regulations that control the number of visitors allowed to tube or canoe the river, which greatly improved the health of the sub-aquatic vegetation and helped stabilize the banks. Over the past several years, volunteers have removed most of the concrete dumped into the head spring, which has resulted in an apparent increase in spring discharge volumes. The latest threat to the river ecosystem stems from a conversion from macrophyte dominated to algal dominated benthic communities. An ongoing debate exists in the community about causes for the shift in community structure.

**Stop 3: Santa Fe River Sink-Rise system (410 SE O'Leno Park Road)**

The Santa Fe River originates in Lake Santa Fe, approximately 40 km east of the Cody Scarp (Fig. 5). The river flows west toward the Cody Scarp where it sinks into the subsurface through a 36 m deep sinkhole called River Sink (Fig. 9). Approximately 7 km south of River Sink is a first-magnitude spring, called River Rise, that is the headwater of the lower Santa Fe River, which flows south from River Rise for ~30 km to the Suwannee River. Numerous sinkholes and karst windows exist between River Sink and River Rise. These sinkholes are commonly elongate with long dimensions of a few hundred meters and widths of a few tens of meters. Most of these features have flow that originates in a spring on the upstream side and a sink on the downstream side. Their morphology and flow suggest they represent sections of the river exposed on the surface that are sourced and drained by conduits. This inference is supported by cave diving exploration that has found most surface water features are connected to an extensive network of conduits including River Sink, River Rise, and Sweetwater Lake, all of which we will visit today if time permits.

A new sinkhole opened in 1991 (New Sink), which led the park service to commission a dye trace study to determine the characteristics of hydrologic connections between River Sink, downstream sinkholes, and River Rise. The dye trace was conducted in 1991 using $SF_6$ as a tracer with samples collected at eight of the downstream sinkholes and River Rise (Hisert, 1994). After the initial injection, $SF_6$ returned to all of the monitored sinkholes, except River Rise (Fig. 9). A subsequent injection of $SF_6$ in the southernmost sinkhole, Sweetwater Lake, showed returns at the River Rise. The trace was conducted during relatively high discharge of 42 $m^3$/sec and the dye breakthrough indicated flow rates that average 4.3 km/day, which indicates water flows from River Sink to River Rise in about a day and a half. Flow rates between River Sink and River Rise were evaluated using high resolution measurements (15 minute intervals) of the water

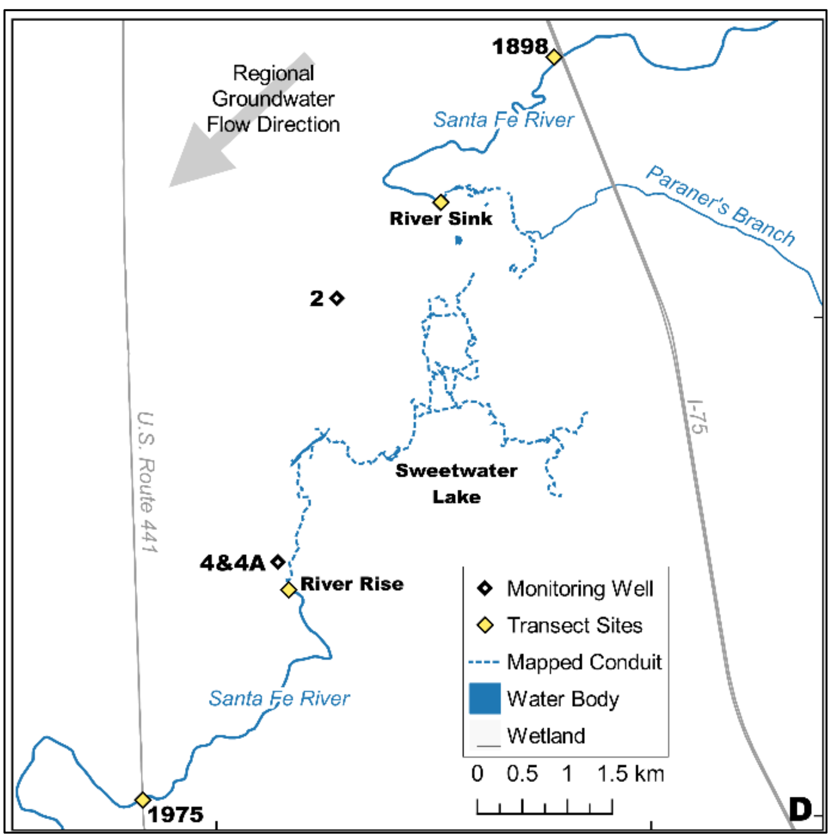


**Figure 9.** Sketch map of the Santa Fe Sink/Rise system. The direction of regional ground water flow is from Meadows (1991). From our parking spot we will have an approximately 750 m walk to the River Sink. We will also visit River Rise and Sweetwater Lake with parking near to these features. Modified from Hisert (1994) and Martin and Dean (2001).

temperature at River Sink, Sweetwater Lake, and River Rise as a natural tracer (e.g., Martin and Dean, 1999). These results showed that flow rates vary systematically with river discharge. Time required for water to flow from River Sink to River Rise ranges from ~18 hr at high flow to several days at low flow. The temperature tracing supports dye trace results as well as cave mapping to indicate that River Sink is almost certainly connected to River Rise by continuous conduits.

At the time the temperature tracing experiment was done, discharge through the system was not being gauged. However, in the past decade the USGS has established gauging sites a few kilometers upstream of River Sink (USGS gauge 02321898), at River Rise, and a few kilometers downstream of River Rise (USGS gauge 02321975; Fig. 9). These discharge measurements show that at low flow conditions, less water discharges into River Sink than from River Rise but at elevated flow, more water flows into River Sink than from River Rise (Fig. 10). The downstream increase in discharge is presumed to represent times when conduits gain water from the Floridan aquifer matrix porosity while in contrast, the downstream decrease in discharge is presumed to represent times when conduits lose water to the aquifer matrix porosity (Martin and Dean, 2001). The cross over point occurs at discharges of 19 ± 8 $m^3$/sec on the rising limb of the hydrograph and 46 ± 24 $m^3$/sec on the falling limb. The Sink-Rise system thus provides an ideal site to evaluate geochemical reactions caused by surface water-groundwater interactions that are common to karst aquifers.

The river water typically is stained dark brown because of high concentrations of tannic acids derived from dissolved organic matter in wetlands of the upland catchment. The dark color, which causes low visibility, coupled with a high alligator population, restricted exploration of the conduit systems by cave divers. However, below-average rainfall from 1999 through 2001 lowered the concentration of tannins (although not the alligators) and allowed some of the conduits to be mapped. These maps show connections to River Sink, River Rise, Sweetwater Lake, many intermediate sinkholes in the park, and an unnamed sinkhole east of the park (M. Poucher, personal communication). The distribution of conduits and their connections with

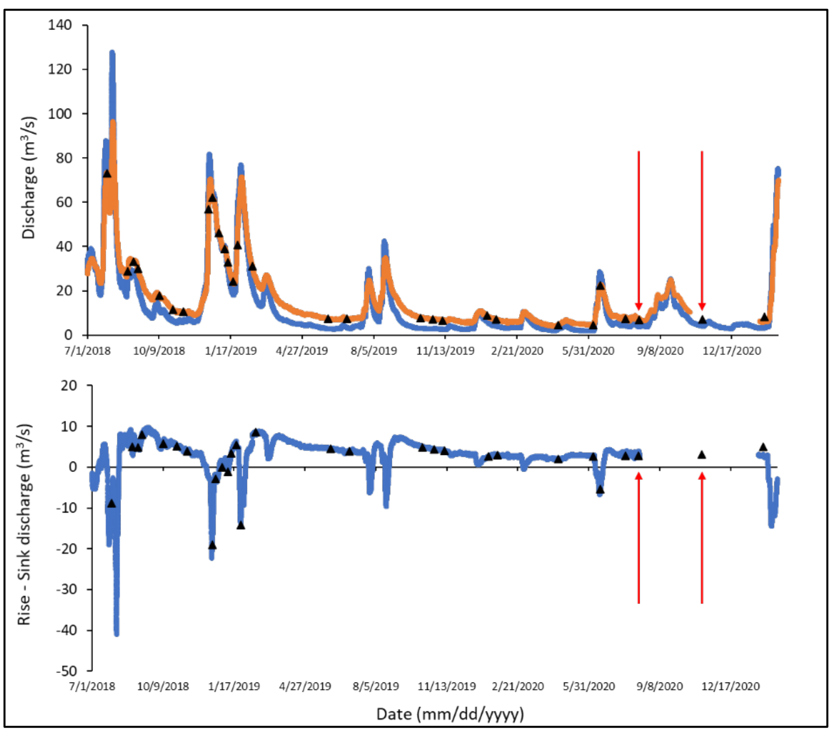


**Figure 10. Upper panel:** Discharge at River Sink (orange line; Site 1898) and River Rise (blue line). **Lower Panel:** Difference in discharge at River Rise from River Sink. Positive values indicate River Sink has less discharge than River Rise and thus conduits gain water from matrix porosity. Negative values indicate River Sink has greater discharge than River Rise and thus conduits lose water to matrix porosity. From Flint et al., in prep.; the black triangles and red arrows represent sampling collection times.

surface features suggest the sinkholes result from collapse of the conduits as indicated by the formation New Sink and morphology of the intermediate sinkholes. Complete conduit connections have been mapped from River Sink to Sweetwater Lake, but Sweetwater Lake has never been completely connected to River Rise. However, the furthest extent of mapped conduits connected to Sweetwater Lake and River Rise are separated by only a few tens of meters.

Locations of mapped conduits have also been identified based on time series measurements of electrical resistivity tomography (Meyerhoff et al., 2012; Meyerhoff et al., 2014). This method relies on reduced electrical resistivity of conduit water that has been diluted by the introduction into conduits of surface water with low dissolved ion concentrations compared with the mineralized Floridan aquifer water (Fig. 11). The contrasting resistivity is seen clearly at the location of conduits mapped by cave divers, as well as at a second location ~200 m east of the main conduit, which indicates an additional location of water with low dissolved solid concentrations and potential existence of a nearby unmapped high permeability zone such as a conduit with a connection to surface water. A precipitation event increased discharge during the experiment, which appears as an expansion of the diameter of conduit through time. The expansion is interpreted to indicate loss of water to the matrix porosity surrounding the conduits (e.g., Martin and Dean, 2001; Moore et al., 2009).

Water in conduits connecting River Sink and River Rise and the surrounding groundwater in the matrix porosity of the Floridan aquifer has been shown to consist of mixtures of three separate end member sources (Jin et al., 2014; Moore, 2009). One end member is surface water draining into River Sink that is characterized by elevated organic matter concentrations and

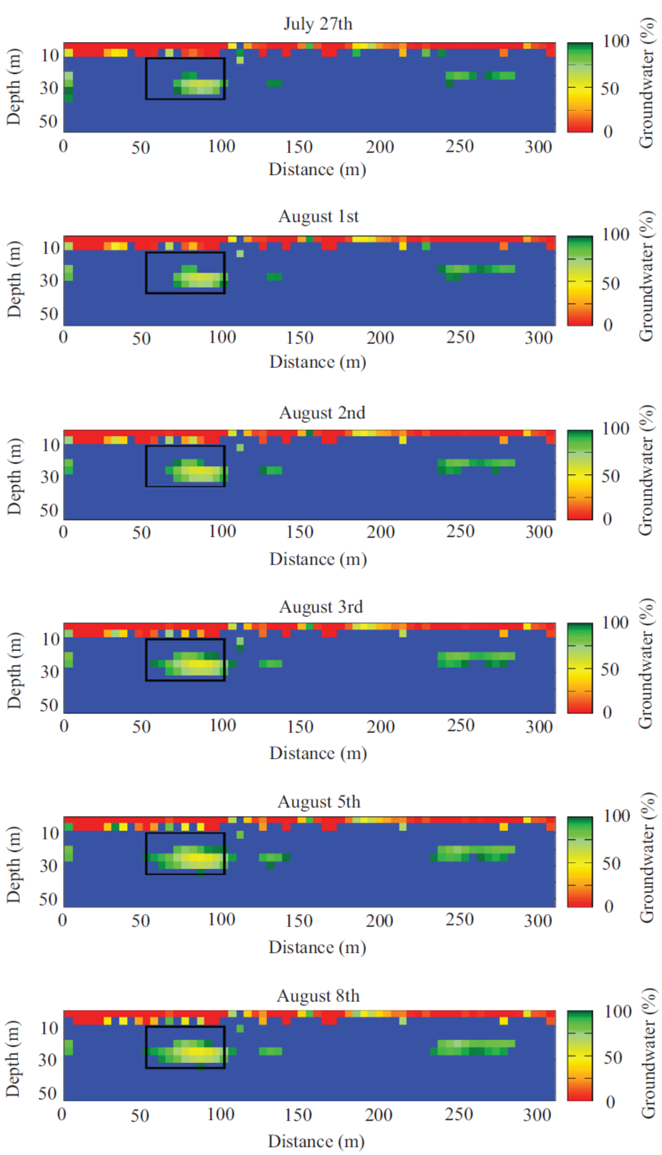


**Figure 11.** Modeled values of mixing between groundwater and surface water recharged to the conduit system based on time series electrical resistivity tomography at the Santa Fe River Sink-Rise System. The transect starts near well 4 and extends across the mapped conduit (Fig. 9). The black box indicates the location of mapped conduits. The high modeled groundwater fraction derived from low resistivity of surface water at a distance of ~250 m on the cross section suggests the presences of an additional unmapped high permeability zone connected to a source of surface water. From Meyerhoff et al., 2014.

dissolved oxygen at equilibrium with the atmosphere. Another end member consists of shallow groundwater from ~30 m below the surface, similar to the depth of the conduits. This end member has low organic matter concentrations, has been mineralized by carbonate mineral dissolution, and has elevated $NO_3$ concentrations, much of which may be derived from fertilizer application in the surrounding agricultural fields. The third end member consists of groundwater that originates from depths of ~ 400 m below the land surface based on models of temperature anomalies. The third end member has elevated Mg and $SO_4$ concentrations derived from coupled gypsum dissolution and dedolomitization reactions in the Avon Park Formation (Moore et al., 2010). The amount of each end member varies through time corresponding to variations in flow. Mixing of these water sources represents a site of reactions that alter the dissolved organic and inorganic carbon fluxes from the watershed and supports dissolution of the conduits (Khadka et al., 2014; Moore et al., 2010). These reactions also provide reactants driving denitrification reactions, but the short residence times in the subsurface and the presence of dissolved oxygen appear to limit complete denitrification to $N_2$ and instead produce $N_2O$, which has concentrations that are ~20 times greater than expected if at equilibrium with the atmosphere (Flint et al., in prep.). These elevated concentrations suggest that reactions within karst aquifers may impact cycling of $N_2O$, a potent greenhouse gas.

The area between River Sink and River Rise provides a natural bridge over the river. Consequently, it was the site of the old Bellamy Road that was used by 17$^{th}$ century European settlers to travel between Tallahassee in northwestern Florida and St. Augustine, a small town on the Atlantic coast that is the oldest continuous European settlement in North America. In the early 20$^{th}$ century, the stretch of the river upstream from River Sink was the site of numerous lumber mills because the relatively steep gradient provided enough hydropower to run the saws. An old mill race can be seen from the swinging bridge that we'll walk past on the way to River Sink. The area was heavily deforested at the time, but has since been reforested through development of O'Leno State Park in the 1930s.

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**Appendix A.** Road map of field trip travels.