ENGINEERING GEOLOGIC ASSESSMENT OF RISK TO VISITORS:

CANYON LAKE GORGE, TEXAS

A Thesis

by

BENJAMIN DAVID KOLKMEIER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Geology

ENGINEERING GEOLOGIC ASSESSMENT OF RISK TO VISITORS:

CANYON LAKE GORGE, TEXAS

A Thesis

by

BENJAMIN DAVID KOLKMEIER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Christopher C. Mathewson
Committee Members,	John R. Giardino
	Jean-Louis Briaud
Head of Department,	Andreas K. Kronenberg

May 2010

Major Subject: Geology

ABSTRACT

Engineering Geologic Assessment of Risk to Visitors: Canyon Lake Gorge, Texas.

(May 2010)

Benjamin David Kolkmeier, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Christopher Mathewson

Presented here are the results of a study of geological hazards conducted in Canyon Lake Gorge of Central Texas. Canyon Lake Gorge formed in 2002 when the emergency spillway of Canyon Lake was overtopped. Since that time, the gorge has been opened to public tours, and the organization governing the gorge has expressed concern regarding visitor safety. The surveys in this study gathered data through field observations and supplemented those data with non-destructive tests from an impact test hammer. The goal of this study was to gather original field data on potential hazards of the gorge with the hope that insight from these data could be used to enhance visitor safety in the gorge.

The field observations made in this study identified the presence of undercut rock ledges that could present varying degrees of risk to visitors. Easily eroded clayey wackestone facilitated formation of these potential hazards. Lithologies such as packstone and grainstone serve to form ledges atop the wackestone. Preexisting fractures and joints in the ledge forming rock, which compound the danger of the unstable masses of undercut ledges, provide failure planes. This study identified current areas of unstable masses by location and differentiates the degree of risk present at each location, using simplified classes of low, medium, and high risk. Level of risk was determined primarily by the potential injuries incurred. Often, the height was dependent upon the thickness of an easily eroded wackestone bed that undercuts ledge forming rock.

Canyon Lake Gorge is a young and dynamic geomorphological environment seeking equilibrium through gravity facilitated erosional events. In time, natural formation of riser beds will mitigate the potential hazards of some undercut ledges.

Based on the potential hazards identified in Canyon Lake Gorge, four safety recommendations are proposed:

- Visitors should always be guided by trained personnel. This practice is in place.
- Visitors should be educated on the dangers of Canyon Lake Gorge before entering.
- Unavoidable hazards should be evaluated for ways to mitigate risk.
- The gorge should be continually monitored to insure safety of the visiting public.

ACKNOWLEDGEMENTS

Thanks to all my friends and my family for their encouragement and support, and for making my experience at Texas A&M one I will never forget.

Thanks to both Tommie Rhoad and Jaynellen Ladd from the Guadalupe Brazos River Authority (GBRA) for their cooperation and making this study possible.

Also, I would like to thank all of the department faculty and fellow graduate students that helped me and my many questions along the way. Thanks to my committee members, Dr. Giardino and Dr. Briaud, for their guidance. And finally, I would like to thank my committee chair, Dr. Mathewson, for his guidance and support throughout my time at Texas A&M.

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

Page

LIST OF TABLES

INTRODUCTION: CANYON LAKE GORGE

Canyon Lake Gorge was formed as the result of a major erosional event in 2002 when a low pressure system stalled over the Guadalupe River Basin, causing large amounts of precipitation, resulting in flood waters overtopping Canyon Lake and scouring out the associated emergency spillway (CCEO, 2002a). The gorge that formed is a attractive environment exposing attractive geomorphic formations, fossils and geology. Since the flood, the area of land encompassing the gorge was leased to the Guadalupe Blanco River Authority (GBRA) to manage tourist interest and related educational opportunities. Inherent in managing Canyon Lake Gorge and allowing visitors to tour the gorge is the responsibility of visitor safety. This study is an investigation into the potential natural hazards of Canyon Lake Gorge, accomplished at the encouragement of the GBRA through a personal communication to Dr. Mathewson of Texas A&M University. The intent of this research is to enhance visitor safety in Canyon Lake Gorge through identifying the potential geologic hazards of the gorge (Figure 1).

This study is concerned only with the geologic hazards of the gorge, and is not concerned with other potential hazards such as slipping, insects, and the possibility of snake bites.

This thesis follows the style of *Environmental & Engineering Geoscience.*

Furthermore, an engineering geologic approach was taken during the field work of this study, meaning stratigraphy was classified into general classes with the focus on the strength and weathering characteristics of the lithology. For an in depth discussion of the stratigraphy of Canyon Lake Gorge, please refer to Ward and Ward's 2007 work.

Figure 1. Canyon Lake Gorge.

Canyon Lake Gorge is located by Canyon Lake in Comal County of central Texas on the Guadalupe River, approximately 24 km (15 mi) north west of New Braunfels (Figure 2).

Figure 2. Texas Road Map. Canyon Lake is located west of San Marcos (Google).

The creation of Canyon Lake Gorge would not have been possible without the construction of the Canyon Lake dam and reservoir, which is an earth filled dam completed in 1964 by the U.S. Army Corps of Engineers (CCEO) (Figure 3). The reservoir serves multiple purposes by protecting the land of the Lower Guadalupe River from floods, aiding the management of water resources, and providing economic stimulation to the surrounding area through recreational tourism. Foremost among the reasons of constructing Canyon Lake is flood control. West of Canyon Lake, the upper portion of the Guadalupe River flow is bounded by high canyon walls that can safely conduct large flows of 1415 m^3 per second or 50,000 ft^3 per second (cfs). However, the Lower Guadalupe channel can safely channel only one-third the capacity of the Upper Guadalupe, resulting in the need for water management to prevent the Lower Guadalupe from floods (CCEO, 2002a).

Figure 3. Pre-flood aerial photo of Canyon Lake (CCEO, 2002b). Spillway featured at bottom left, dam featured on the right. View is towards the northwest. Photo courtesy Comal County Corp of Engineers Office.

The design specifications of the Canyon Lake reservoir allows for flow from the Upper Guadalupe to accumulate in Canyon Lake while being released into the Lower Guadalupe River at a safe rate. The dam is capable of releasing 141.5 m^3/s (5,000 cfs), but the lake is designed with an emergency spillway to prevent water from overtopping the dam. The site of the emergency spillway was selected to take advantage of an existing shallow valley that drains east into the Lower Guadalupe River (Figure 4). Although the emergency spillway was used in 2002, that was the solitary occurrence. Canyon Lake successfully managed the flow of the Upper Guadalupe without resorting to use of the emergency spillway during rain storms in 1978, 1987, 1991, 1992 and 1997 (CCEO, 2002a). .

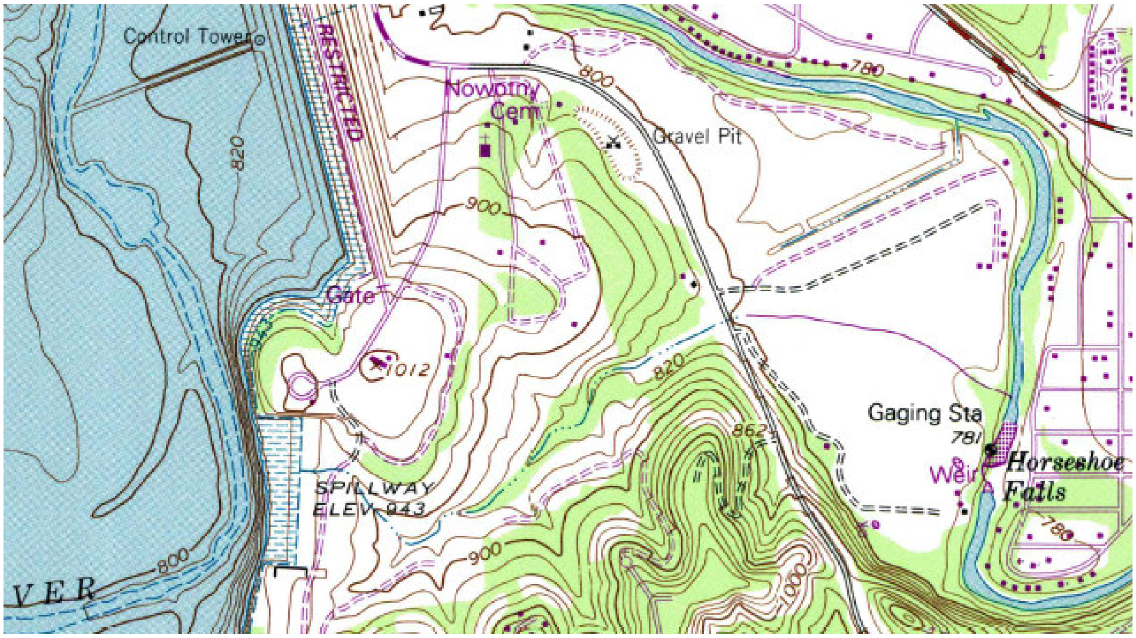


Figure 4. Pre-flood topographic map showing the dam and spillway. The spillway takes advantage of a preexisting drainage valley. USGS 1994 map (http://store.usgs.gov).

In July of 2002, the Canyon Lake emergency spillway was used for the first time. A low-pressure weather system stalled over the Upper Guadalupe watershed, causing rain in excess of 88.9 cm (35 in). During the night of July 4, water breached the spillway for the first time in the history of Canyon Lake. On July 6, Canyon Lake reached 289 m (950.32 ft) above mean sea level (msl), 2 m (7 ft) above the spillway crest of 287 m (943 ft) above msl, and 13 m (42 ft) above the designed conservation level of 277 m (909 ft) above msl (CCEO, 2002a). Flow over the spillway at this point is approximated at 1,891 m^3/s (66,800 cfs) (CCEO, 2002b). For reference, the Guadalupe is considered to be at average flow around 8.5 m^3/s (300 cfs), whereas any flow greater than 15.5 m^3/s (550 cfs) the river is considered to be hazardous for typical recreational use. For six weeks after overtopping the spillway, water continued to flow until the water level of the lake receded below the spillway crest (Figure 5, Figure 6).

In the short period of time flood waters flowed over the spillway, Canyon Lake Gorge was scoured out of the previously shallow valley. Immediately the gorge was an attraction to both the general public and scientists. The area of Canyon Lake Gorge was leased from the Corp of Engineers to the Guadalupe Blanco River Authority (GBRA). Under the management of the GBRA, the gorge has become an excellent geologic teaching area, as well as a tourist attraction. The Guadalupe Blanco River Authority (GBRA) opened the gorge in late 2007 to guided educational tours. Since the opening of the gorge to the public, the GBRA has expressed concern about the risks inherent to the unstable masses of rock present in the gorge. This concern has led the GBRA to require any visitors to the gorge to sign an injury release form prior to entering the gorge, and to authorize this engineering geologic investigation into slope stability and other potential hazards that put the visiting public at risk.

Figure 5. Photo showing flood waters overtopping the spillway (http://www.cceo.org/FloodPics/index.htm, 2002). Canyon Lake Dam is seen in background. Comal County Engineers Office.

Figure 6. Photo showing flow directed over the breached spillway (http://www.cceo.org/FloodPics/index.htm, 2002). Flow is through the shallow valley towards the Guadalupe River. View is towards the East. Comal County Engineers Office.

OBJECTIVE

The objective of this study is to investigate potential geomorphic hazards affecting public safety in Canyon Lake Gorge, and to provide information for mitigating risks to future visitors. Preliminary observation of Canyon Lake Gorge completed in this study indicated different gravity driven erosional processes to be present and active (Figure 7).

Figure 7. Rock fall process.

Rock falls and toppling of rock blocks were indicated by large blocks of rock strewn at the base of ledges and small cliffs. The aforementioned unstable masses of rock can be a danger to personal safety if presently active. These processes are the focus of this study.

Specific objectives include:

- Investigate the factors involved in the flooding event that led to the creation of the geomorphology of Canyon Lake Gorge;
- Identify slope processes present in the gorge that may result in a hazard to visitors;
- Identify erosional processes that may lead to formation of new unstable masses;
- Investigate relationships between the geometry of the unstable formations and the sequence stratigraphy;
- Locate and classify by risk the geomorphic hazards in the gorge to assist the GBRA to enhance visitor safety; and
- Provide a visitor safety training program for tour guides to present to visitors.

Investigation

The GBRA allowed Texas A&M University access to the gorge in May and August of 2008. Since 2002, the GBRA permits research within the 64 acres of land that encompass Canyon Lake Gorge, but, in the interest of preserving the gorge, removing rock or fossils is prohibited. Under these guidelines, all data were obtained through field observations and non-destructive field tests. The area of study encompassed a 1.6 km (1 mile) long reach of the gorge used for educational tours. Whereas this study was not restricted to a particular reach of the gorge, the benefit of this study was maximized by focusing on the areas adjacent to the pathway used to guide visitors through the gorge. By investigating pathway adjacent areas, potential geomorphological hazards that could affect visitors would be recognized. By locating potential hazards, the GBRA can in the future mitigate the located potential hazards through professional planned construction stabilizing the hazard, or avoid the potential hazards by altering the pathway used to guide visitors.

Current literature specific to Canyon Lake Gorge is limited because of the short duration of the existence of the gorge. Past studies have accomplished comprehensive analysis of the 2002 flood circumstances and the metrics of the gorge (CCEO, 2002a; Wilkerson and Schmid, 2007). Wilkerson and Schmid (2007) have measured the length of Canyon Lake Gorge to be 1,310.64 m (4,300 ft), and determined the flood displaced approximately 481,385.6 m^3 (17,000,000 ft^3) of bedrock from the gorge. As of April 2007, scientists from the Southwest Research Institute have been conducting an in-depth study of the stratigraphy of Canyon Lake Gorge, and the associated Hidden Valley Fault which trends the length of the gorge (Southwest Research Institute, 2007). Currently, data they have gathered are not available to the public, but recently Ferrill and Morris (2008) authored a study using Canyon Lake Gorge as a study area.

Prior to the flood of 2002, the shallow drainage valley that was the emergency spillway of Canyon Lake had an elevation drop of 43.5 m (143 ft) from the spillway crest to the south access road (Figure 8). This drop in elevation occurred over a distance of 1,392 m (4,569 ft), resulting in a gradiant of 0.0312. Recalling that the water level overtopped the spillway by an additional 2.1 m (7 ft), the top of the flood waters had

45.7 m (150 ft) in elevation of which to accelerate in velocity of flow from the crest to the base of the spillway.

Given $\frac{1}{2}mv_{bottom}^2 = mgh$, $v_{bottom} = \sqrt{2gh} = \sqrt{2*9.8\frac{m}{s^2}*45.7m} = 29.9\frac{m}{s}$

m = mass
g = gravity
h = height
v = velocity

This is a large velocity that represents the maximum velocity of an uninhibited freefall. Considering that the flood waters had velocity before entering the spillway and the mass of all the water in the lake pushing down the spillway, the 29.9 meters per second (98 ft/sec) velocity could be possible. Taking into account the peak volume of 1,891 m^3/s (66,800 cfs) was estimated to flow at the floods high stand, the floodwater flow should have be capable of significant rock mass erosion.

The velocity of 29.9 m/s (98 ft/s) can be correlated to the size of rock capable of being moved by water flow using a chart by Briaud (2008, Figure 9). Using the equation found in the chart and solving for the mean grain size (D_{50}) using the critical velocity of 29.9 m/s (98 ft/s).

$V_c = 0.35(D_{50})^{0.45}$, $29.9 = 0.35(D_{50})^{0.45}$, $D_{50} = 19.7$ m (64.6 ft)

According to Briaud's equation, a flow of 29.9 m/s (98 ft/s) is capable of moving blocks of rock up to 19.7 m^3 (64.6 ft^3) in size. In effect, the water flow down the emergency spillway would have been able to move any rock block that was scoured from the bedrock.

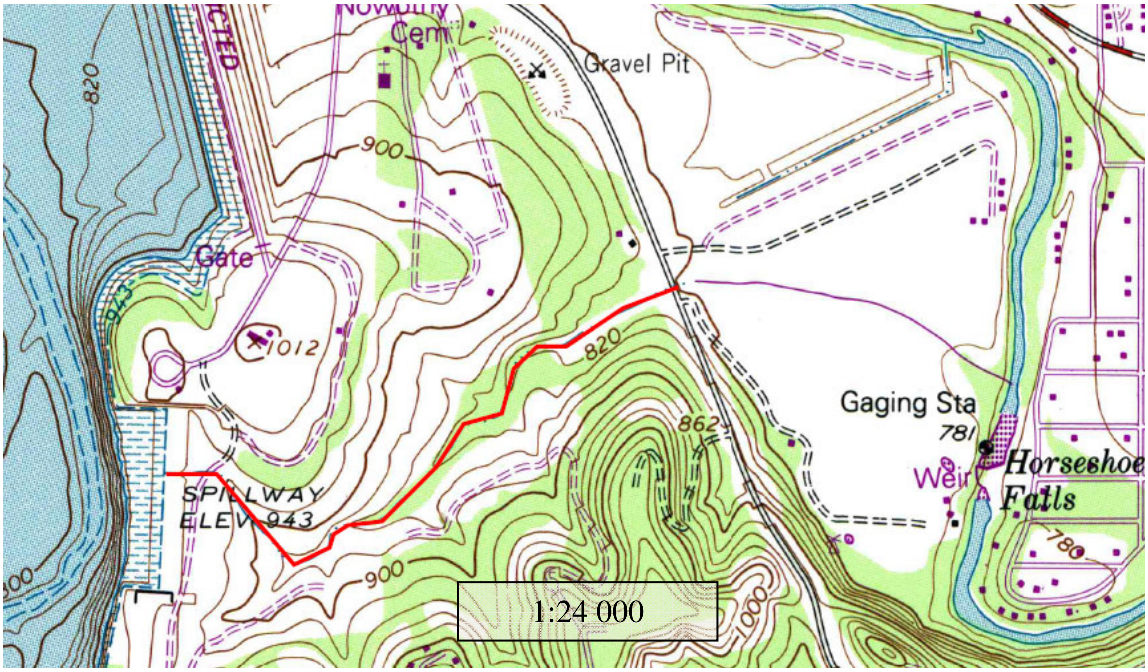


Figure 8. USGS topographic map of the Canyon Lake Spillway, 1994. Red line is a reach following the spillway channel thalweg.

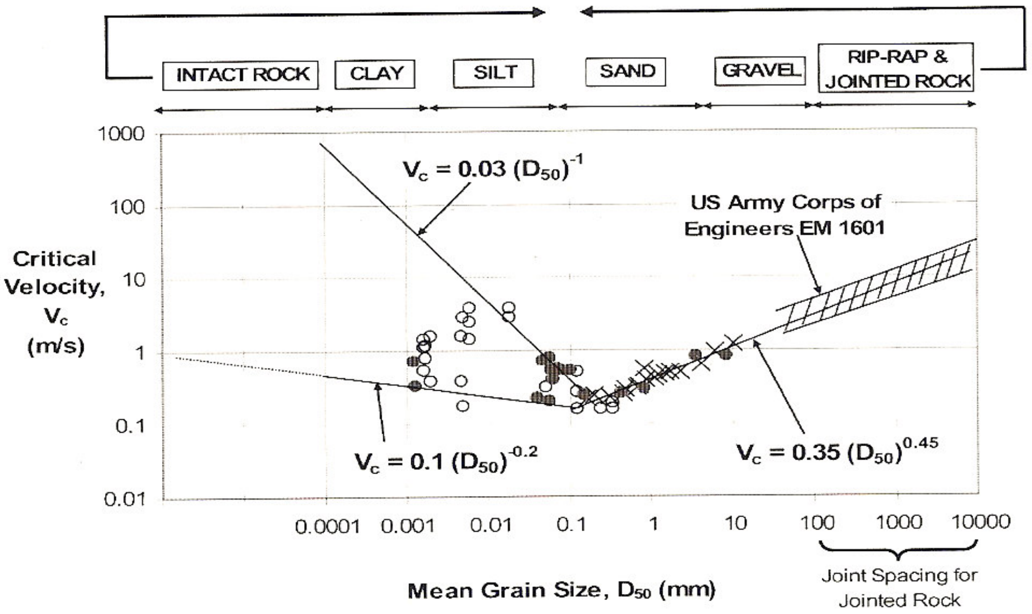


Figure 9. Briaud chart, (2008). The chart shows correlation of water flow velocity versus the mean grain size capable of being moved.

A comparison of the spillway profile before the flood with the profile of the gorge formed after should lend credence to the power of the flood waters. A rough profile of the Canyon Lake spillway can be constructed using the USGS topographical map of Figure 8. The channel thalweg which the profile will be constructed upon follows a southeast path before turning northeast towards the Guadalupe River. The profile shows a drop of 43.5 m (143 ft) over a distance of 1,392 m (4,569 ft).

After the flood, a field study was conducted by by Wilkerson and Schimd (2007) produced a profile of the gorge post-flood. Their work measured the dimensions of the new gorge, as well as quantified the amount of bedrock displaced by flood scour. They measured elevation changes along the spillway channel thalweg, yielding a profile of the gorge. The study transect trended from the spillway crest to a point 60.9 m (200 ft) east of the south access road, where the end of bedrock erosion was declared. The results of the study showed that after the 2002 flood, the newly scoured Canyon Lake Gorge dropped from 287.4 m (943 ft) above msl to 231.9 m (761 ft) at the point 200 ft east of the road (Wilkerson and Schmid, 2007). Preceding the flood, the USGS topographical map indicates an elevation of 243.8 m (800 ft) above msl at the point of intersect between the spillway channel and south access road. The 11.9 m (39 ft) difference in post-flood elevation at a location less than 60.9 m (200 ft) apart is the end result of the considerable force of the flood water flow of 2002 (Figure 10).

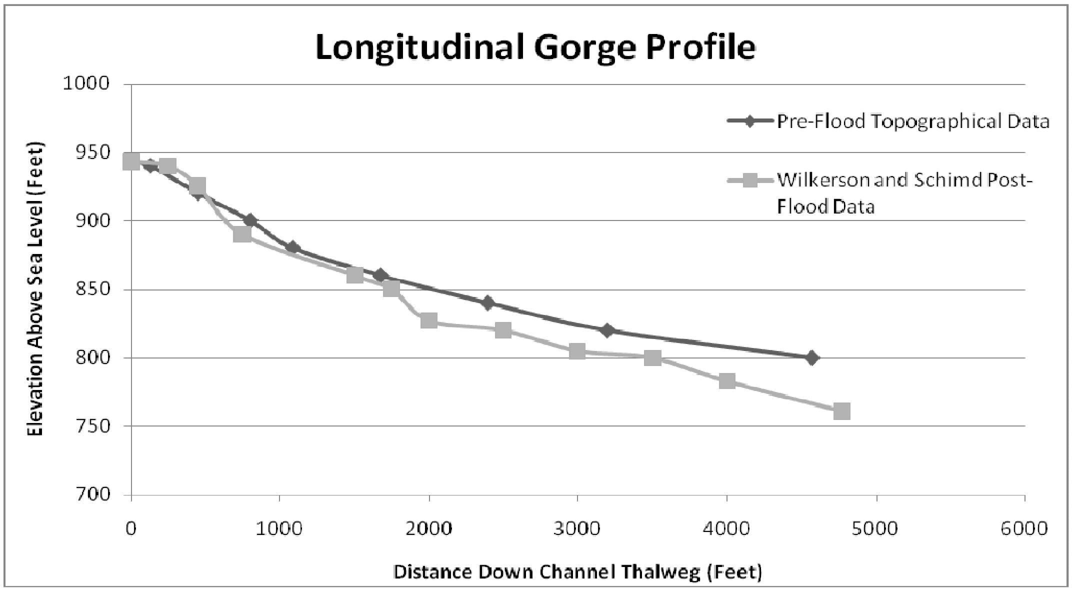


Figure 10. Canyon Lake Gorge profile and spillway profile overlaid. Post-flood profile from Wilkerson and Schmid (2007). The comparison found in Figure 10 should be considered an approximate pre-flood and post-flood profile of the spillway.

Geology of the Gorge

Canyon Lake Gorge is cut into the strata of the Glen Rose Formation. This Cretaceous age formation is the product of cycles of rising and falling sea levels, resulting in alternating sets of limestone and dolomitic beds (Mancini and Scott, 2006). Geologic composition of the Glen Rose Formation varies between relatively homogenous limestones and heterogeneous clay dominated strata (Stricklin et al, 1972; Barker and Ardis, 1996). One prominent characteristic of the formation is the high clay content found in many layers that increases the erosional susceptibility caused by subsequent expansion and contraction of the clay (Woodruff and Wilding, 2007).

The high clay content of the wackestone of the gorge study area is the primary reason that erosion in the gorge will proceed at vastly differing rates. Clay content has been associated with rapid structural deterioration of rock caused by the expansion and contraction of clay particles (Jimenez-Gonzalez et al, 2008). The expansion and contraction process is based upon the interaction of the clay with water molecules that are electrostatically attracted to the alkali ions in the crystal structure of the clay, causing the clay to swell (Wangler et al, 2006). The prevalence of clayey wackestone in the gorge guarantees a high rate of weathering not matched by other lithologies in the gorge. Aside from the wackestone layers, the rock of the gorge is relatively homogenous and very resistant to weathering. Currently, the wackestone is always seen undercutting more competent rock above it, as no other lithologies found in the gorge can claim to be more incompetent at forming ledges.

Precipitation and Canyon Lake provide the water needed to facilitate erosion in the gorge (Figure 11). Precipitation is the primary source of water, but water from Canyon Lake is also delivered through conduits present in the stratigraphy, such as bedding planes and fractures. Water promotes both chemical and physical degradation among the clayey layers, while the homogenous limestone has little reaction. Also, water can infiltrate rock, causing increased pore pressure and lowered shear strength, and increasing the likelihood of failure along planes of weakness (Braathen et. al., 2004). Precipitation would also reduce any frictional resistance inhibiting ledge failure or slope.

Figure 11. Photograph showing water flow conducted through bedrock.

It should be noted that the strata of the Glen Rose Formation appears well indurated in geologic cores or fresh road cuts. Once exposed to the elements, certain clay bearing layers, such as wackestone, can break down quickly (Woodruff and Wilding, 2007). A study by Woodruff and Wilding (2007) notes that a highway cut into the Glen Rose Formation located west of Austin initially looked to consist of completely competent rock, and did not display any of the characteristic weathering commonly described as marly or friable. After 25 years, erosion of the highway cut had begun to incise into the clayey carbonate, causing the steep vertical face to become a hazard to auto traffic. As a result, the highway cut had to be redesigned. The progression of erosion in the situation of the highway cut could be comparable to the processes affecting the steep cliff faces of Canyon Lake Gorge.

Differential weathering is the process responsible for the situation of the highway cut, and is a defining characteristic of the Glen Rose Formation. Previous studies of the Glen Rose Formation have termed the topography “stair-stepped” because the sequences of fast and slow eroding beds is seen resembling a set of stairs in Central Texas (Woodruff and Wilding, 2007; Wilcox et al, 2007). This stair-stepped topography can be observed in a stable state throughout the hill country of Central Texas. Considering the gorge is cut into the same geologic formation as the stair-stepped topography, the hillsides surrounding the gorge is a likely representation of the geomorphic equilibrium Canyon Lake Gorge will reach. Weather-resistant beds of competent homogenous limestone serve as the stair-step platforms, whereas the less competent beds erode quickly, providing a slope or riser bed (Wilcox et al, 2007). Riser beds form as a culmination of the weathering and erosion of the less resistant beds, when the buildup of sediment and debris form a sloping bed to the base of a weather-resistant bed. Riser beds serve to slow the erosion of weathering susceptible rock by providing a buffer against the erosional elements of precipitation and wind, thus preventing the formation of any unstable geomorphic structures (Woodruff and Wilding, 2007).

Geomorphic Equilibrium – Riser Beds

Extrapolating on the geomorphic processes such as the failure of an undercut ledge, it is the opinion of this study that such geomorphic processes will become less active as the gorge settles towards the geomorphic equilibrium of stair-step topography exhibited by the hills of the Glen Rose Formation. A primary geomorphic component of stair-step topography is riser beds. Formed as a result of debris and sediment accumulation, the absence of riser beds differentiates the unstable gorge geomorphology from the stable stair-step topography of the surrounding hills. The stable geomorphology of the hill country is predicated upon riser beds protecting the clayey limestone layers (wackestone) from erosion.

Equilibrium in Canyon Lake Gorge will occur once a sufficient amount of erosion has taken place, forming riser beds that will slow erosion in the gorge. As evident by the debris seen in Figure 12, the competent ledge forming rock above the wackestone has failed and fallen in large and small blocks that accumulate at the base of the vertical cliff face. The resulting accumulation of debris will slow down erosion of the clayey wackestone layers, shielding them from precipitation and runoff. A study by Woodruff and Wilding (2007) has stated that contrary to public belief, the steeply sloped riser beds of the hill country are very stable geomorphologically, and show very little sediment loss caused by precipitation runoff. The most runoff was measured along the gently sloping tread that extends out onto stable platforms of resistant limestone (Woodruff and Wilding, 2007). It stands to reason that once the gorge has built up enough debris to form its own riser beds, formation of new undercut rock ledges would cease, and rock falls would be less of a safety concern.

Figure 12. Photograph of rock erosion accumulation.

Based on the observations of this study and that of other literature on the Glen Rose formation, the geomorphology of the gorge is predicted to evolve through three successive stages (Wilcox et al, 2007; Woodruff and Wilding, 2008). Figure 13 diagrams the three proposed stages based on the observations of this study and previous studies.

Stage 1 – The first stage is a short time period of time immediately following the formation of the gorge. The gorge exhibits bare rock cliff faces, and some undercut rock ledges. All rock appears consolidated and competent. There is a relative absence of gravity driven processes such as rock falls and rock toppling. Clay sediments are rapidly facilitating weathering, hastened by precipitation and the conduction of water through joints and fractures.

Stage 2 – This is the current stage of the gorge. Differential weathering has led to undercut rock ledges throughout the gorge. Constant rock fall events occur as rock ledges fail. Vegetation has started to enter the gorge.

Stage 3 – Stability of the landform has been reached. Riser beds have formed through accumulation of debris and sediments. Erosion of wackestone is slowed or prevented by the riser beds. The gorge now resembles the stair-step geomorphology of the surrounding hills.

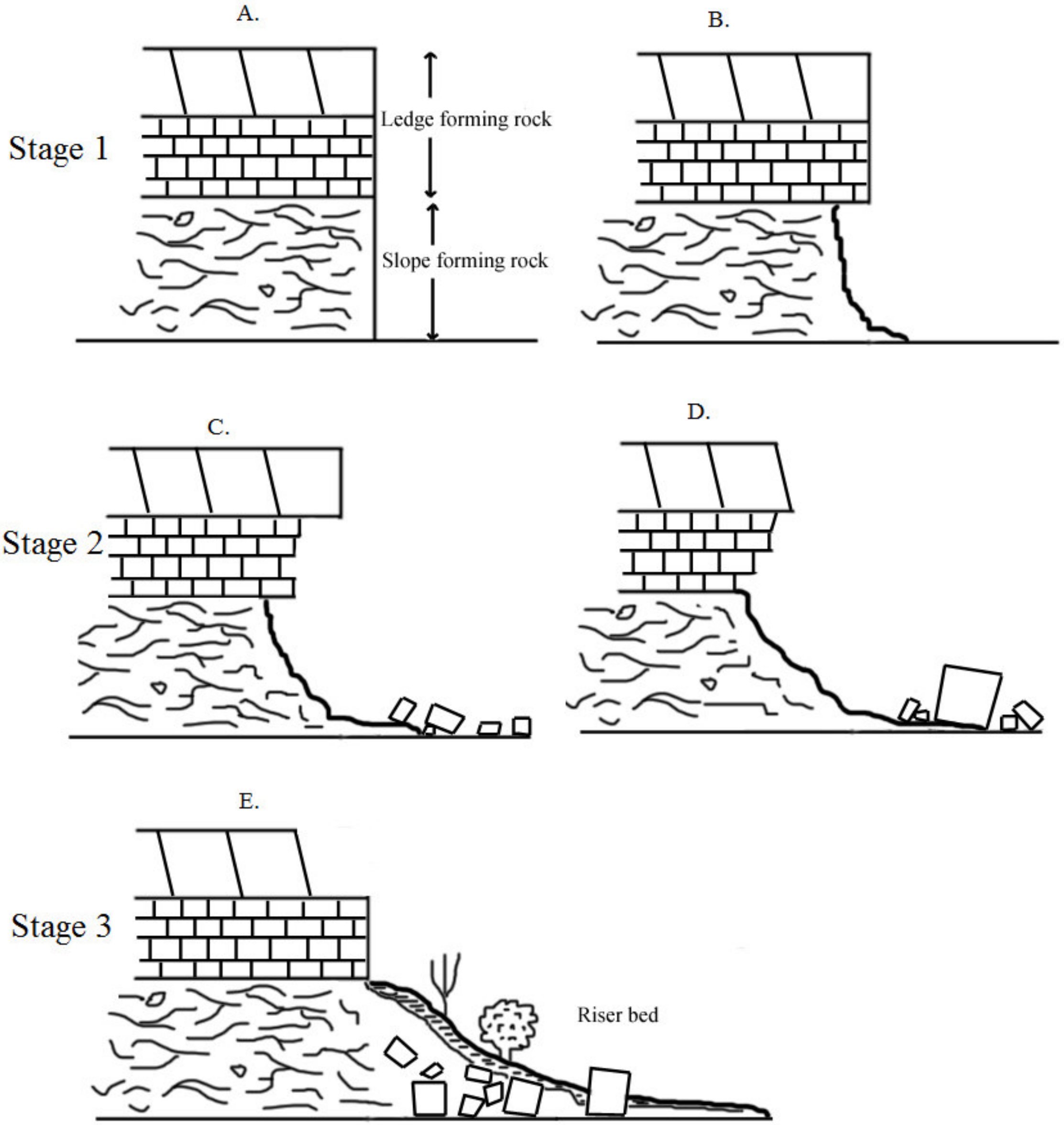


Figure 13. Erosion progression diagram. Diagram predicts an erosion model that leads to rock falls and eventual formation of a riser bed. (A) is equivalent to a fresh road cut. (B) represents a sequence in the gorge immediately after the 2002 flood. (C) represents the current state of many areas in the gorge. (D) shows progression of erosion and blocks of rock accumulating at the base of the ledge. (E) is the final stage where the landscape has reached a relative equilibrium, when erosion proceeds much slower.

Canyon Lake Gorge is also located within the Balcones, a large fault system which is noted for its N40-70E trending faults (Collins, 1995). Smaller faults, fractures and joints are also noted to trend parallel to or at an angle acute to the primary strike of faulting (Collins, 1987; 1995). Furthermore, fault propagation is postulated to occur more often in the competent limestone and dolomitic layers that are susceptible to brittle failure, and less often in the incompetent clayey layers capable of accumulating strain (Ferrill and Morris, 2003). Competent layers of the Glen Rose are noted to be characterized by steep fault dips and low fault displacement, where the incompetent layers of rock promote high amounts of displacement in relation to fault length (Ferrill and Morris, 2008). The faults, fractures and joints of the Glen Rose are associated with transport of groundwater through an otherwise low permeability rock matrix, thus facilitating the dissolution of carbonate minerals and formation of karst features (Ferrill et al, 2004).

FIELD METHODS

The methodology of this study was designed to gather information pertaining to potentially hazardous unstable masses of the gorge adjacent to a pathway used for guided tours. On the pathway, undercut rock ledges were the unstable masses of interest, as failure of these ledges has the possibility of causing injury to the visiting public and guides (Figure 14).

Three distinct phases of field work were performed: a) survey of rock surface discontinuities, including fractures and joints, b) comprehensive survey of stratigraphy of the guided visitor pathway, c) testing of each stratigraphic unit by the impact test hammer.

Figure 14. Photo of Canyon Lake Gorge in July 2008. Person on right side of photo for scale. View is from the western end of the gorge towards the east, down the flow of water.

Rock Surface Discontinuities

Geological field studies were carried out to map rock surface discontinuity orientations and their locations in the gorge. Strike direction was recorded for each discontinuity, though dip direction was not obtained. GPS coordinates were taken for each discontinuity orientation. Measured discontinuity orientations were then mapped approximately on an aerial photograph of the gorge using the GPS coordinates of each discontinuity.

Impact Test Hammer

Use of a concrete impact hammer was employed on each rock unit to obtain rebound value measurements. The concrete impact test hammer tests a surface resistance to the impact of a spring loaded plunger, on which the rebound is measured. Ten tests were performed on each rock unit surface with the goal of picking representative test locations on each unit, as recommended by the Concrete Test Hammer instruction manual of Soiltest Incorporated (Concrete Test Hammer, 1970). Each test measures a value on the impact hammer that represents an amount of force resisted which can be correlated to a force via a graph provided in the Soiltest Instruction Manual (Figure 15).

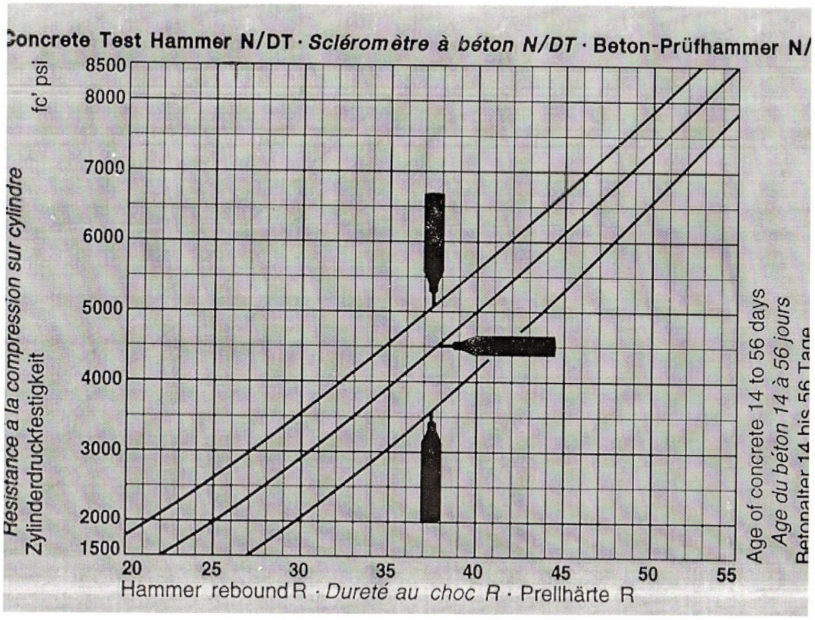


Figure 15. Soiltest graph of rebound value vs. PSI resisted (Soiltest Inc., 1970).

Test values of solid rock measure between 20 and 60. Post data analysis was done to remove values that were deemed the result of operator error. This meant eliminating values that varied from the median value by more than five or fewer than five. Eliminated test values were most often caused by the rock fracturing under the impact of the test hammer, dampening the rebound value.

Stratigraphy/Lithology

Three separate stratigraphic data reaches were completed by studying rock units along the path used to traverse the gorge. The three reaches are not contiguous, as areas covered by quaternary sediment necessitated two separate breaks in the observed reaches by obstructing rock from observation. The study of the first reach began from the base of the gorge by the South Access Road where visitors begin tours, and the third reach ends at a point of the gorge approximately 518 m (1,600 ft) west of the road, up the gorge. All reaches are observable from the tourist pathway used by GBRA trail guide docents. Figure 16 illustrates the three reaches all field studies were performed upon.

Each reach was subdivided into lithologic units that were then described using Dunham's (1962) system for categorizing carbonate rock. Weathering characteristics of each rock unit were noted. Erosional patterns and characteristics were studied to establish to what degree each rock unit was a slope or ledge former. Thickness of a rock unit was measured to the nearest tenth of a foot. Photos were taken of each rock unit and of potential hazardous areas of rock fall or toppling. Other data gathered included observations of color, weathered color, composition, fossil presence, and degree of consolidation.

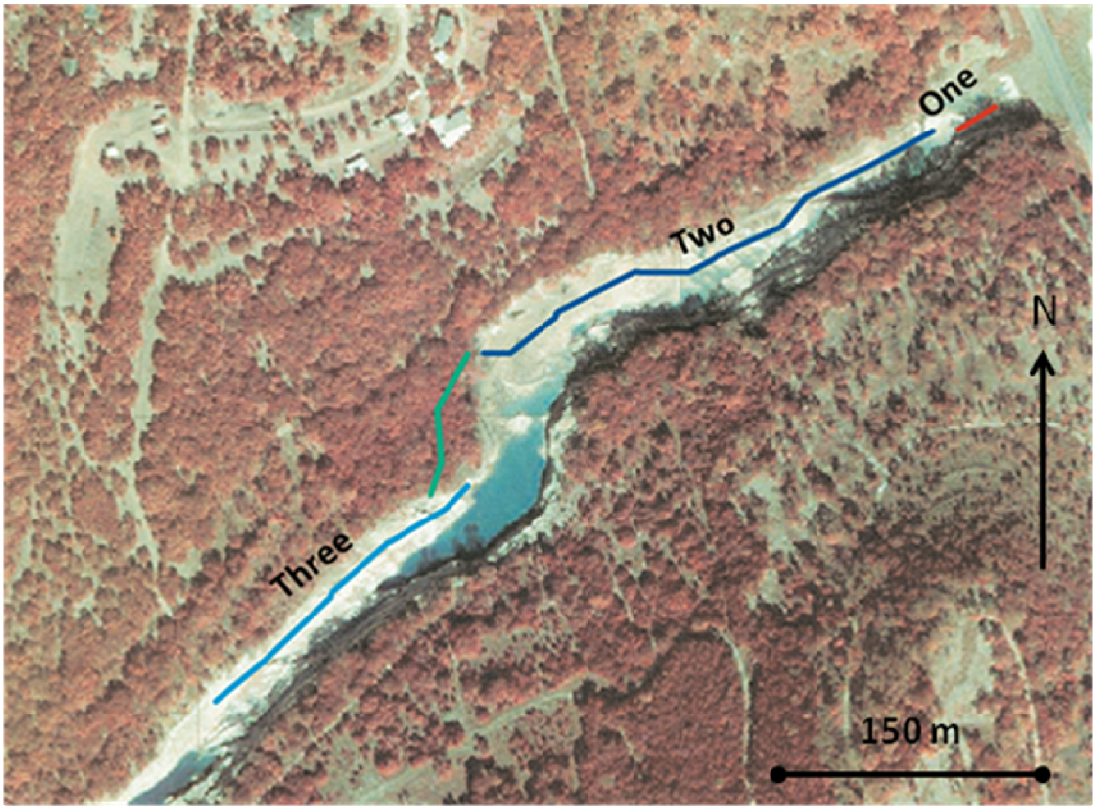


Figure 16. Map of Reaches of Stratigraphic Studies. Reach One is a short reach in the north-east corner, Reach Two is the longest reach, the green reach is a pathway over quaternary sediments, and reach three is the south-west reach.

RESULTS AND ANALYSIS

From the observations made during this study of reaches of the gorge, three general carbonate lithologies were noted.

- Wackestone – Defined as mud supported, with more than 10% grains (Dunham, 1962). Seen predominantly in the gorge as weathered gray debris, forming a slope.
- Packstone – Defined as grain supported, but also contains clay and silt sized carbonate (Dunham, 1962). Seen predominantly in the gorge as an either gray or tan ledge forming rock. Two sub-varieties are seen in the gorge, clay-dominated and grain-dominated packstone. Clay-dominated packstone contains clay partings, and generally has an uneven weathered surface. Grain-dominated packstone contains very little clay, has very discrete fractures and joints, and possesses an average rebound value near that of grainstone.
- Grainstone – Defined as grain supported with an absence of mud (Dunham, 1962). Seen in the gorge as a gray ledge forming rock. Commonly appears as a vuggy rock with many obvious fossils, but also appears as a smooth surfaced gray rock. Grainstone possesses the highest average rebound values of all rock tested in the gorge.

Discontinuities

The end result of the discontinuity orientation map displays a sampling of surface rock discontinuities along an approximately 305 m (1,000 ft) stretch of the gorge (Figure 17). A total of 81 discontinuity orientations and their GPS locations show that the fracture or joint orientations are dominated by a north-westerly strike that runs approximately perpendicular to length of the Gorge. A complimentary set of fractures strike north-east in a parallel manner to the Hidden Valley Fault that runs the length of the Gorge. Attributing slope failures to discontinuity spacing and density has been practiced in predicting hazardous areas (Gokceoglu et al, 2000 ; Topal et al, 2007; Wieczorek et al, 2008).

Figure 17. Fracture orientation map. Strike of a sampling of fractures is shown.

Certain principles can be applied when observing undercut rock ledges. Closely spaced discontinuities may indicate that a rock cliff or ledge can fail in small blocks. Conversely, an unstable mass with sparse discontinuity density may indicate a greater capacity to accumulate strain, which should allow the rock to better withstand the stresses of being undercut before failing. In the field, the size of rock debris at the base of a ledge can indicate whether the rock masses located up-slope fail as small blocks, or sparsely in large blocks.

The mechanical properties of individual rock units greatly affect the density of jointing and fractures found within each rock unit. Competent layers (most packstones and all grainstone) behave in a relatively brittle fashion, and exhibit distinct discontinuities. Incompetent layers (wackestone and clay dominated packstone) appear to inhibit propagation of fractures and joints from unit to unit, deforming under strain without failing.

In Canyon Lake Gorge, observed discontinuities were relatively equally spaced in individual units of rock, but not across multiple units. Observations by Collins (1995) in other areas of the Balcones fault zone support the previous observation by noting that variation in joint density and orientation occurred amid rock units, and even rock units adjacent to one another. In the gorge, a number of units have widely spaced fractures and joints ranging from 2.1-4.5 m (7-15 ft) apart, whereas others have very dense discontinuity patterns spaced by a 0.3 m (1 ft) or less. Horizontal discontinuity density varies from very dense discontinuity sets only inches apart, to almost a complete lack of discontinuities. Bedding planes commonly form jointed discontinuities in Canyon Lake Gorge.

At the western end of the studied area, the majority of the discontinuities are oriented roughly 45° -55° west of North. Other discontinuities are oriented in the region of 50° to 70° East of North, approximately parallel to the length of the Gorge and the strike of Hidden Valley Fault. These northeast orientations are consistent with Collins's (1995) observations of N40° -70°E striking faults in the Balcones fault zone.

Past literature has categorized rock slope areas by the way the mass fails according to the gradient of the rock slope and the orientations of the slope discontinuities (Braathen et al, 2004; Shroder et al, 2005). In-situ discontinuities have been attributed to detachment zones of rock falls (Varnes, 1978; Gokceoglu et al, 2000; Park et al, 2005). Based on the vertical and horizontal discontinuity sets seen, the failure of rock masses of Canyon Lake Gorge would be classified as rock falls. In the gorge, the highest concentrations of joints and fractures are found in undercut portions of rock ledges, especially in packstones. Many of these fractures were presumably induced by the increased tensile stress brought on by the stress concentration distribution of undercut ledges. Because of this, current joints or fractures could be a future area of failure for an undercut rock ledge, but new potential rock fall areas could form as new fractures propagate and rock is undercut.

The field observations of this study are supported by a recent manuscript by Ferrill and Morris (2008) who made use of Canyon Lake Gorge as a study area. Ferrill and Morris (2008) noted the propensity of competent rock layers to facilitate rapid early fault propagation, followed by displacement accumulation. Incompetent layers were noted for arresting fault propagation, while accumulating large amounts strain (Ferrill and Morris, 2008).

Role of Knickpoint Erosion Mechanism in the Formation of the Gorge

A sudden change in gradient in a stream or spillway profile is termed a Knickpoint (May, 1988). Photos taken during the flood appear to support a theory of the erosional progression of knickpoints “stepping up” the gorge toward the lake (Figure 5, page 7). Knickpoint erosion requires a flow of water over a steep gradient or vertical face, creating an unvented pocket of air behind the falling water (May, 1988). Water flow can then be drawn into that unoccupied space, scouring the rock or even causing sufficient pressure to uplift large blocks of rock and transport them with the prevailing flow of water. Large boulders measuring greater than five ft (1.52 m) are positioned in areas far from the parent bedrock (Figure 18). Post-flood discontinuity orientations mapped in this study indicate that in-situ fractures would have aided a knickpoint erosional progression model that could have created the current gorge geomorphology. Knickpoints would have been prone to form at the junction of vertical and horizontal discontinuities. The two main surface discontinuity orientation sets observed in this study can be considered important remnants of factors that played large in the formation of the gorge. When the flood waters scoured out the emergency spillway while flowing toward the river to the north-east, any north-western oriented discontinuities would have effectively divided the bedrock into blocks easily excavated by the immense amount of flood water flow.

Figure 18. Canyon Lake Gorge. Large boulders scoured from the bedrock were moved during the 2002 flood

Impact Test Hammer

Below is a plot of each lithologic unit's average rebound value in presented semblance in a vertical column (Figure 19).

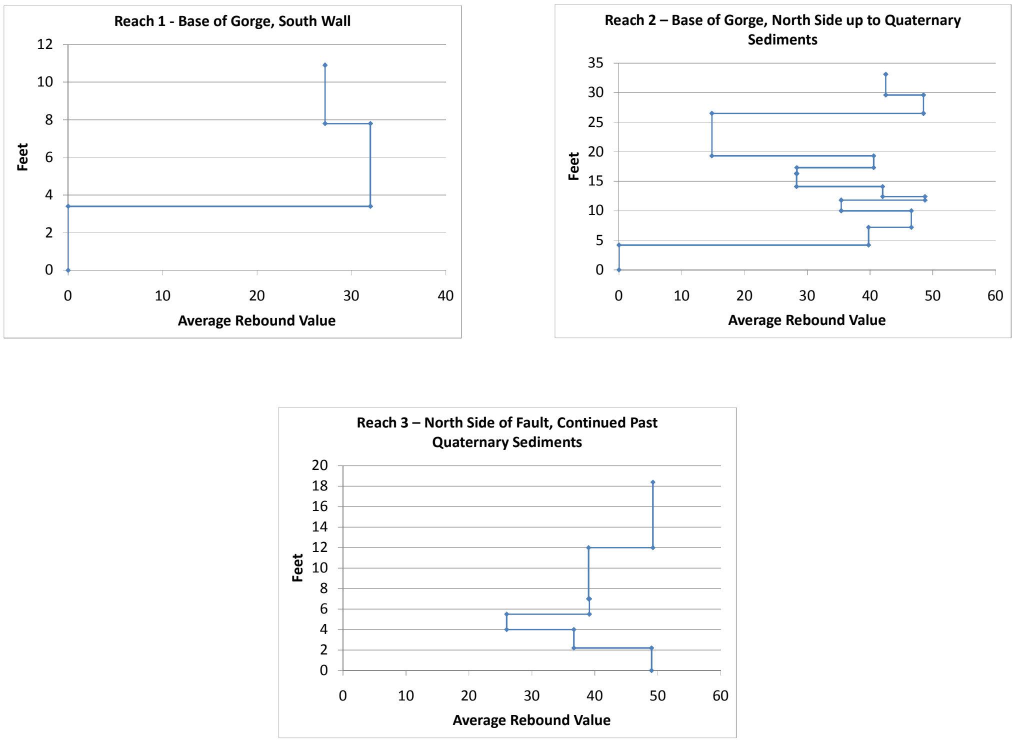


Figure 19. Graphs of average rebound value vs. thickness.

In all three stratigraphic surveys, a high average rebound value (greater than 30) correlated well with units resistant to weathering such as grainstone, where a low average rebound value correlated with rock units more susceptible to weathering such as wackestone. Precedent has been set supporting the correlation of the rebound values of an impact hammer with density, porosity, and the compressive strength of the tested rock (Erdogan and Yasar, 2004; Aydin and Basu, 2005). In the case of this study, a lithologic unit possessing a high average rebound value always is characteristic of grainstone or packstone and is subsequently more resistant to weathering then those possessing a low average rebound value. This phenomenon is most likely caused by the inherent characteristics associated by previous studies with high rebound values, for example high density, low porosity, and high compressive strength.

Stratigraphic Survey

The stratigraphic study details the engineering geologic characteristics of each lithologic unit along three different reaches of the gorge (i.e., weathering characteristics, rock competency, and structural characteristics).

There are a total of five wackestone units documented in the three reaches studied. All five of these wackestone units are present beneath a ledge forming rock unit. Eleven of the units studied were packstone, and five units were grainstone. The packstone units varied in composition between grain or clay dominated end members. The grainstone units consistently appeared very resistant to weathering, even when vuggy porosity was present. As noted by Woodruff and Wilding (2007), a vuggy appearance is associated with ledge forming rock in the Glen Rose Formation.

Reach One

Reach One is a prototypical sequence exemplifying the three main lithological units found in the gorge. The sequence consists of a wackestone base overtopped by a more competent and weather resistant packstone, capped by an equally resistant layer of grainstone (Figure 20).

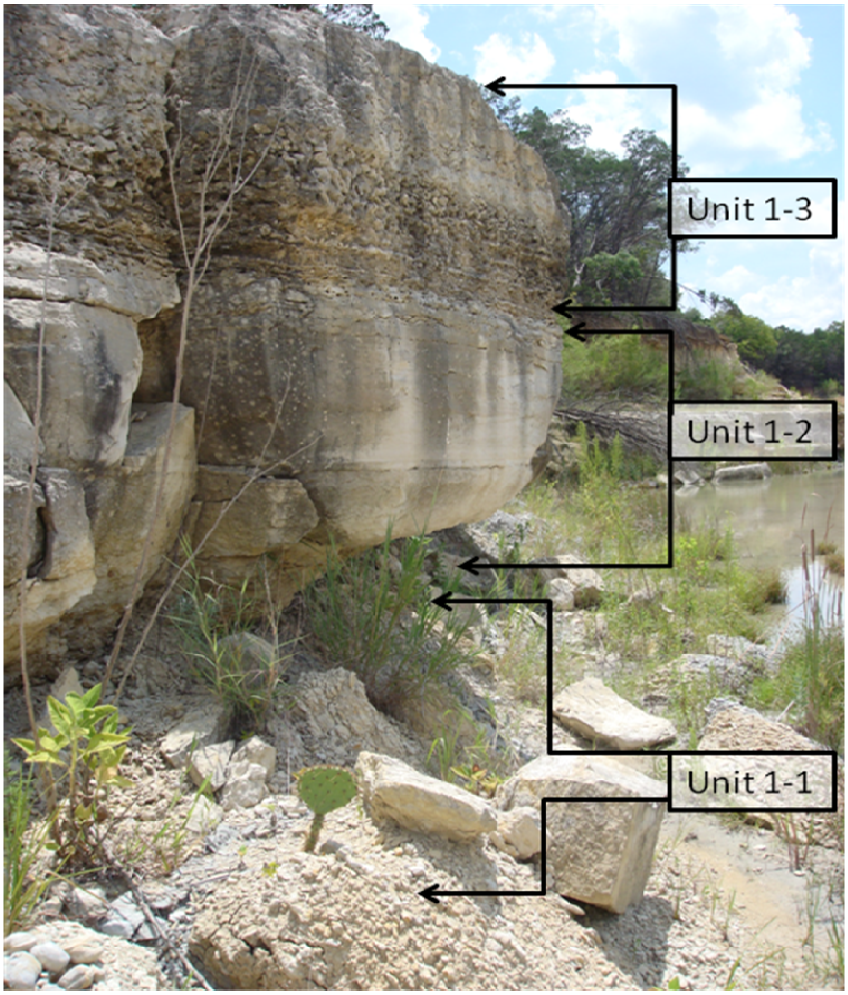


Figure 20. Reach One Stratigraphy. Reach One is a short reach involving only three different units of rock. Reach One can be found on the south side of the gorge immediately upon entering from the South Access Road.

The base unit of Reach One is an easily eroded wackestone that forms a slope underneath a small cliff face. Because of how friable the rock is, the strike of the impact test hammer resulted in unit 1-1 crumbling under impact, yielding only measurements of zero (Figure 21).

Figure 21. Rock unit 1-1. Unit 1-1 is a wackestone that is 1.04 m (3.4 ft) thick. This rock is very friable, and is seen in this reach creating a slope.

Lying overtop unit 1-1 are a layer of packstone and grainstone (Figure 22, Figure 23). Unit 1-2 is a very homogenous packstone, and unit 1-3 is distinguished by its pervasive vuggy porosity. Unlike wackestone, units 1-2 and 1-3 are very resistant to weathering. Vertical fractures run sparsely through the thickness of unit 2-1 before terminating in adjacent units.

Figure 22. Rock unit 1-2. Unit 1-2 is a homogenous packstone that is 1.34 m (4.4 ft) thick.

Figure 23. Rock unit 1-3. Unit 1-3 is a grainstone that is 0.94 m (3.1 ft) thick.

The impact test hammer results of Reach One revealed results that correlated high values with the ledge forming rock, and low values with the wackestone base unit (Figure 24 Table 1). Ten impact test hammer measurements were taken of each unit, resulting in an average rebound value of 32.1 (3,990 psi) for unit 1-2 and rebound value of 27.2 (3,020 psi) for Unit 1-3. The wackestone measured readings of zero, whereas the more competent packstone and grainstone had many measurements exceeding 30 (2900 psi).

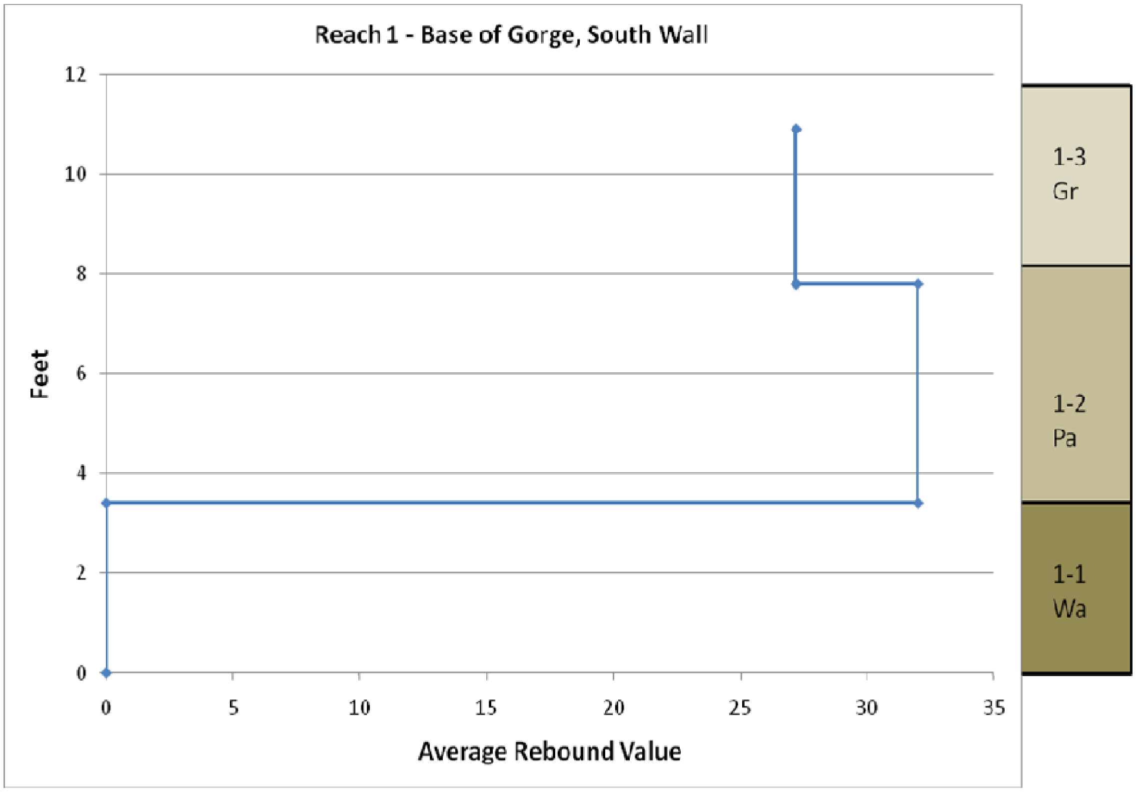
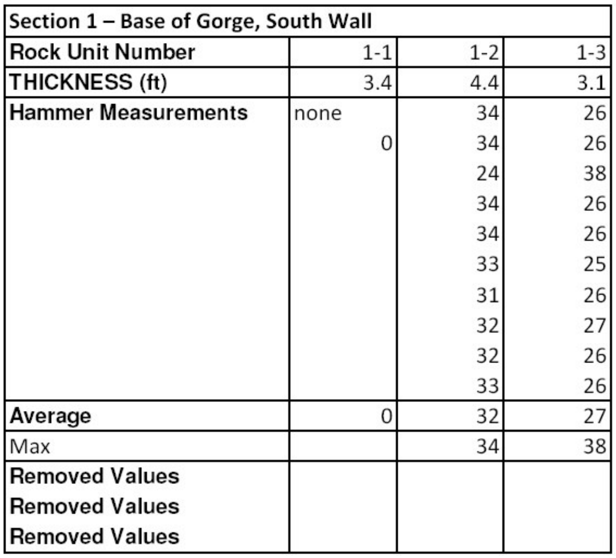


Figure 24. Reach One Graph, average rebound vs. thickness. The thickness is of the lithologic unit. Wa (wackestone), Pa (packstone), Gr (grainstone).

Table 1. Data table of the impact test hammer test results for Reach One.



Section 1 – Base of Gorge, South Wall			
Rock Unit Number	1-1	1-2	1-3
THICKNESS (ft)	3.4	4.4	3.1
Hammer Measurements	none	34	26
	0	34	26
		24	38
		34	26
		34	26
		33	25
		31	26
		32	27
		32	26
		33	26
Average	0	32	27
Max		34	38
Removed Values			
Removed Values			
Removed Values			

Reach One contains the stratigraphic units that combine to form the circumstances necessary for formation of an undercut rock ledge. Previous erosion at this site has occurred to a degree enough to provide a sloping pile of debris at the base of the sequence. By the same token, the large boulders of packstone and grainstone found at the base indicate the ongoing process of rock ledge failure, possibly presenting a potential hazard to visitors.

The location of Reach One compounds the risk presented by rock fall. Reach One is seen as a small cliff face occupying the south wall of the Gorge by the entrance from the south access road. During the field work of this study, the area by Reach One was seen to be the first stop by a tour of visitors entering from the south access road. The wackestone base layer also contains many fossils that would be of interest to visitors. Because of the hazard of rock falls and the location of Reach One, it should be considered a high risk area.

Reach Two

Reach Two is thickest reach and consists of 12 lithologic units seen along the longest reach (Figure 25). Most lithologic units are weather-resistant packstone or grainstone.

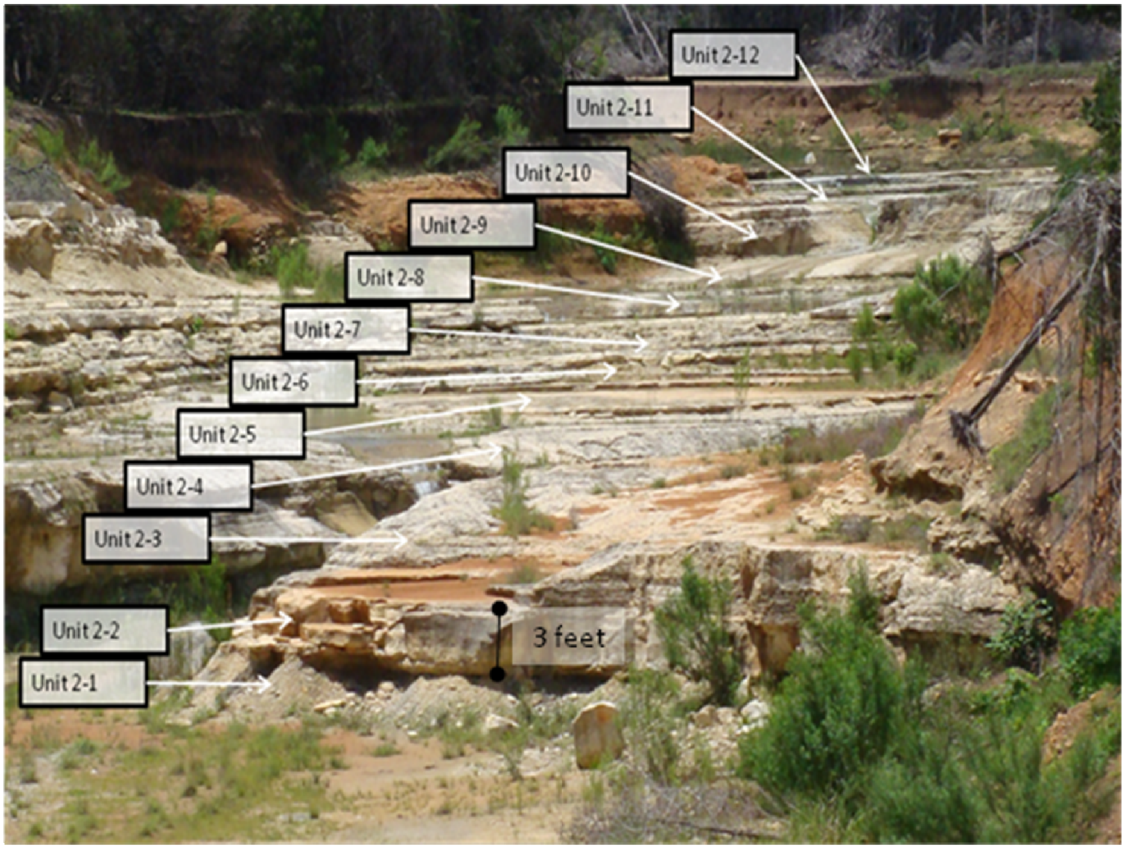


Figure 25. Reach Two Stratigraphy. Reach Two is a sequence of twelve units of rock. This reach displays the variety of carbonate rock that can be found in the Glen Rose Formation.

Units 2-1 and 2-2 create a noteworthy sequence (Figure 26, Figure 27). Unit 2-1 is a very friable wackestone unit, and Unit 2-2 is a ledge forming packstone. Located directly in the path used to trasverse the gorge, the undercut ledge of unit 2-2 over unit 2-1 form a sloped feature that is unavoidable to hikers. The weathered slope of unit 2-1 rises up 1.28 m (4.2 ft) to a competent layer of packstone (unit 2-2), undercutting the layer of packstone. The wackestone is very friable, consequently the impact test hammer failed to read any measurement above zero, whereas the packstone has an average value of 38. Additionally, unit 2-2 has obvious fractures running through undercut portions of the ledge, adding to the danger of ledge failure underfoot of a hiker.

Figure 26. Rock unit 2-1. Unit 2-1 is a wackestone and is 1.28 m (4.2 ft) 1.28 m thick.

Figure 27. Rock unit 2-2. Unit 2-2 is a packstone that is 0.91 m (3.0 ft) thick. The impact test hammer averaged a rebound value of 38.43 (367.7 Kg/cm^2, 5230 psi) in seven successful measurements.

Above the packstone of unit 2-2 is a sequence of competent packstones and grainstones (Figures 28-34). The sequence of unit 2-3 through unit 2-9 do not present any potential hazards to the visiting public. However, these units do display many interesting geological characteristics. Unit 2-3 and unit 2-9 showcase the vuggy porosity characteristic of Glen Rose grainstone. Unit 2-6 is a packstone that exhibits an almost perfectly rectangular fracture pattern, perhaps indicative of past geologic pressure regimes. Also of interest are large channels set at right angles that run in the surface of the wackestone in unit 2-8.

Figure 28. Rock unit 2-3. Unit 2-3 is a grainstone that is 0.85 m (2.8 ft) thick. Fracture density is low; at least seven ft (2.13 m) separate the larger surface fractures.

Figure 29. Rock unit 2-4. Unit 2-4 is a packstone that is 0.55 m (1.8 ft) thick. Weathering of the surface causes the rock to break into laminar sheets.

Figure 30. Rock unit 2-5. Unit 2-5 is a grainstone or a grain dominated packstone that is 0.18 m (0.6 ft) thick.

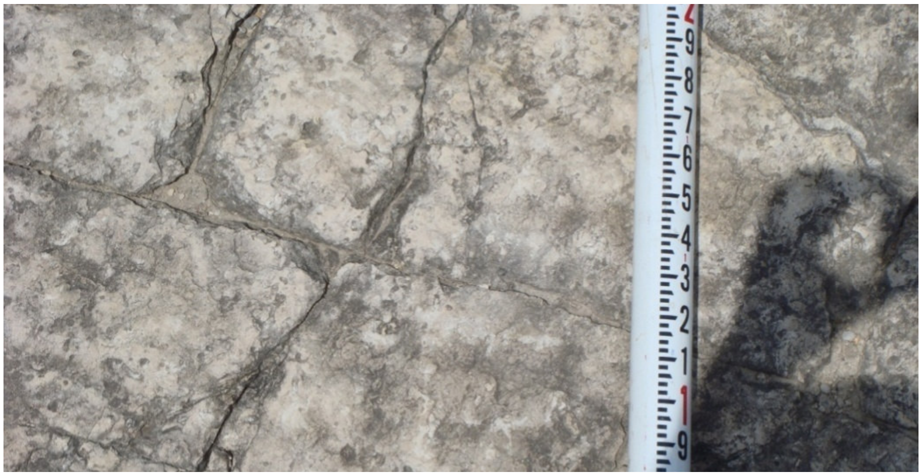


Figure 31. Rock unit 2-6. Unit 2-6 is a packstone that is 0.52 m (1.7 ft) thick. Fracture spacing is approximately 0.5 ft (0.15 m) and a very distinct rectangular pattern is displayed.

Figure 32. Rock unit 2-7. Unit 2-7 is a packstone that is 0.67 m (2.2 ft) thick.

Figure 33. Rock unit 2-8. Unit 2-8 is a wackestone that is 0.3 m (1.0 ft) thick. Large channels run through the surface of the rock.

Figure 34. Rock unit 2-9. Unit 2-9 is a homogenous grainstone that is 0.61 m (2.0 ft) thick. This is a very competent unit, and displays vuggy porosity.

Overlying unit 2-9 is a wackestone and packstone bed (Figure 35, Figure 36). This is a similar sequence to that of the unit 2-1 and unit 2-2 wackestone packstone sequence. In an expected pattern, the wackestone unit 2-9 undercuts the overlying competent packstone, forming an undercut rock ledge. The undercut rock ledge present at the junction of 2-10 and 2-11 is an obstacle to visitors of the gorge. The wackestone layer 2-10 is 7.2 ft (2.2 m) thick, and at some points presents a vertical face not easily climbed.

Figure 35. Rock unit 2-10. Unit 2-10 is a heavily clay dominated wackestone that is 2.2 m (7.2 ft) thick.

Figure 36. Rock unit 2-11. Unit 2-11 is a homogenous packstone that is 0.95 m (3.1 ft) thick. This unit is a ledge former that is very consolidated and indurated, with sparse vuggy porosity.

The final lithologic unit surveryed in Reach Two was a grainstone with an average impact test hammer measurement of 43 (Figure 37). The surface of the rock presents a unique display of large surface ripples

Figure 37. Rock unit 2-12. Unit 2-12 is a grainstone that is 1.07 m (3.5 ft) thick. Ripples are prominent on the surface.

The lithologic units of Reach Two own some of the highest rock strengths measured in this survey (Figure 38, Table 2). In particular, the packstone units 2-3 and 2-11 and the grainstone unit 2-5 measured high average values on the impact test hammer.

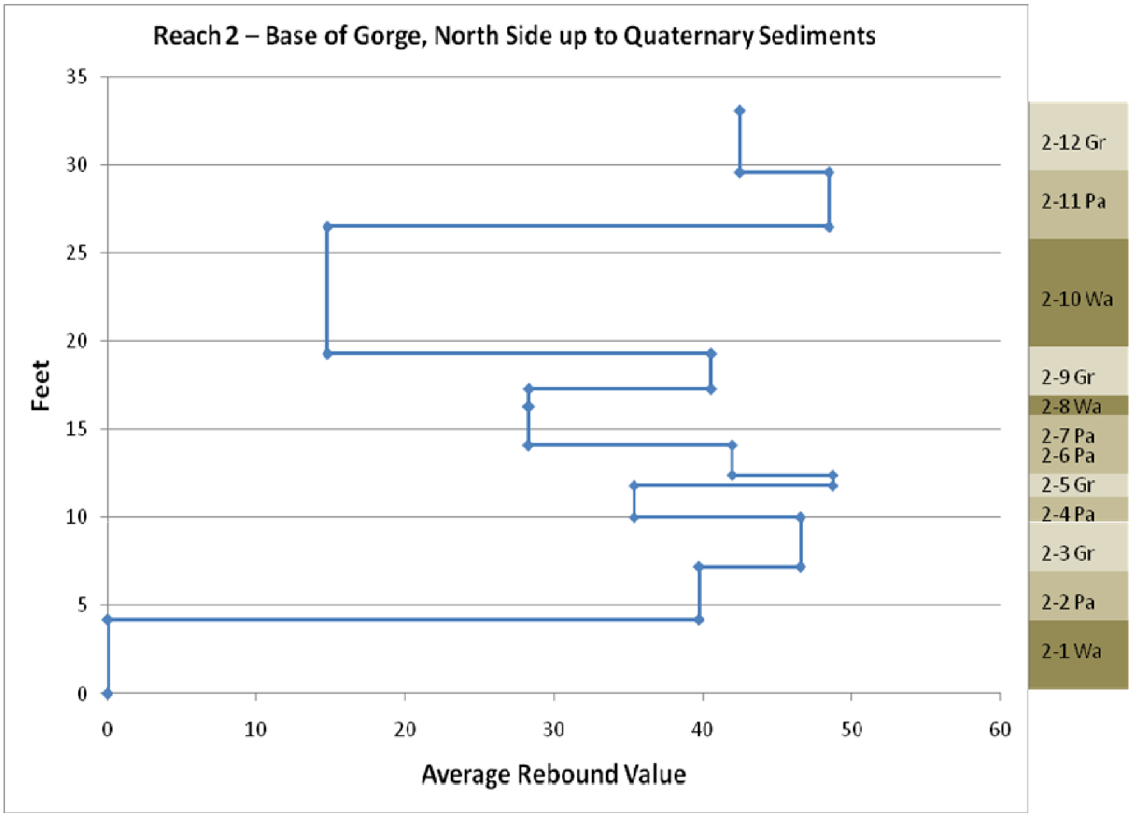
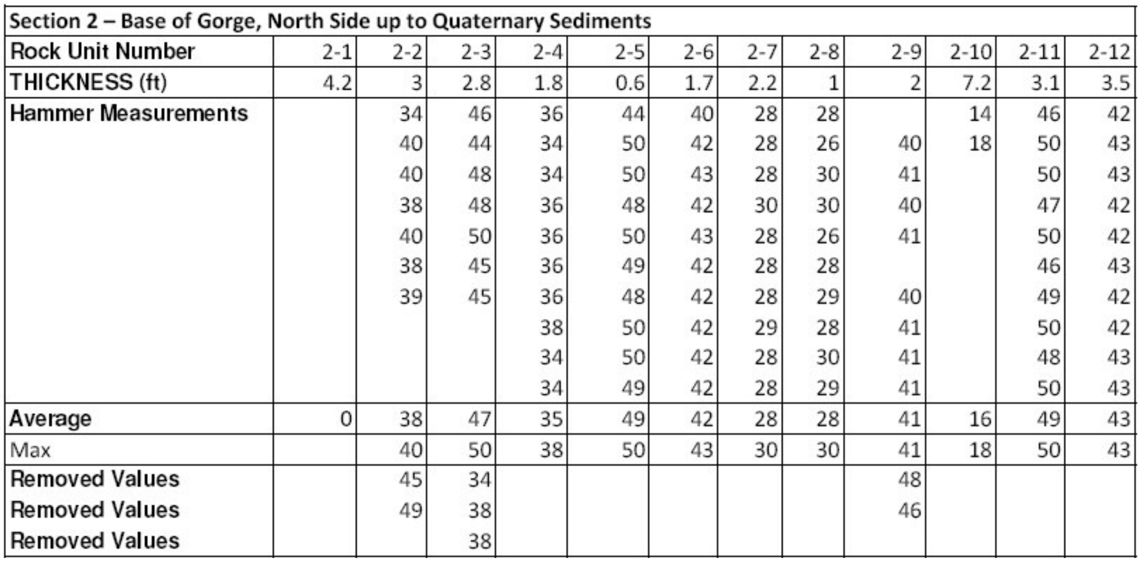


Figure 38. Two Graph, Average Rebound vs. Thickness. Graph of average rebound value vs. thickness of lithologic unit. Wa (wackestone), Pa (packstone), Gr (grainstone).

Table 2. Data table of the impact test hammer test results for Reach Two. Outlying test values were removed.



Section 2 – Base of Gorge, North Side up to Quaternary Sediments												
Rock Unit Number	2-1	2-2	2-3	2-4	2-5	2-6	2-7	2-8	2-9	2-10	2-11	2-12
THICKNESS (ft)	4.2	3	2.8	1.8	0.6	1.7	2.2	1	2	7.2	3.1	3.5
Hammer Measurements		34	46	36	44	40	28	28		14	46	42
		40	44	34	50	42	28	26	40	18	50	43
		40	48	34	50	43	28	30	41		50	43
		38	48	36	48	42	30	30	40		47	42
		40	50	36	50	43	28	26	41		50	42
		38	45	36	49	42	28	28			46	43
		39	45	36	48	42	28	29	40		49	42
				38	50	42	29	28	41		50	42
				34	50	42	28	30	41		48	43
				34	49	42	28	29	41		50	43
Average	0	38	47	35	49	42	28	28	41	16	49	43
Max		40	50	38	50	43	30	30	41	18	50	43
Removed Values		45	34						48			
Removed Values		49	38						46			
Removed Values			38									

Reach Two has two major wackestone beds in units 2-1 and 2-10, and both are seen undercutting the overlying packstone. Both of the wackestone-packstone junctions are unavoidable obstacles in a hike through the gorge. Collapse of a rock ledge under the weight of a person is a hazard to any visitors traversing these two geologic structures. Injury resulting from a small fall is possible in such a situation, but can be avoided by picking a careful path over the wackestone-packstone intersects. If a tourist or guide attempts to travel up the gorge using a route other then the marked path, the risk of falling or destabilizing a rock slope is high.

Reach Three

Reach three is a sequence of six units of rock, consisting of four packstone units, one wackestone, and one grainstone (Figure 39). The pathway used to traverse the gorge is on the north side of a large fault that runs through the center of the gorge. There are no notable structures that would present a high risk in this reach of stratigraphy. Only small risks are present in reach three.

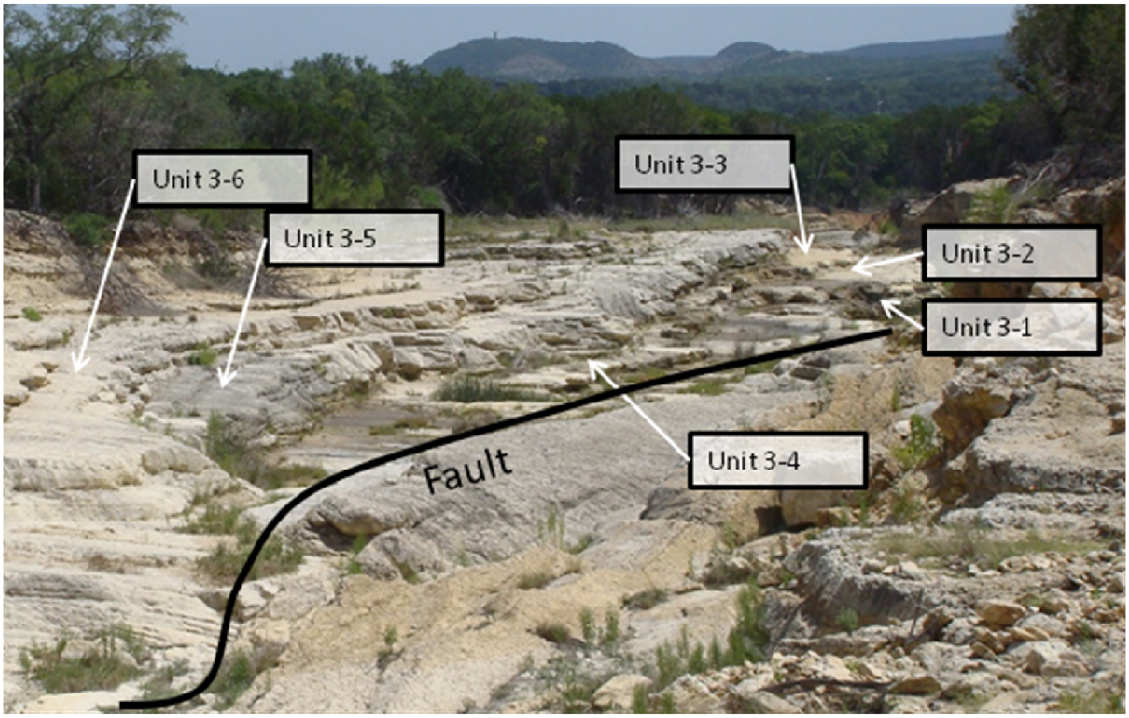


Figure 39. Reach three stratigraphy. Picture showing rock units of reach three, and the fault running through the gorge.

Reach three is the highest in elevation of the three reaches, and is consequently composed of strata younger then that seen in Reach Two. The first two units of reach three are packstones (Figure 40, Figure 41). Unit 2-1 is a more homogenous packstone and measured a higher rock strength then unit 2-2. The lower average impact hammer results of unit 2-2 appear to be accounted for by a slightly higher clay content.

Figure 40. Rock unit 3-1. Unit 3-1 is a packstone that is 0.67 m (2.2 ft) thick. It is consolidated and relatively homogenous in appearance.

Figure 41. Rock unit 3-2. Unit 3-2 is a packstone that is 0.55 m (1.8 ft) thick. Clay content appears greater than other packstones.

Unit 3-3 marks the first occurrence of wackestone in reach three (Figure 42). Unit 3-3 is a wackestone that undercuts the packstone of unit 3-4, but the thickness of unit 3-3 (1.5 ft (0.46 m)) makes any rock ledge failure a low risk of injury (Figure 43).

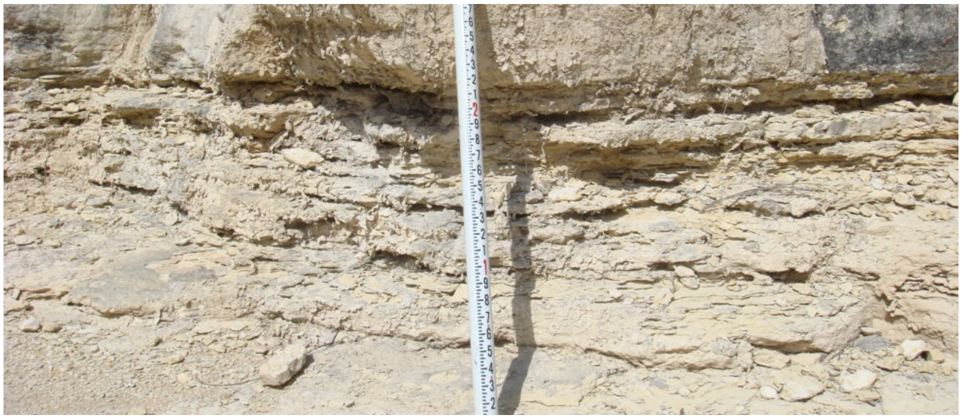


Figure 42. Rock unit 3-3. Unit 3-3 is a wackestone that is 0.46 m (1.5 ft) thick. This unit exhibits nodular weathering, and is friable.

Figure 43. Rock unit 3-4. Unit 3-4 is a packstone that is 0.46 m (1.5 ft) thick. This unit is a consolidated, ledge forming rock.

The final two units surveyed in reach three were two competent packstone units. Units 3-5 and unit 3-6 do form steep slopes in some locations, but the rock is very well consolidated and provides solid footing for visitors (Figure 44, Figure 45). The near vertical slopes found traversing units 3-5 5.0 ft (1.52 m) and 3-6 (6.4 ft (1.95 m)) can be a minor risk if a visitor is not guided up the proper pathways.

Figure 44. Rock unit 3-5. Unit 3-5 is a packstone that is 1.52 m (5.0 ft) thick. This unit is highly fractured at its base, but grades up to a more consolidated state near its top.

Figure 45. Rock unit 3-6. Unit 3-6 is a grain dominated packstone that is 1.95 m (6.4 ft) thick.

The lithologic units of reach three possessed very high rock strength values (Figure 46, Table 3). With the exception of unit 3-3, a wackestone, all the units of reach three averaged 40 (351 Kg/cm^2, 5,000 psi) or higher in the impact test hammer tests.

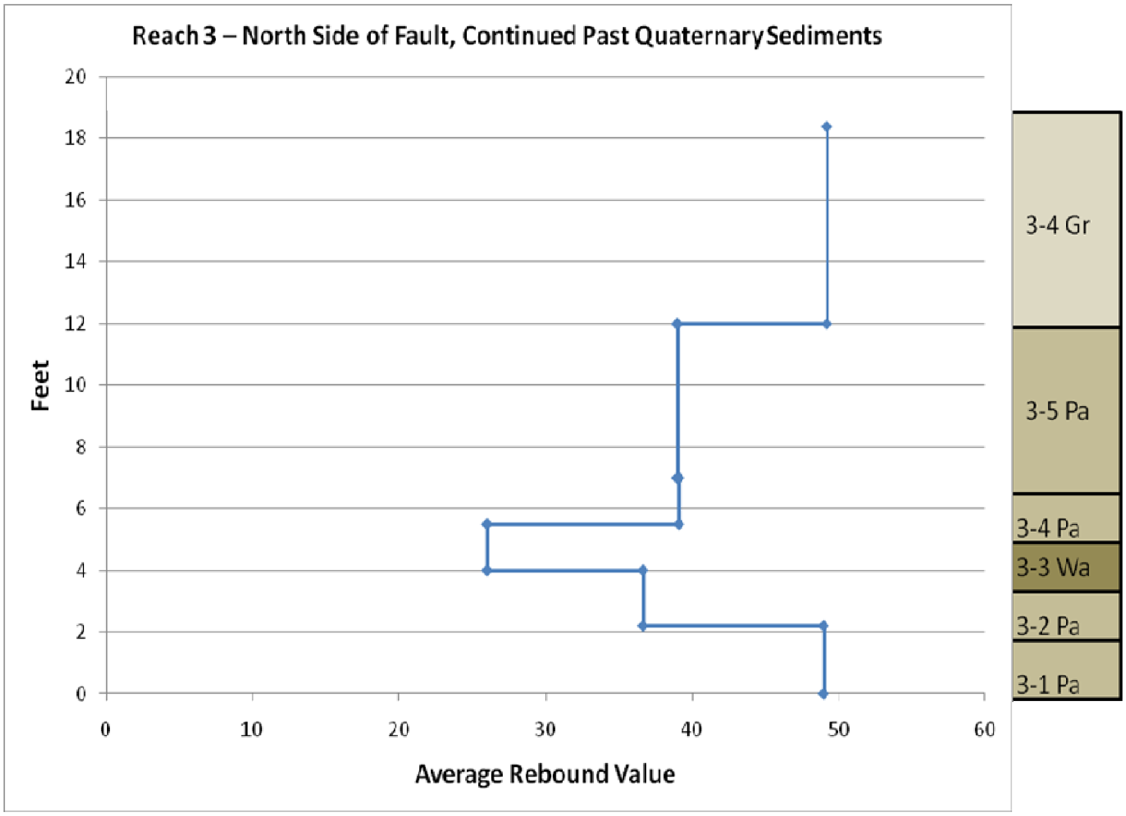


Figure 46. Reach Three Graph, Average Rebound vs. Thickness . Thickness is of the lithologic unit. Wa (wackestone), Pa (packstone), Gr (grainstone).

Table 3. Data table of the impact test hammer test results for Reach Three. Outlying test values were removed.

Section 3 - North Side of Fault, Continued Past Quaternary Sediments						
Rock Unit Number	3-1	3-2	3-3	3-4	3-5	3-6
THICKNESS (ft)	2.2	1.8	1.5	1.5	5	6.4
Hammer Measurements	50	40	26	38	38	49
	46	40		39	40	50
	50	40		40	40	48
	50	38		40	38	49
	47	40		40	38	49
	50	40		40	39	48
	50	39		38	40	50
		40		38	39	50
						50
						50
Average	49	40	26	39	39	49
Max	50	40	26	40	40	50
Removed Values		36		34	50	
Removed Values		34		36	50	
Removed Values						

The area encompassed by reach three contains low risk situations where a minor fall is possible. The junction of unit 3-3 and 3-4 has a potential fall hazard, although any fall is unlikely to cause serious injury because the thickness of unit 3-3 is small. Units 3-5 and 3-6 can be difficult to climb to continue on the path up the gorge, and thus represent a potential fall hazard. In summary, tourists and guides are at very low risk of injury when traversing this reach of the gorge.

CONCLUSIONS AND RECOMMENDATIONS

The potential hazards of Canyon Lake Gorge can present dangerous situations to visitors. Canyon Lake Gorge is a young, dynamic geomorphic environment, and is thus subject to fast acting gravity driven erosional processes as the gorge proceeds toward a more stable equilibrium. New geomorphological hazards are likely to form as the landscape settles.

This study of Canyon Lake Gorge has revealed that aside from the current geomorphology, the lithology and structural characteristics predispose the gorge to the formation of areas at risk. Large differentials in the weathering rates of lithologic units are evident in the undercut ledges of the gorge. The presence of expansive clay in the wackestone is likely the culprit behind the fastest eroding units of the gorge, providing the upper limit of the disparate rates of weathering found in different rock of the gorge. When clay-rich wackestone is situated below a ledge forming unit such as grainstone, the result is the conditions needed for development of an undercut ledge. Ultimately, while any undercut ledge can present a hazard to a hiker, the greatest risks will be associated with ledges high above a stable platform of rock. The thickest wackestone unit documented by this study was 2.2 m (7.2 ft), a dangerous height to fall from.

The field studies of Canyon Lake Gorge detailed above revealed the presence of geomorphological features that are potentially hazardous to visitors of the gorge. The risk level varies by location, and is the product of many considerations. Foremost among those considerations is the height of the undercut ledge. Often, the height is dependent on the thickness of an easily eroded wackestone bed that undercuts the ledge forming rock. Also worth considering is the trail of the gorge. Currently, the gorge trail is a series of marker flags used to guide the visitor through the site. While the absence of a permanent path preserves the natural beauty of the gorge, the fact does bring into consideration potential hazards present off the marked path.

Risks to Public

From this study, a number of geomorphological hazards of varying levels of risk were found near the path used in the gorge (Figure 47). The following sites in the gorge should be observed as potentially dangerous situations. The sites are grouped into three simplified classes of risk (Low, Medium, and High).

Figure 47. Aerial view of hazard locations in gorge, 2005. High risk – red, Medium risk – blue, Low risk – green. Base map courtesy Comal County Corp of Engineers (http://www.co.comal.tx.us/giswebsite.htm).

High Risk Areas – Potential for serious injury or death. The two primary high risk hazards are rock fall onto a visitor, or ledge failure beneath a visitor.

1. Area of Reach One. The area is located at the base of the gorge on the south side. This area has a wackestone layer that contains many fossils that are of interest to visitors. Unfortunately, the wackestone layer is underneath a small undercut cliff face comprised of ledge forming packstone and grainstone, making rock fall a danger.

2. The area of unit 2-12, north wall of gorge (Figure 48-A). This area is always of great interest to tourists because of the large ripples present on the surface of the rock. Along the north side of this area there is a great risk for rock fall from ledges 6.1 m (20 ft) above the gorge floor. On a hot day this area provides the only shade around, but it must be avoided.

3. The waterfall areas, center of gorge (Figure 48-B). There are many areas in the gorge that are appealing to tourists because of water flowing from conduits within the rock. Some of these areas are at high risk of rock ledge failure.

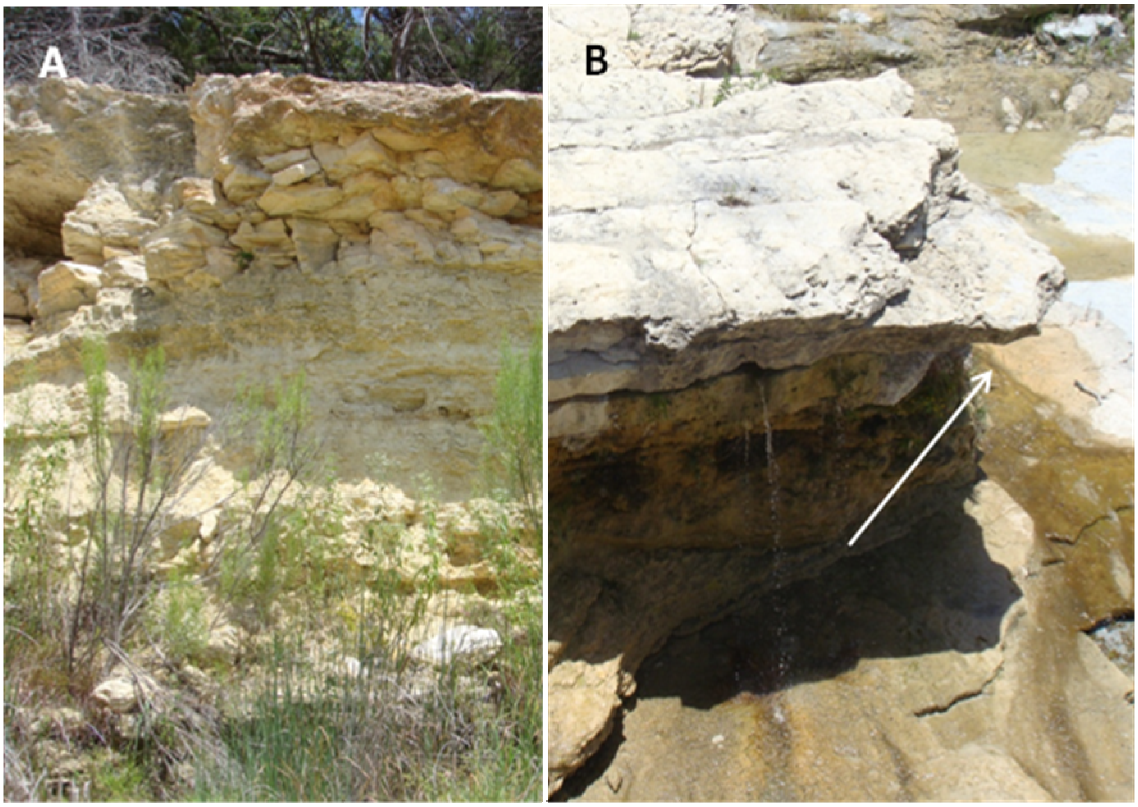


Figure 48. High Risk Areas. (A) is area of unit 2-12 where rock fall is a high risk hazard. (B) is an area in the center of the gorge where ledge failure is a high risk hazard.

Medium Risk Areas – Injury possible.

1. All junctions of rock unit 2-1 and 2-2 (Figure 49-A). The wackestone of unit 2-1 must be climbed to continue up the gorge, and its surface is weathered and unconsolidated. The rock ledge of unit 2-2 could collapse under foot travel, causing injury to the hiker.
2. All junctions of unit 2-10 and 2-11 (Figure 49-B). Unit 2-10 is a thick wackestone unit, and unit 2-11 often forms a ledge above it. The rock ledge of unit 2-11 could collapse under foot travel, causing a potential fall of near 2.13 m (7 ft).
3. All junctions of unit 3-3 and 3-4. There is risk here of a small fall if the poorly consolidated rock of unit 3-4 collapses underneath a hiker.

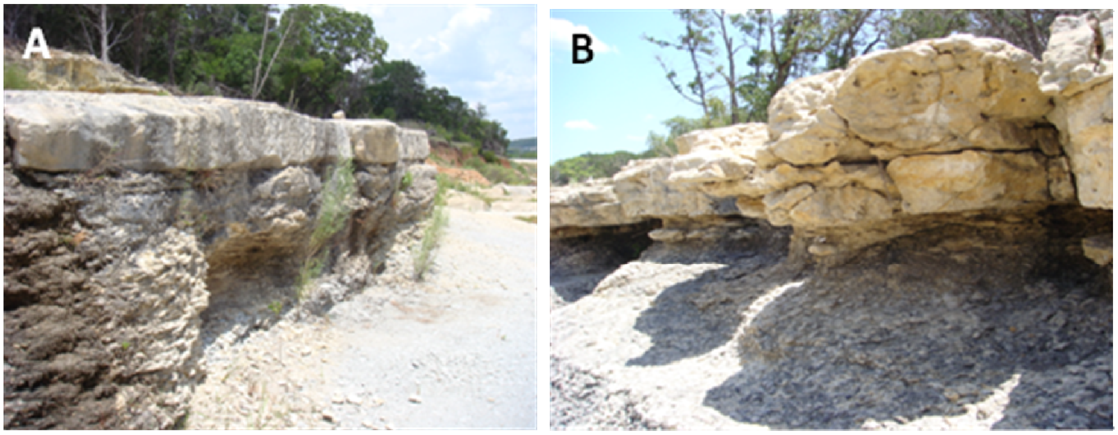


Figure 49. Medium Risk Areas. (A) is the junction of unit 2-1 and 2-2. (B) is of the junction of unit 2-10 and 2-11.

Low Risk Areas – Safe under most circumstances

1. Unit 3-5 creates a 1.5 m (5 ft) high slope that is easily climbed. This unit is highly weathered, and could break away underfoot.
2. Unit 3-6 creates a 1.95 m (6.4 ft) high slope that is easily climbed. This unit is highly fractured, and could break away underfoot.

Safety Practices and Recommendations

Current precautions already in practice by the GBRA include:

- Visitors are required to sign a liability form releasing the GBRA from injury liability while visitors are in the gorge.
- Visitors are always guided by trained personal that are familiar with the pathway to guide tours.
- Visitors are guided along a marked pathway which avoids dangerous areas of the gorge. Some areas of particularly high risk are marked with flags to warn visitors to keep their distance.

The results of this study allow for a number of recommended practices concerning safety, liability, and gorge preservation.

1. Visitors should be educated on the dangers of Canyon Lake Gorge before entering. Visitors of the gorge should avoid walking along the edges of ledge drop offs, and avoid walking underneath overhanging rock (Figure 50). The two high risk situations present in the gorge are potential rock fall hazards and potential fall hazards. Potential rock fall

hazards are most commonly present in the gorge as an undercut ledge of competent packstone or grainstone, where a visitor may rest underneath the ledge. Potential fall hazards are present in the gorge as undercut ledges and unstable slopes of rock. This is especially true after any periods of rainfall, when unstable masses are wet and more likely to fail.

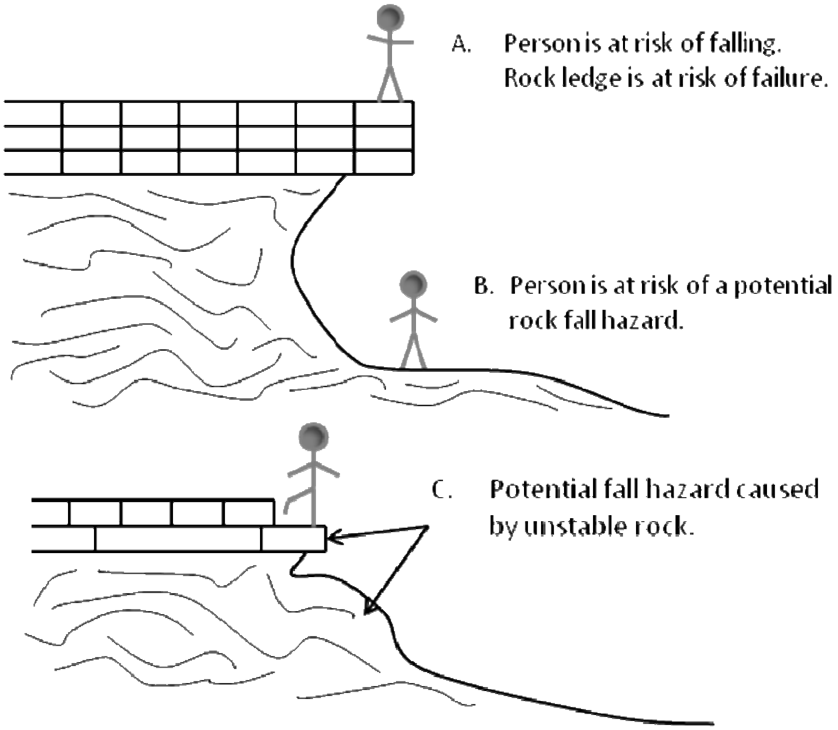


Figure 50. Illustrations of the potential hazards present in the gorge.

2. Unavoidable dangerous areas should be evaluated for possible ways to mitigate the risk of injury to visitors. It is possible that some areas will become more hazardous as erosion and weathering proceeds. In that case, it is recommended that a qualified professional be employed to evaluate risk in the gorge. The professional should be able to offer some options on how to mitigate danger in Canyon Lake Gorge.

Continued monitoring of the gorge is vital to the safety of the visiting public. The friable wackestone layers of the gorge deserve particular attention with respect to safe travel. This study has shown that the wackestone layers tend to be recessed underneath another layer of rock, with a steep slope of weathered material accumulating out away from the exposed rock. It is recommended that each point in the tourist pathway that crosses over exposed areas of the wackestone be evaluated for risk and slope stability. It should be possible to stabilize those areas of crossing so that tourist travel is not the cause of failure. One relatively cost effective solution would be to use available debris and blocks of rock to build a natural, but artificial riser bed for the aid of hikers traveling over the wackestone. This artificial riser bed would prevent erosion at the location where it was built. Geotextiles could be used in construction of the riser bed, reinforcing the stability of the riser bed. The objective would be to stabilize slopes of the gorge in an effort to provide a safe transit point over previously unstable rock.

REFERENCES

Aydin, A. and Basu, A., 2005, The Schmidt hammer in rock material characterization: *Engineering Geology*, Vol. 81, pp. 1-14.

Barker, R. A. and Ardis, A. F., 1996, Hydrogeologic framework of the Edwards-Trinity aquifer system, west-central Texas: *U.S. Geological Survey Professional Papers,* 1421-B, p.61.

Braathen, A.; Blikra, L. H.; Berg, S. S.; and Karlsen, F., 2004, Rock-slope failures in Norway; type, geometry, deformation mechanisms and stability: *Norwegian Journal of Geology*, Vol. 84, pp. 67-88.

Brandolini, P.; Faccini, F.; and Piccazzo, M., 2006, Geomorphological hazard and tourist vulnerability along Portofino Park trails (Italy): *Natural Hazards and Earth System Sceinces*, Vol. 6, pp. 563-571.

Briaud, J. L., 2008, Case histories in soil and rock erosion: Woodrow Wilson Bridge, Brazos River Meander, Normandy Cliffs, and New Orleans Levees: *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 134, No.10.

Collins, E.W., 1987, Characterization of fractures in limestones, northern reach of the Edwards Aquifer and Balcones Fault Zone, Central Texas: *Gulf Coast Association of Geological Societies Transactions*, Vol. 37, pp. 43-54.

Collins, E.W., 1995, Structural framework of the Edwards Aquifer, Balcones Fault Zone, Central Texas: *Gulf Coast Association of Geological Societies Transactions*, Vol. 45, pp. 135-142.

Comal County Engineer's Office (CCEO), 2002a, Flood rainfall and river flow data. Electronic document, available at http://www.cceo.org/

Comal County Engineer's Office (CCEO), 2002b, Aerial pictures of Canyon Lake Dam. Electronic document, available http://www.cceo.org/FloodPics/index.htm

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture: *American Association of Petroleum Geologists Memoir,* Vol. 1, pp. 108–121.

Erdogan, Y. and Yasar, E., 2004, Estimation of rock physicomechanical properties using hardness methods: *Engineering Geology*, Vol. 71, pp. 281-288.

Ferrill, D. A. and Morris, A. P., 2003, Dilational normal faults: *Journal* *of Structural Geology*, Vol. 25, pp. 183–196.

Ferrill, D. A.; Sims, D. W.; Waiting, D. J.; Morris, A. P.; Franklin, N. M.; and Schultz, A. L., 2004, Structual framework of the Edwards Aquifer recharge zone in south-central Texas: *Geological Society of America Bulletin*, Vol. 116, No. 3/4, pp. 407-418.

Ferrill, D. A. and Morris, A. P., 2008. Fault zone deformation controlled by carbonate mechanical stratigraphy, Balcones fault system, Texas: *American Association of Petroleum Geologists Bulletin*, Vol. 92, No. 3, pp. 359-380.

Gokceoglu, C.; Sonmez, H.; and Ercanoglu, M., 2000, Discontinuity controlled probabilsistic slope failure risk maps of the Altindag (settlement) region in Turkey: *Engineering Geology*,Vol. 55, pp. 277-296.

Mancini, E.A. and Scott, R.W., 2006, Sequence stratigraphy of Comanchean Cretaceous outcrop strata of Northeast and South-Central Texas: Implications for enhanced petroleum exploration: *Gulf Coast Association of Geological Societies Transactions*, Vol. 56, pp. 539-550.

May, James H., 1988, *Geologic and Hydrodynamic Controls on the Mechanics of Knickpoint Migration*: Ph. D. Diss. Texas A&M University.

Park, H. J.; West, T. R.; and Woo, I., 2005, Probabilistic analysis of rock slope stability and random properties of discontinuity parameters, Interstate Highway 40, Western North Carolina, USA: *Engineering Geology*, Vol. 79, pp. 230-250.

Shroder, J. F. Jr; Cverckova, L.; and Mulhern, K. L., 2005, Slope-failure analysis and classification: Review of a century of effort: *Physical Geography*, Vol. 26, pp. 216-247.

Southwest Research Institute, 2007, *Southwest Research Institute creates a Laboratory at a Flood-Carved Gorge in Central Texas for Industry Geologists to Study Limestone Oil Reservoirs*, Electronic document, available at http://www.swri.org/9what/releases/2007/flocar.htm

Soiltest Inc., 1970, *The Concrete Test Hammer* Electronic document, available at http://www.eleusa.com/pdf/oldmanuals/CT-320A.pdf

Stricklin, F. L.; Smith, C. I.; and Lozo, F. E., 1972, *Stratigraphy of Lower Cretaceous Trinity Deposits of Central Texas.* The University of Texas at Austin, Bureau of Economic Geology Report of Investigations, No. 71.

Topal, T.; Akin, M.; and Ozden, U. A., 2007, Assessment of rockfall hazard around Afyon Castle, Turkey: *Environmental Geology*, Vol. 53, pp. 191-200.

Wangler, T.P.; Wylykanowitz, A.K.; and Scherer, G.W., 2006, Controlling stress from swelling clay. In Konsta-Gdoutos, M.S. (ed.), *Measuring, Monitoring and Modeling Concrete Properties*: Springer, Printed in the Netherlands, pp. 703-708.

Ward, W. C. and Ward, W. B., 2007, Stratigraphy of Middle Part of Glen Rose Formation (Lower Albian), Canyon Lake Gorge, Central Texas, U.S.A., *Society for Sedimentary Geology Special Publication*, No. 87, pp. 193-210.

Wieczorek, G. F.; Stock, G. M.; Reichenbach, P.; Snyder, J. B.; Borchers, J. W.; and Godt, J. W., 2007, Investigation and hazard assessment of the 2003 and 2007 Staircase Falls rock falls, Yosemite National Park, California, USA: *Natural Hazards and Earth System Sciences*, Vol. 8, pp. 421-432.

Wilcox, B. P.; Wilding, L. P.; and Woodruff Jr., C. M., 2007, Soil and topographic controls on runoff generation from stepped landforms in the Edwards Plateau of Central Texas: *Geophyiscal Research Letters*, Vol. 34, L24S24.

Wilkerson, Forrest D. and Ginger L. Schimd., 2007, *The creation of Baranca de Caliza: Excavation of the Canyon Lake spillway gorge, Comal County Texas, July 2002*. The James and Marilyn Lovell Center for environmental Geography and Hazards Research, Department of Geography Texas State University, San Marcos.

Woodruff, C. M. Jr., and Wilding, L. P., 2007, Bedrock, soils, and hillslope hydrology in the Central Texas Hill Country, USA: Implications on environmental management in a carbonate-rock terrain: *Environmental Geology*, Vol. 55, pp. 605-618.

VITA

Benjamin David Kolkmeier received his Bachelor of Science degree in geology from Texas A&M University at College Station in 2006. He entered the graduate program at Texas A&M University Geology and Geophysics Department in the Spring of 2007. His research interests include applied and structural geology.

Mr. Kolkmeier may be reached at 16823 Middle Forest Drive, Houston, TX 77059. His email is benkolkmeier@gmail.com.