Spring 2016

Controls on Joint Formation During Glacial Unloading of the Sharon Sandstone at Gorge Metropark, Akron, Ohio

Abigail N. Ritter
The University of Akron, anr54@zips.uakron.edu

Recommended Citation
Ritter, Abigail N., "Controls on Joint Formation During Glacial Unloading of the Sharon Sandstone at Gorge Metropark, Akron, Ohio" (2016). *Honors Research Projects*. 328.
http://ideaexchange.uakron.edu/honors_research_projects/328

Controls on Joint Formation During Glacial Unloading of the Sharon Sandstone at Gorge Metropark, Akron, Ohio

A Thesis

Presented to

The University of Akron Honors College

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

Abigail N. Ritter
April, 2016

ABSTRACT

The transition between significantly different materials is known to inhibit crack propagation, i.e. automobile glass, machinable ceramics and joints in different lithologies. In order to determine if a significant material transition, or a surface, such as a bedding plane, has a greater impact on inhibiting joint formation, I investigated discontinuous joints that formed during glacial unloading of the Sharon Sandstone, which is exposed at Gorge Metropark in Akron, Ohio. The Sharon Sandstone is a medium-grained quartz arenite of Early Pennsylvanian age with significant cross-bedding, and contains many continuous (i.e. through-going), and discontinuous, joints in similar orientations. Stress fields created by unloading during glacial retreat following the last glacial maximum influenced joint orientations, spacing, and termination. 50% of the discontinuous joints observed terminated randomly within the outcrop, 20% terminated at free surfaces created by other joint sets, and 30% terminated at bedding planes. These results indicate that stress relaxation caused by joint formation exerts a larger control on joint termination than bedding planes or other surfaces in moderately homogenous rocks.

ACKNOWLEGEMENTS

I would first like to thank my advisor, Dr. Caleb Holyoke, III, for agreeing to be my sponsor and for his guidance and support throughout this project. I also would like to thank Dr. Ira Sasowsky and Gina Filiano, for supplying me with information and maps of my field sites.

I appreciate Ira Sasowsky, James McManus, and Caleb Holyoke for agreeing to be my readers. I also appreciate the help of James Thomka and John Peck for their reviews and suggestions that helped to improve my research.

Finally, I would like to thank my friends and family for keeping me in good spirits and supporting me throughout the whole process. A special thanks to Christopher Kanters for helping me with field work and with any technical problems I ran into throughout my research.

Table of Contents

LIST OF FIGURES

1. Introduction

Fractures are surfaces across which the material has lost cohesion and broken along a plane of weakness. Fractures are classified according to the motion of the walls relative to the fracture surface. The walls of extension fractures, or mode I fractures, move away from each other in a direction perpendicular to the fracture surface. The walls of mode II shear factures have scissor-like motion that is parallel to the fracture surface, but perpendicular to the fracture tip. Walls of mode III shear fractures have a sliding motion parallel to both the fracture plane and fracture tip. Finally, mixed mode fractures have components of displacement parallel and perpendicular to the fracture surface (Filiano, 2014). Decompression joints that form in rocks are mode I fractures.

If a group of joints occurs in the same area and have a similar orientation they are referred to as a joint set. Joints that are regularly spaced and parallel to each other are systematic (Dean et al., 1991). Whereas, joints that are curved and irregular are non-systematic. Non-systematic joints will often curve and terminate into other joint sets (Dean et al., 1991).

Joints are the result of brittle deformation of a rock due to tensile stresses. Tensile stress can be created by external or internal events. Compression and stretching of rock layers due to tectonic events can induce external stresses as well as rises in pore pressure. Tensile stresses can also be created through internal events such as heating or cooling of the rock unit. When the tensile stress in the joint exceeds the tensile strength of the rock a joint will propagate until the tensile stress in the tip of the fracture dissipates.

Some features that cause dissipation in tensile stress are: changes in lithology, joint surfaces (i.e. free surfaces), and stress field relaxation. Coarsely bedded rock units have a lower tensile strength and tend to fracture more than thinly bedded units. Weak bedding planes can also dissipate stress. A weak bedding plane is able to accommodate the joint stress by opening up and sliding; this dissipates the stress concentration on the fracture tip causing it to terminate. The tensile stress on a joint tip tends to release and terminate when the joint encounters a free surface, such as another joint set (Dean et al., 1991). Joints will also terminate when stresses within the rock unit diminish; stress relaxation can be accomplished through the formation of large joints that release most of the stress within the rock.

Joints can also be categorized by the spacing between them. Joint spacing is the average distance between joint surfaces and is dependent on the bed thickness, lithology, tensile strength of the rock, stress shadow, and the magnitude of extensional strain (Van der Pluijm & Marshark, 2003). Thinner beds contain joints that are more closely spaced than in thicker beds composed of the same material. Stiffer lithologies yield a closer joint spacing than less stiff lithologies. Rocks with a low tensile strength and a large magnitude of extensional strain will produce more joints with a tighter spacing than rocks with a high tensile strength and small magnitude of extensional strain (Van der Pluijm & Marshark, 2003)

1.1 Statement of Problem

In order to determine if the bedding surfaces in the largely homogeneous Sharon Sandstone, or stress relaxation due to nearby joint formation was responsible for inhibiting joint propagation, I performed a field based analysis of joint orientation, length and morphology at Gorge Metropark from August-October of 2015 (Figure 1). I measured the spatial distribution of the continuous and discontinuous joints, the vertical lengths of discontinuous joints and the features present at the termination of each joint. Continuous joints propagated through the entire vertical length of the outcrop, while discontinuous joints terminated within the outcrop. The features present at the termination of each joint indicated whether the joints terminated because of bedding plane intersections, interactions with a free surface due to another joint, or if planes within the outcrop had no effect on joint termination. These reasons for joint termination helped to determine whether surfaces in the rock or stress relaxation had a greater effect on joint propagation. In addition, the orientation of the joints also determined if the joints formed due to stress fields related to late Alleghenian orogeny, the current stress field in Ohio, or the stress field during glaciation.

1.2 Structural Setting of the Mid-Continent Region

Joint sets in the Appalachian basin formed due to the paleostress field during the Paleozoic Era and the contemporary stress field that currently affects the Eastern United States. The paleostress field formed in response to deformation events in the later stages of the Allegenian orogeny. These later stages mostly affected parts of Pennsylvania, New York, and eastern Ohio. Deformation during the last two stages of the Allegenian orogeny caused jointing in the areas mentioned above. The first event created an NNW directed compression with a SSE stress trajectory, and the second event created a northern transmission of stress, with a southward stress trajectory (Engelder and Geiser 1980). Ultimately, the maximum compression direction in the paloestress field had an orientation of 270˚ (Evans, 1994). In addition, the contemporary stress field also influenced joint formation in the eastern United States (Filiano, 2014). The contemporary stress field is oriented 76˚ in a NNE direction and has an ENE compression direction

(Heidbach et al., 2008).

1.3 Rock Units Exposed at Gorge Metropark

There are two rock units exposed at Gorge Metropark: the first is from the Mississippian era and the second is from the Pennsylvanian era. The Mississippian sequence is composed of rocks of varying lithologies, most of which have been highly eroded at Gorge Metropark. The lithologies were composed of shale with intermittent siltstone beds (Corbett & Manner, 1988). The Pennsylvanian sequence succeeds the Mississippian sequence and is composed of a homogenous, medium grain quartz arenite interbedded with pebble- sized conglomerates (can be seen in appendix A) with a great amount of crossbedding (Corbett & Manner, 1988). The Mississippian sequence was deposited in a low energy environment such as a flood plain. A flood plain would have allowed the small particles that make up the shale and siltstone to settle out and lithify into the rocks seen today in the Mississippian Sequence. The Pennsylvanian sequence was deposited by stream (Corbett & Manner, 1988). The energy in a stream is capable of transporting medium- pebble sized grains, it is also capable of producing the cross bedding seen in the unit.

1.4 Glaciation

The Ice Age in Ohio started during the Pleistocene era. During this time temperatures cooled and snow/ice built up in Canada forming a large ice sheet (Hansen,1997). The sheet became so massive that it started spreading outward due to its own weight and migrated south into Ohio (Hansen,1997). This early migration is classified as the pre- Illinoian glaciation episode (Hansen,1997). There is not much known about this early advance in Ohio because any evidence of it has been eroded away and is poorly preserved. 300,000 years ago after a period of interglaciation, the Illinoian ice sheet migrated through Ohio into northern Kentucky (Hansen, 1997). Another Interglacial period occurred eroding evidence of the Illinoian ice sheet (some evidence of this ice sheet can be seen in Hocking, Ohio, today) (Hansen, 1997). 24,000 years ago the most recent ice sheet (Wisconsian) made its way into Ohio and covered the northern western and central parts of the state (Hansen, 1997). 14,000 years ago, the last of the Wisconsian ice sheet finally retreated from Ohio, this episode was well preserved in Ohio though since the evidence for it has not been exposed as long as the other ice sheet deposits or modified by subsequent glaciations (Hansen, 1997).

2. Methods

2.1 Initial site selection

The main exposures of Sharon Sandstone observed in Ohio are located in eastern Scioto, eastern Pike, and western Jackson Counties in southern Ohio, and in the northern part of the state the outcrops are observed in eastern Wayne, Stark, Mahoning, South Trumbull, Portage, Summit, eastern Medina, southeastern Cuyahoga and Geauga Counties (Stout, 1944). Two exposures of the Sharon sandstone were chosen based upon their proximity to the maximum extent of the glacial limit. The first site is Gorge Metropark in Summit County Ohio, north of the boundary marking the southern most advance of the glaciers during the Wisconsin glaciation. The second site, Hocking Hills State Park in south central Ohio, was chosen to be south of the glacial boundary. Both sites were chosen based on the following parameters: accessibility of the outcrops, quality of the outcrops, and proximity from the glacial limit.

2.2 Field Data Collection

At Gorge Metropark an initial survey was formed to identify outcrops (Figure 1). The Outcrops were identified and marked as waypoints using the Apple Iphone app, Topo Maps Plus. After outcrops were identified and labeled, joint spacing measurements were collected at the outcrop using an open reel measuring tape. The eastern most joint in the outcrop was designated as the starting point with a distance of 0 meters, from there, the position of each joint, relative to the first joint, was recorded while noting if the joint was continuous or discontinuous. The total distance between the first joint and the last joint was 164 meters. General observations about the joints were recorded. Observations included what outcrop the joint was located in, the date the joint was observed, a brief rock description, if the joint was continuous or discontinuous, the reason for termination, height of the joint, and the joints relationship with other joints. The orientation of the joint was then measured using a Brunton compass pocket transit with a magnetic declination set to -8° 25’.

The procedures followed at Hocking Hills State Park were similar to the procedures followed at Gorge Metropark. However, at Hocking Hills State Park only two outcrops were studied and joint spacing measurements were not collected; all other procedures outlined in the study of Gorge Metropark were followed at Hocking Hills State Park.

3. Results

A total of 6 lower hemisphere equal area projections were generated for the two sites studied using a stereonet program created by Richard Allmendinger. Lower hemisphere equal area projections were created for the total population of joints measured, the population of continuous joints measured, and the population of discontinuous joints measured at each location. The measured joint orientations are concentrated in two primary directions. The strongest concentrations strike northwest-southeast and northeast southwest, these concentrations were best represented by measurements taken from the Gorge (Figure 2). Joint patterns were similar at both sites (Figure 2 & 3). The joint populations were then subdivided in concurrence with observations made in the field to categorize the joints into two sets: J1) joints striking Northwest-Southeast (making up the face of the outcrop), and J2) joints striking Northeast- Southwest (normal to the face of the outcrop) (Figure 2). All the joint faces encountered during the study were highly eroded, showing evidence of mechanical weathering, making it difficult to study the original joint structure.

3.1 Joint Set J1

This joint set was most commonly observed as the vertical faces of the outcrop. In some cases, this joint manifested as a separation between a large block and the main face of the outcrop. This separation was due to gravitational sliding after the joint plane disconnected the block from the main outcrop (Filiano, 2014). A few of the outcrop faces curved into a free surface formed by pre existing joints that between outcrop face and rocks that have completely eroded. The orientations of both the continuous and discontinuous J1 joints were predominantly northwest-southeast (Figure 2)

3.2 Joint Set J2

The second set of joints was commonly orthogonal to the first joint set. The second joint set could be seen as vertical continuous joints cutting straight back into the outcrop perpendicular to the outcrop face, joint set J1, but they could also be seen as discontinuous joints that terminated within the outcrop face. The discontinuous joints were often irregular in shape and changed positions when changes in lithology were encountered. These joints also caused separation of large blocks from the main outcrop due to gravitational. The orientations of the continuous and discontinuous joints were predominately northeast-southwest (Figure 2).

3.3 Jointing in Each Field Area

3.3.1 Gorge Metropark

Gorge Metropark is located off of Front Street in Cuyahoga Falls, Summit County, Ohio and is north of the nearest terminal moraine. 106 total joint measurements were recorded. Of the recorded joints, 47.2% were discontinuous and 52.8% were continuous. Of the discontinuous joints 34% of the joints were striking Southwest-Northeast, 48% were striking southeast-northwest, 4% were striking east-west, and 14% were striking north-south. Of the continuous joints 55.4% of the joints were striking southwest-northeast, 39.3% were striking southeast-northwest and 5.3% were striking east-west (Figure 2). Of the best-fit orientations, 50% of the joints were oriented northwest-southeast and 50% were oriented northeast- southwest (Figure 4).

The reasons for termination within the discontinuous joints varied: 37.5% of all discontinuous joints terminated due to other joint sets, 25% terminated because of changes in lithology, and 37.5% did not terminate due to planes within the outcrop (Figure 5a). Discontinuous joints in this area were all under 8m in length (Figure 5b) 10% of all discontinuous joints were <1 meter in length, 55% were approximately 1 meter in length, 22.5% were approximately 2 meters, 2.5% were approximately 3 meters, 5% were approximately 4 meters, 2.5% were approximately 6 meters, and 2.5% were approximately 7 meters in length (Figure 5b).

Joint spacing measurements were also collected at this site. The spacing between 30 joints was measured: of the joints 30 joints observed, 50% of all joints were continuous and 50% were discontinuous (Figure 6b, 6c). The average spacing between discontinuous joints was 8.4 meters while the average spacing between continuous joints was 15 meters in length (Figure 6b, 6c). The minimum spacing between continuous joints was 4 meters while the maximum spacing was 31 meters. 36.4% of the spacing between continuous joints were less than 15 meters, while 63.6% of the spacing were greater than 15 meters in length (Figure 6b, 6c). The minimum spacing between discontinuous joints was less than one meter while the maximum spacing was 38 meters. 85.7% of spacing between discontinuous joints were less than 19 meters, while 14.3% of spacing were greater than 19 meters in length (Figure 6b, 6c).

3.3.2 Hocking Hills State Park

Hocking Hills State Park was the second location that was studied and is located in Logan County, Ohio (Figure 7) 42 joint measurements were taken at this site. Of the 42 joints 78.6% were discontinuous and 2.1% were continuous (Figure 3). Of the discontinuous joints 48.5% were striking southeast- northwest, 48.5% were striking southwest-northeast, and 3% were striking north-south. Of the continuous joints 55.6% were striking southeast- northwest and 44.4% were striking southwest-northeast (Figure 2). Of the best-fit orientations, 50% of the joints were oriented northwest-southeast and 50% were oriented northeast- southwest (Figure 3).

The reason for joint termination varied within the discontinuous joints. Of the 33 discontinuous joints measured 63.6% of joints did not terminate due to planes within the outcrop and 36.4% of joints terminated because of changes in lithology within the rock, none of the discontinuous joints in this location terminated because of interactions with other joints sets (Figure 5c).

4. Discussion

4.1 Joint Orientation

Two main joint sets were observed in Gorge Metropark. The joints were categorized into two sets: J1) joints striking northwest-southeast making up the face of the outcrop, and J2) joints striking northeast- southwest normal to the face of the outcrop (Figure 2). The joints were classified as mode I extensional fractures due to the lack of evidence of slip, shear, and offset along the joints. In a mode I extensional fracture, σ_1 represents the maximum compressive stress which is parallel to the fracture plane of mode I fractures and σ_3, represents the minimum compressive stress which is perpendicular to the fracture plane. Once σ_3 is able to overcome the tensile strength of the rock, a joint forms and stresses are reoriented (Filiano, 2014). The least compressive stress becomes the maximum compressive stress and a new joint can propagate perpendicular to σ_3 (Filiano, 2014).

4.2 Stress Fields Responsible for Jointing at Gorge Metropark

Three stress fields may be responsible for the joints at Gorge Metropark and Hocking Hills State Park: 1) late Alleghanian stress fields, 2) the current stress field, and 3) the stress field created during deglaciation. The orientation of the maximum horizontal compressive stress during the Alleghanian Orogeny was N270W (Evans, 1994). This stress field should produce joints with an average orientation of N270W (east). The orientation of the current stress field should produce joints with an orientation of N75E. However, the orientations of the joints at Gorge Metropark are N117W and N25E, which is 25 degrees away from the orientations of the joints produced by the Alleghanian Orogeny and 55 degrees away from the orientations of joints produced by the current stress field (Figure 4). Therefore, the joints at Gorge Metropark are likely due to the stress field during deglaciation.

Glacial retreat created stress relaxation within the outcrop through unloading. This relaxation caused the maximum tensile stress to reorient itself so that the stress was now perpendicular to the outcrop (Filiano, 2014). Glacial unloading caused failure along planes of weakness resulting in the formation of the J1 joint set.

After the formation of the J1 joint set, the local stresses within the outcrop reoriented and the minimum compressive stress became the maximum compressive stress (Filiano, 2014). In order to relieve stress in this new orientation, joints formed perpendicular to the σ_3 direction creating the J2 joint set. At Gorge Metropark, J2 joints were observed to be terminating normal to J1. This observation suggests that J1 joints formed first (in response to glacial unloading) and J2 joints formed second (in response to changing stress orientations caused by the formation of the J1 joint set).

4.3 Joint Propagation and Termination

Fractures in rocks can be created through tension, compression, or unloading of the rock. Fractures are commonly formed from stresses exceeding the rocks own tensile strength, causing the rock to split along its weakest planes. In sedimentary rocks the most common reason for joint formation and propagations is flaws in the rocks lithology such as Griffith cracks (Cooke et al., 2006). Flaws in the rock concentrate tensile stress, when this tensile stress exceeds the tensile strength of the rock, a joint propagates where the flaw is located. Coarsely bedded rocks have a lower tensile strength than finely bedded rocks, therefore they are more brittle and tend to fracture more often than finely bedded rocks. Fractures commonly begin within bedding planes because the high concentration of flaws within them, and terminate when the stress concentration on the joint tip is reduced (Cooke et al., 2006). In homogenous strata weak bedding planes within the outcrop cause joint termination. A weak bedding plane is able to accommodate stress by opening up and sliding, dissipating the stress concentration on the fracture tip causing it to terminate (Cooke et al., 2006).

The controls on joint termination and propagation in homogeneous sedimentary rocks outlined in Cooke et al.'s study (2006) do not coincide with the controls observed at Gorge Metropark. The outcrops observed at Gorge Metropark were also homogenous, but the minor changes in lithology did not inhibit joint propagation. More than half of all discontinuous joints measured did not terminate due to intersecting planes within the outcrop. (Figure 5a). It is most likely that these joints terminated due to local stress relief by the formation of continuous joints.

At Gorge Metropark, continuous and discontinuous joints had the same orientation indicating that the local stress field had more of an impact on joint formation than the regional stress field (Figure 1). At Gorge Metropark, the unloading of the glaciers initiated local stresses that overpowered the regional stresses in the area (Filiano, 2014) When the glacier retreated from the area, the confining overburden pressure was removed creating tensile stresses within the rock (Filiano, 2014). Exhumation of the glaciers and the resultant unloading stresses caused vertical extensional stress relief fractures and reactivated minor joints. Most of the stresses were relieved through propagation of the major vertical continuous joints. Any residual stress in the strata was released by the reactivation of minor joints; that terminated once the tensile stress in the tip of the fracture dissipated.

4.4 Joint Spacing

Joint spacing is the average distance between joint surfaces and is dependent on the bed thickness, lithology, and tensile strength of the rock, stress shadows, and the magnitude of extensional strain. Thinner beds contain joints that are more closely spaced than in thicker beds (Van der Pluijm & Marshark, 2003). Stiffer lithologies yield a closer joint spacing than less stiff lithologies. Rocks with a low tensile strength and a large magnitude of extensional strain will produce more joints with a tighter spacing than rocks with a high tensile strength and small magnitude of extensional strain (Van der Pluijm & Marshark, 2003).

Cooke et al.'s study (2006) observed that joint spacing was due to stress shadows, which they defined as a zone of decreased stress adjacent to an open fracture that inhibits new fracture growth. The size of the stress shadow in their study controls the spacing of the joints as well as joint length. Thicker rock units had taller more widely spaced joints than thinner units.

The factors that control joint spacing outlined in Cooke et al.'s study (2006) are similar to the factors that control the spacing at Gorge Metropark with one difference: Bedding planes present in outcrops at Gorge Metropark were homogeneous and did not vary in lithology enough to inhibit joint growth. Therefore, lithologic differences within units did not control joint spacing in the area of study. Bedding and unit thickness at Gorge Metropark was also uniform. This suggests that joint spacing at Gorge Metropark was not affected by the thickness of the units.

The average spacing between the longer vertical continuous joints was 15m, while the average spacing between the shorter discontinuous joints was 8.4m (Figure 6b, 6c). This data supports the hypothesis of stress shadows being the main control on joint spacing at Gorge Metropark. In short discontinuous joints, significant reduction of stress only occurs in the immediate joint vicinity. In contrast, in the tall continuous joints, the reduction of stress extends over a much longer distance (De Paor, 1996). Stress reduction explains why the average joint spacing between continuous joints is larger than the average spacing between discontinuous joints. The information mentioned above also explains the pattern in joint spacing observed at Gorge Metropark. A general repeating spacing pattern is observed. The pattern starts out with two continuous joints side by side, followed by 1-5 discontinuous joints that occur before the next continuous joint is observed, and ending with another continuous joint right beside it. The two continuous joints are closely spaced and fairly large in length, so they are able to relive all the stress in the area they occur in without the need of any additional stress relief from intermediate discontinuous joints. When continuous joints have a larger spacing between them, the stress shadows created do not reach the entire length of the spacing, so intermediate discontinuous joints are needed to relieve the rest of the stress.

5. Conclusions

5.1 Joint Orientation

Two distinct joint orientations were observed at Gorge Metropark. Joint set J1 has an average orientation of 118 and joint set J2 has an average orientation of 26. Both continuous and discontinuous joints have the same orientations (Figure 2). Joint orientation measurements were also collected at Hocking Hills State Park, Ohio in order to compare the distributions with those observed at Gorge Metropark (Figure 1). Continuous joints at Hocking Hills do not appear to have a preferred orientation, but the total measured population is low due to field time constraints *(n = 42)* (Figure 3). Discontinuous joints form two populations with somewhat similar orientations to those observed at the Gorge Metropark. If the joints at the Gorge Metropark were formed by the maximum compressive stress of the current stress field *(red dot)* or the stress field during the Alleghenian Orogeny *(blue dot)*, the orientation of this stress should lie near the best fit of one of the two joint sets (Figure 4). However, neither of these principal stress orientations is within 20 degrees of the best fit joint orientations (Figure 4) suggesting that the joints at Gorge Metropark were formed due to local effects of glaciation.

5.2 Joint Termination

The spacing between 30 joints was measured, 50% of all joints were continuous and 50% were discontinuous (Figure 6a). The average spacing between discontinuous joints was 8.4 meters while the average spacing between continuous joints was 15 meters in length (Figure 6b, 6c). The discontinuous joints occurred randomly between the continuous joints and terminated for a variety of reasons. In total, 73 discontinuous joints were measured at both field areas. 15 of the discontinuous joints terminated at another joint set, 22 terminated because of changes in lithology, and 36 did not terminate due to interse3cting planes within the outcrop (Figure 6a). Most of the discontinuous joints were also less than four meters in length. The fact that more than half the joints did not terminate due to intersecting planes within the outcrop and most of those joints were less than four meters in length suggest that the main control on discontinuous joint termination was stress relaxation.

5.3 Joint Spacing

Stress relaxation also controlled the spacing of the joints. The large, continuous joints (18 meters) relieved significant amounts of stress within the outcrop and created large stress shadows that extended over a great distance. While the discontinuous joints (4 meters) only relieved small amounts of stress, creating a stress shadows that only extended a short distance. The larger stress shadows allowed for stress relief over a greater distance, explaining the larger average spacing distance we see in the continuous joints. The stress shadows created by the discontinuous joints only allowed stress relief over a short distance explain the smaller average spacing we see between them.

6.0 References

Cooke, M.L., Simo, J.A., Underwood, C.A., Rijken, P., 2006. Mechanical stratigraphic controls on fracture patterns within carbonates and implications for groundwater flow. Sediment Geol 184, 225-239.

Corbett, R.G., Manner, B.M., 1988. Geology and Habitats of the Cuyahoga-Valley National Recreation Area, Ohio. Ohio J Sci 88, 40-47.

de Paor, D., 1996. Structural geology and personal computers. Pergamon Press, New York, New York, 1-524.

Dean, S.L., Kulander, B.R., Forsyth, J.L., Tipton, R.M., 1991. Field Guide to Joint Patterns and Geomorphological Features of Northern Ohio. Ohio J Sci 91, 2-15.

Engelder, T., Geiser, P., 1980. On the Use of Regional Joint Sets as Trajectories of Paleostress Fields during the Development of the Appalachian Plateau, New-York. J Geophys Res 85, 6319-6341.

Evans, M.A., 1994. Joints and Decollement Zones in Middle Devonian Shales - Evidence for Multiple Deformation Events in the Central Appalachian Plateau. Geol Soc Am Bull 106, 447-460.

Filiano, G., 2014. Role of Joints and Rock Stresses in the Formation of Sandstone Caves in Northeastern Ohio, MS Thesis, Department of Geosciences. University of Akron, Akron, Ohio, p. 186.

Hansen, C., 1997. Educational Leaflet (Columbus, Ohio), No.7 unpaginated. Publisher: Ohio Division of Geological Survey, Columbus, OH, United States. ISSN: 0739-4195

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., Müller, B., 2008. The World Stress Map database release 2008.

Stout, W., 1944. Sandstones and conglomerates of Ohio. Ohio J Sci 44, 75-88.
van der Pluijm, B., Marshak, S., 2003. Earth Structure. W. W. Norton and Company, New York, New York.

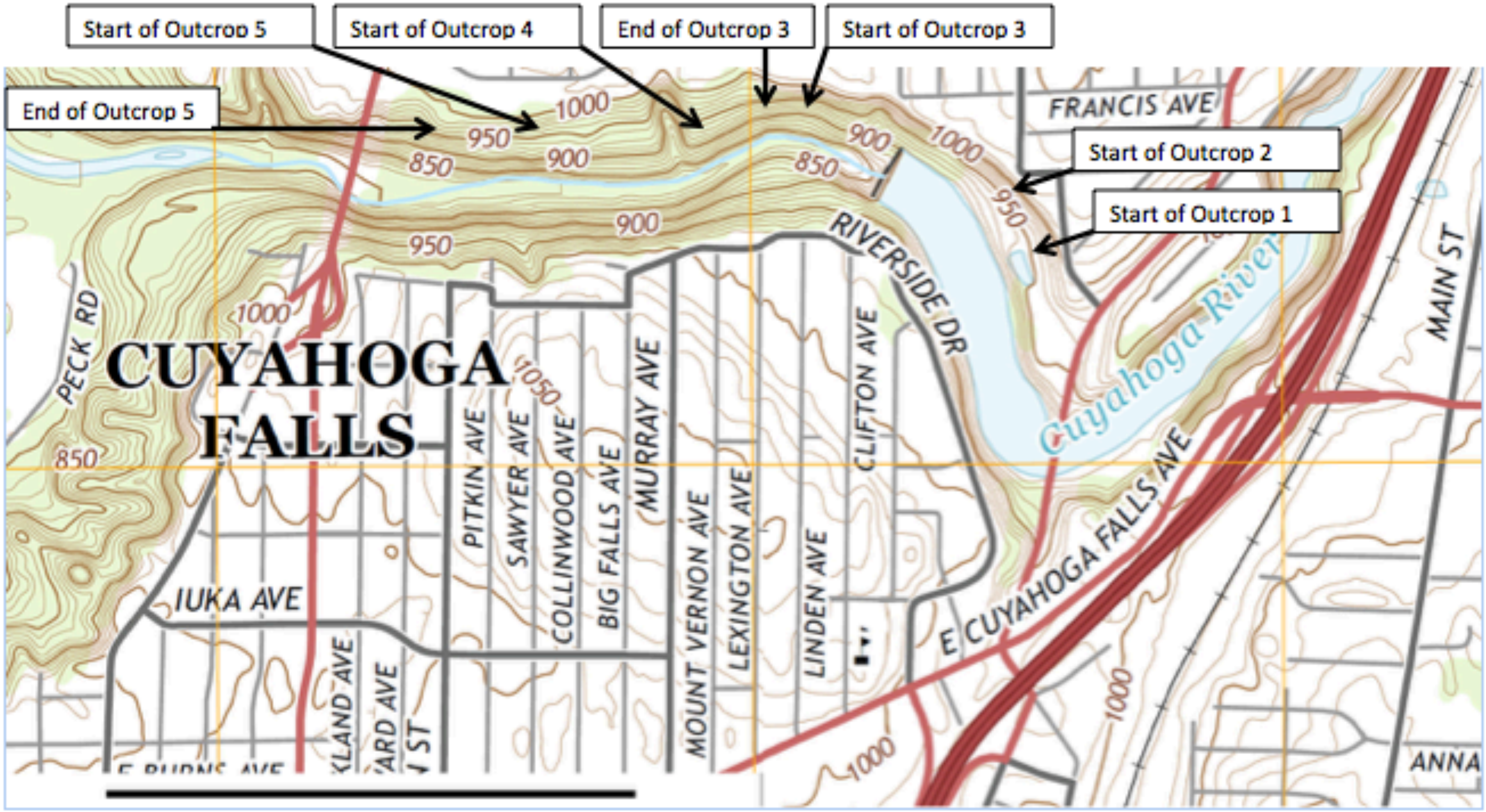
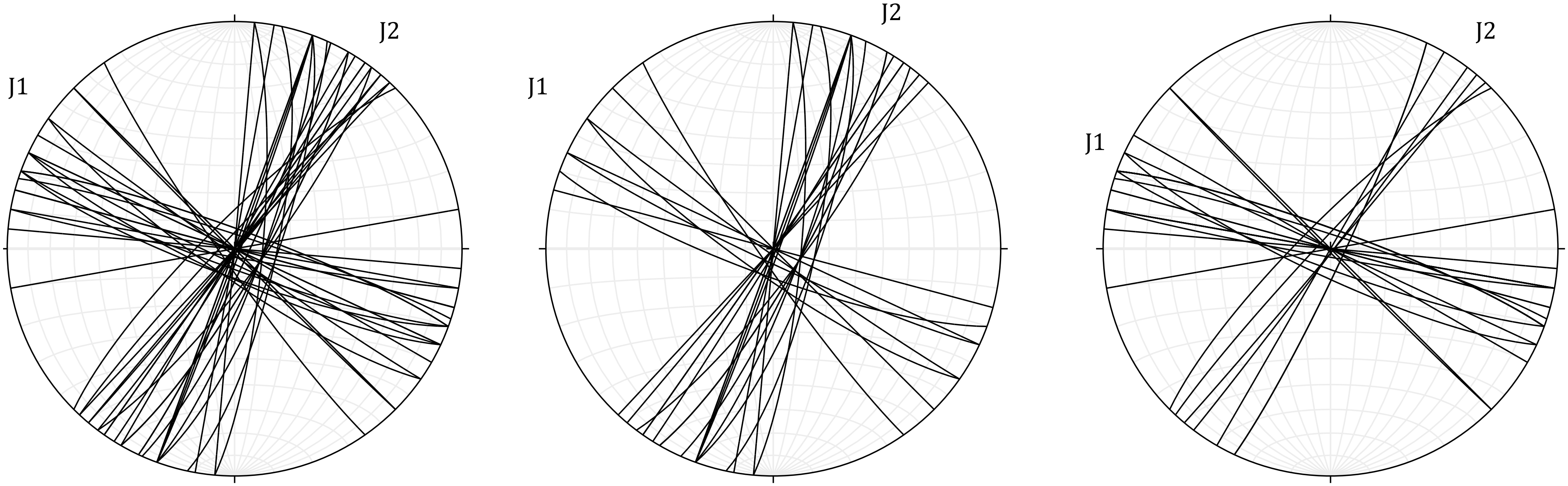


Figure 1: Outcrop locations at Gorge Metropark.
Map taken from USGS Akron east and west 7.5 minute topographic maps.

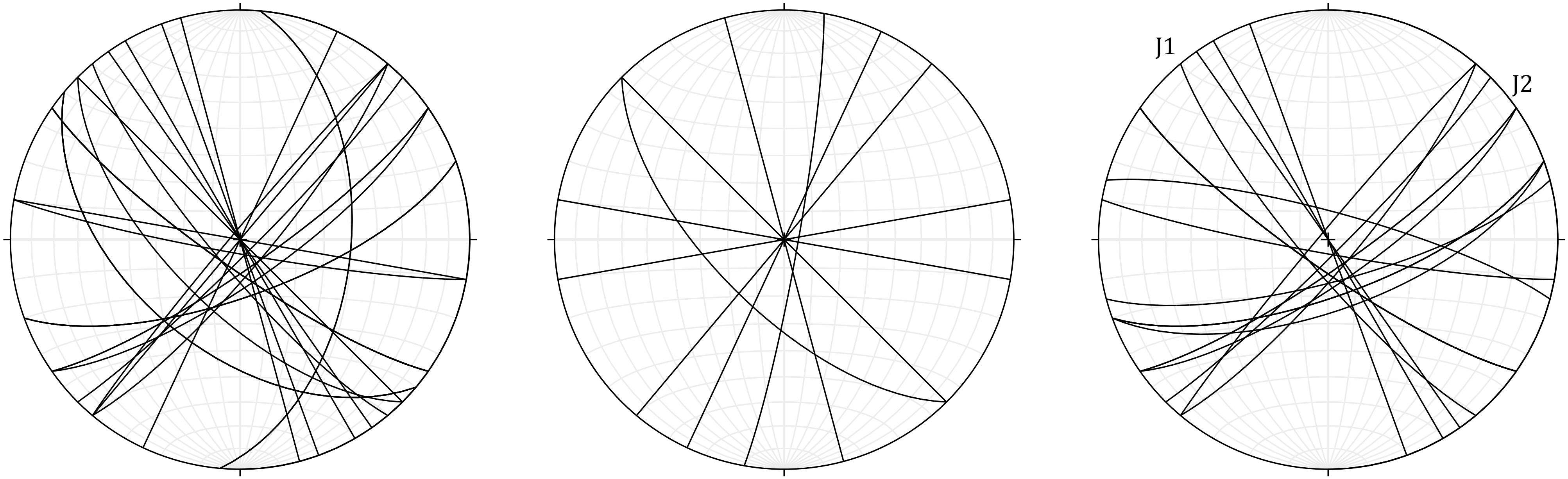


All Joints (n=106)

Continuous Joints (n=87)

Discontinuous Joints (n=19)

Figure 2: Joint sets J1 and J2 at the Gorge Metropark are almost vertical and orthogonal to each other *(above left)*. Joint set J1 has an average orientation of 117°,78 and Joint set J2 has an average orientation of 25°,83. Both continuous and discontinuous joints have the same orientations *(above center and right)*.



All Joints (n=42) Continuous Joints (n=8) Discontinuous Joints (n=34)

Figure 3: Joint orientation measurements were collected at Hocking Hills State Park, Ohio *(above left)* in order to compare the distributions with those observed at Gorge Metropark. Continuous joints at Hocking Hills do not appear to have a preferred orientation, but the total measured population is low *(n = 8, above center)*. Discontinuous joints form two populations with somewhat similar orientations to those observed at the Gorge Metropark *(above right)*.

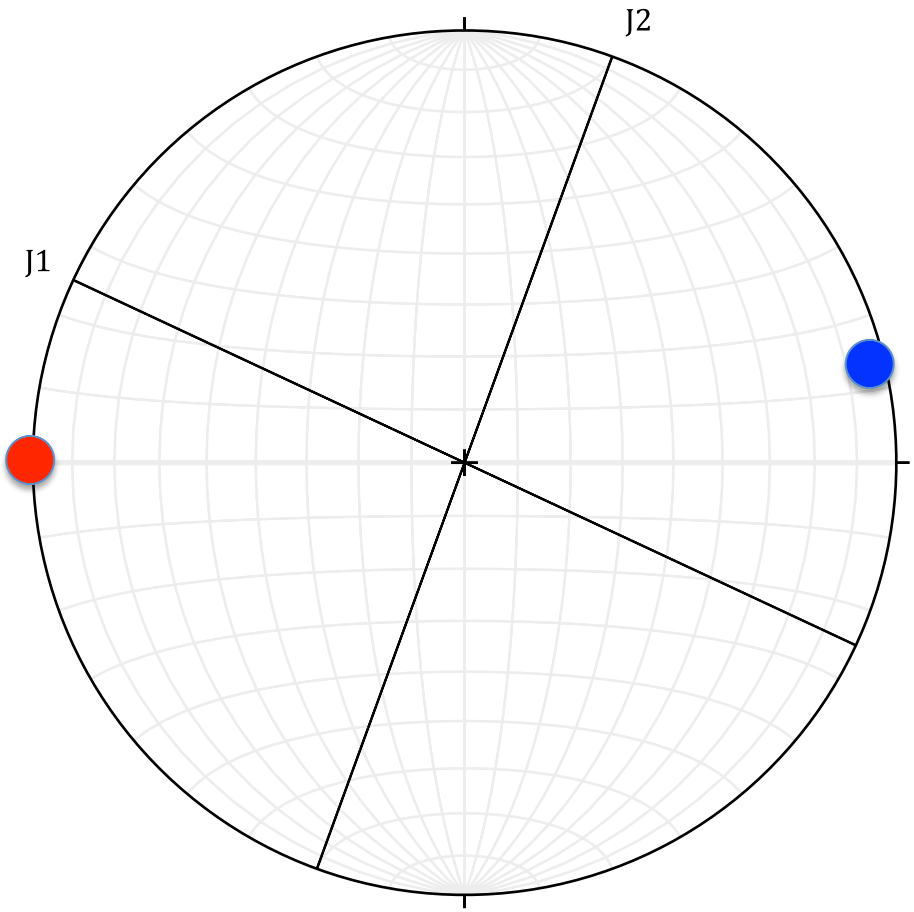


Figure 4: If the joints at the Gorge Metropark were formed by the maximum compressive stress of the current stress field *(red dot)* or the stress field during the Alleghenian Orogeny *(blue dot)*, the orientation of this stress should lie near the best fit of one of the two joint sets. However, neither of these principal stress orientations is within 20 degrees of the best fit joint orientations.

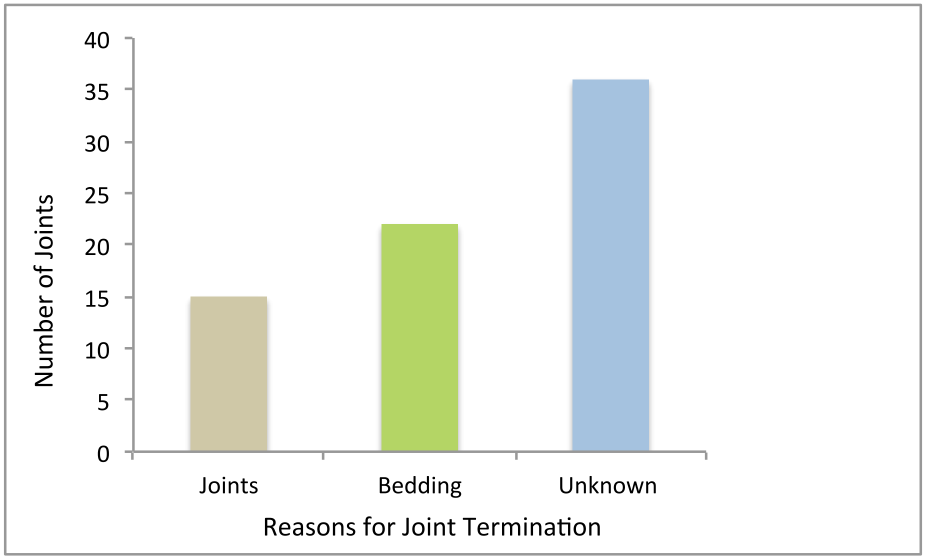


Figure 5a: A total 73 discontinuous joints were measured at both field areas. 15 of the discontinuous joints terminated at another joint set, 22 terminated at a bedding plane, and 36 joints did not terminate due to planes within the outcrop.

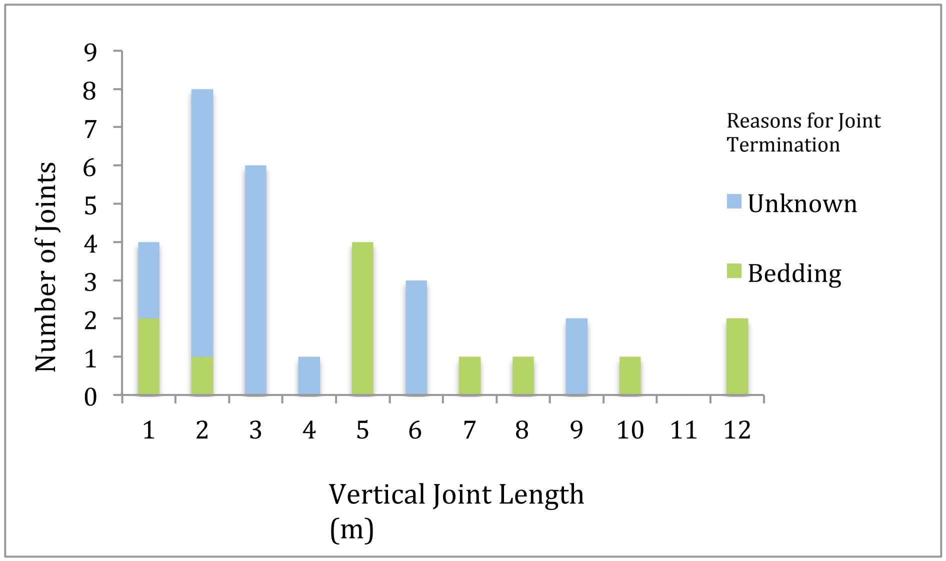


Figure 5b: Of the 40 discontinuous joints measured 15 of the joints terminated at another joint set, 10 terminated at a bedding plane, and 15 joints did not terminate due to planes within the outcrop. Most discontinuous joints were <2 m long.

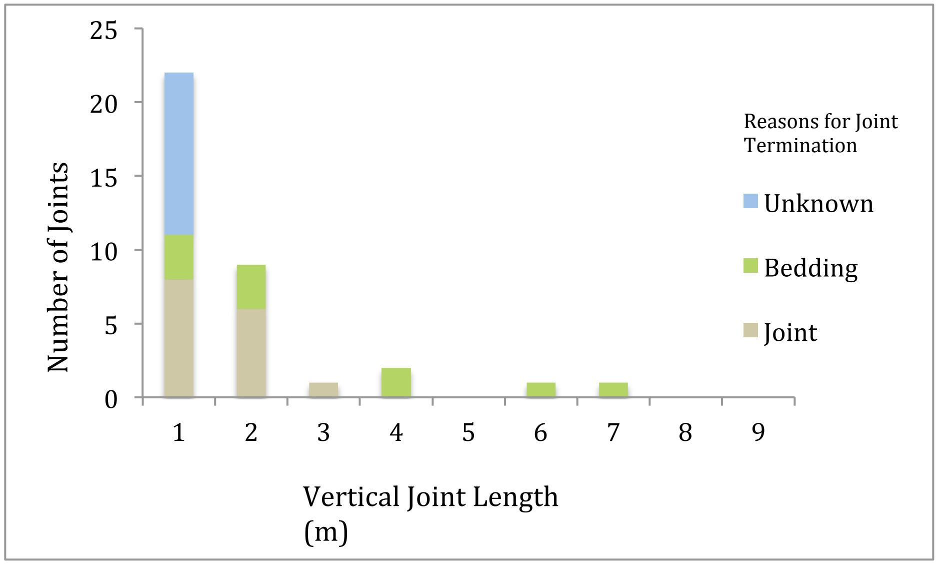


Figure 5c: At Hocking Hills, most (21) of the 32 discontinuous joints joints did not terminate due to planes within the outcrop and the remainder terminated at a bedding plane. Most discontinuous joints are <6 m long.

Figure 6a: J1 joint spacing in the outcrop at Gorge Metropark is somewhat heterogeneous. The spacing between 30 joints was measured, 50% of all joints were continuous and 50% were discontinuous. Continuous joints (green) are spaced ~15 m apart, whereas J2 joints (blue) are spaced at varying lengths between the continuous joints (average spacing 8.4m).

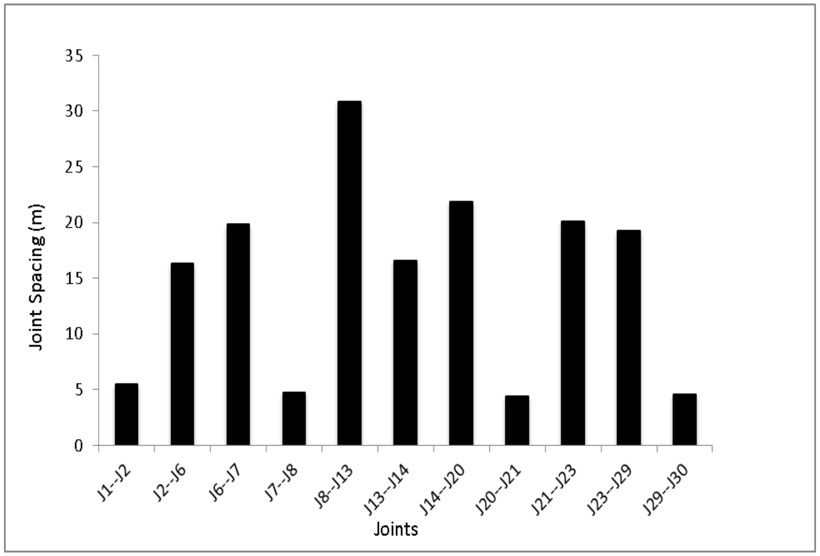


Figure 6b: The average spacing between discontinuous joints was 8.4 meters

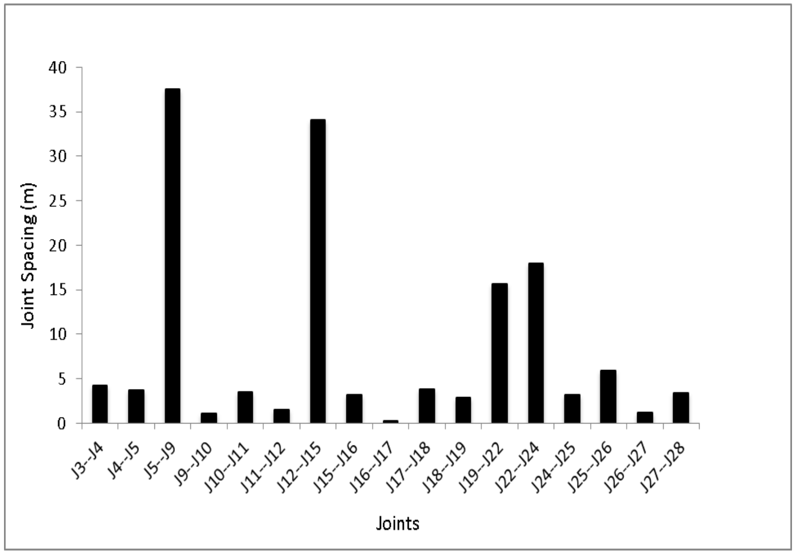


Figure 6c: The average spacing between continuous joints was 15 meters in length.

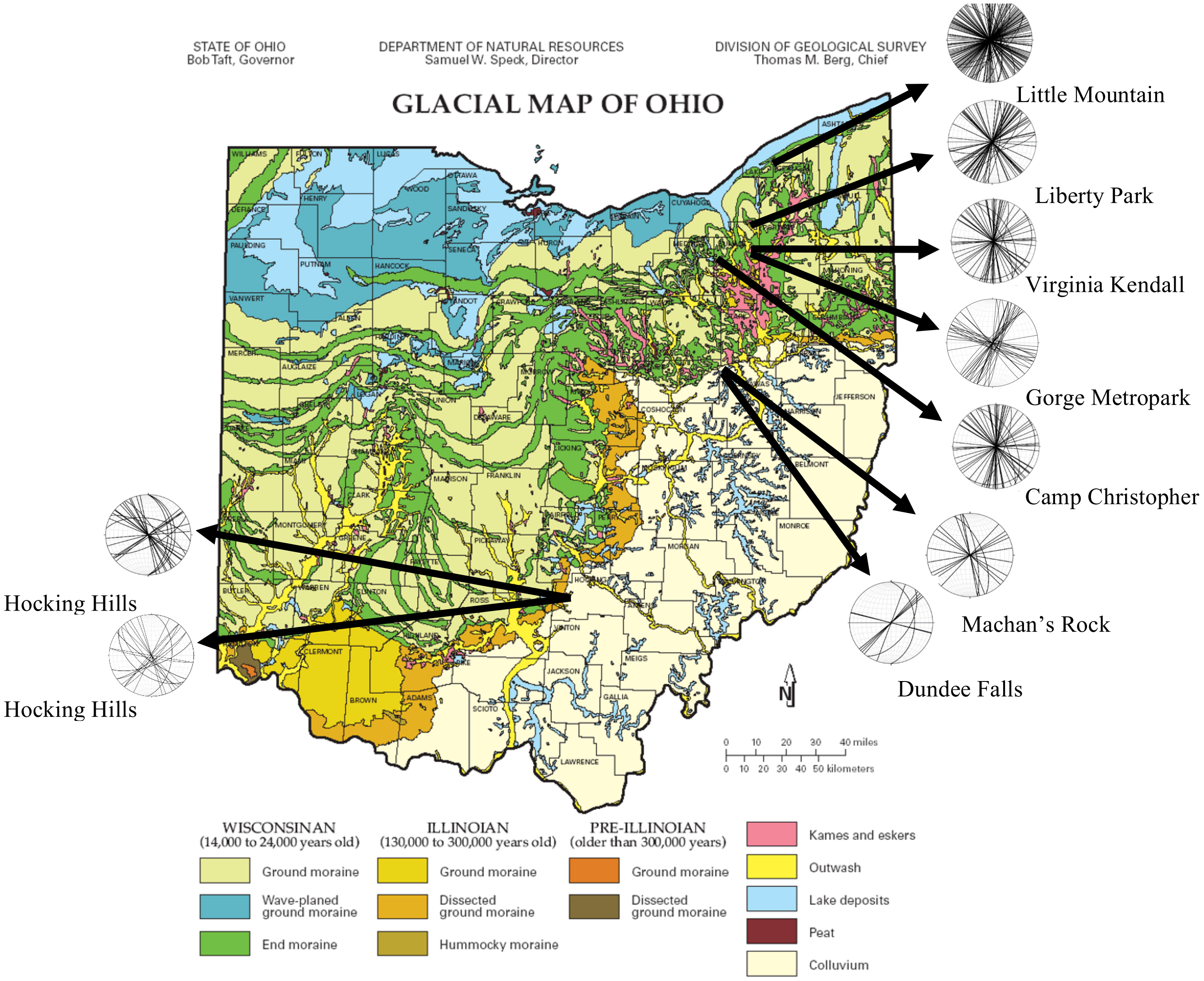


Figure 7: Measurements of joint orientations were collected at several sandstone exposures in eastern and central Ohio by Filiano (2014). Filiano (2014) did not differentiate between continuous and discontinuous joints. However, many of these areas have vertical joints with random strikes, unlike the populations at the Gorge Metropark. Glacial map of Ohio taken from Ohio DNR website, https://geosurvey.ohiodnr.gov/portals/geosurvey/PDFs/Glacial/glacial.pdf

Appendix A: Joint Data

Table 1: Joint Data from Gorge Metropark, Cuyahoga Falls, Ohio.

Joint Number	Outcrop Number	Date observed	Orientation	Joint Length (m)	Rock Description	Continuous or Discontinuous	Reason for Termination	Other notes
1	1	9/15/15	S75W 80NW		-	Discontinuous	-	-
2	1	9/15/15	S80W 90NW	-	Medium grained sandstone	Discontinuous	Bedding plane	-
3	1	9/15/15	S85W 83NW	-	Coarse grained sandstone	Discontinuous	Bedding plane	-
4	1	9/15/15	N70W 83NE	-	Coarse grained sandstone	Discontinuous	Bedding plane	-
5(straight section)	1	9/15/15	S55E 80SW	-	Medium grained sandstone	Continuous	-	Curves into free surface, Makes up face of outcrop
5 (Curved section)	1	9/15/15	S5E 70SW	-	Medium grained sandstone	Continuous	-	Joint 6 is seen right where the straight section of the joint meets the curved section
6	1	9/15/15	N40E 89SE	-	Medium grained sandstone	Discontinuous	Bedding plane	-
7	1	9/15/15	S43W 86NW	-	Medium grained sandstone	Discontinuous	Other joint sets	Joint 7 is vertical and has horizontal joints cross cutting it
8	1	9/15/15	N43E 90SE	-	Medium grained sandstone	Continuous	-	Cuts straight back into the outcrop
9	1	9/15/15	N69E 80SE	-	Medium grained sandstone	Continuous	-	Cuts straight back into the outcrop
10	1	9/15/15	N20E 90SE	-	Medium grained sandstone	Continuous	-	Meets joint 11 at a normal angle
11	1	9/15/15	S70E 80SW	-	Medium grained sandstone	Continuous	-	Makes up the face of the outcrop
12	1	9/15/15	N32E 89SE	-	Medium grained sandstone	Continuous	-	Cuts straight back into the outcrop
13	1	9/15/15	N20E 89SE	-	Medium grained sandstone	Continuous	-	Cuts straight back into the outcrop
14	1	9/15/15	N52W 70NE	-	Coarse grained sandstone	Discontinuous	-	-
15	1	9/15/15	N72W 85NE	-	Coarse grained sandstone	Discontinuous	-	-
16	1	9/22/15	N35E 90SE	3.658	Medium grained sandstone	Continuous	-	Cuts straight back into the outcrop
17	1	9/22/15	N35E 90SE	3.658	Medium grained sandstone	Continuous	-	Cuts straight back into the outcrop
18	1	9/22/15	N25E 85SE	0.6096	Medium grained sandstone	Discontinuous	Bedding plane	-
19	1	9/22/15	N5E 80SE	0.8128	Coarse grained sandstone	Discontinuous	Bedding plane	
20	2	9/22/15	N10E 90SE	1.83	Medium grained sandstone	Continuous	-	Cuts straight back into the outcrop
21	2	9/22/15	S45E 70SW	-	Medium grained sandstone	Continuous	-	Makes up the face of the outcrop
22 (Straight section)	2	9/22/15	S65E 85SW	1.22	Medium grained sandstone	Continuous	-	Curves into free surface, Makes up face of outcrop
22(Curved section)	2	9/22/15	S25E 57SW	1.22	Medium grained sandstone	Continuous	-	-
23	2	9/22/15	N20E 88SE	4	Coarse grained sandstone	Continuous	-	Crossed bedding planes, Cuts straight back into the outcrop
24	2	9/22/15	S55E 88SW	4	Coarse grained sandstone	Continuous	-	-
25	2	9/22/15	N24E 80SE	3.66	Coarse grained sandstone	Continuous	-	Cuts straight back into the outcrop
26	2	9/22/15	N37E 89SE	3.66	Coarse grained sandstone	Discontinuous	Bedding plane	-
27	2	9/22/15	N45W 90NE	1.4224	Coarse grained sandstone	Discontinuous	-	-
28	2	9/22/15	N45W 91NE	1.4224	Coarse grained sandstone	Discontinuous	-	-
29	2	9/22/15	N25E 85SE	-	Coarse grained sandstone	Discontinuous	Bedding plane	-
30	2	9/22/15	N37E 89SE	3.66	Coarse grained sandstone	Continuous	-	-
31	2	9/25/15	S70E 83SW	1.52	Coarse grained sandstone	Discontinuous	Bedding plane	Smaller joint located right next to it in the same orientation
32(Straight section)	2	9/25/15	S45E 70SW	-	Coarse grained sandstone	Continuous	-	Curves into free surface, Makes up face of outcrop
32(Curved section)	2	9/25/15	S12W 65NW	-	Coarse grained sandstone	Continuous	-	Curves into free surface, Makes up face of outcrop
33	2	9/25/15	N20E 80SE	5.5	Medium grained sandstone	Continuous	-	Joint 33 is verical and is interescted by a horizontal joint set, Cuts straight back into the outcrop
34	2	9/25/15	S70E 75SW	5.5	Medium grained sandstone	Continuous	-	Joint 33 and 34 meet at a normal angle, Makes up the face of the outcrop
35	2	9/25/15	N20E 90SE	6.1	Coarse grained sandstone	Continuous	-	Cuts straight back into the outcrop
36	2	9/25/15	S80E 80SW	9.14	Medium grained sandstone	Continuous	-	Makes up the face of the outcrop
37	2	9/25/15	N5E 90SE	3.66	Medium grained sandstone	Continuous	-	Intersects joint 36 at a normal angle, Cuts straight back into the outcrop
38	2	9/25/15	N45E 60SE	0.91	Medium grained sandstone	Discontinuous	Curves into another joint set	-
39	2	9/25/15	N45E 60SE	0.91	Medium grained sandstone	Discontinuous	Curves into another joint set	-
40	2cc	9/25/15	N5E 90SE	5.5	Coarse grained sandstone	Discontinuous	Bedding plane	Propogates through bedding plane of medium quartz grains but terminates at bedding plane containng large quartzs grains
41	2cc	9/25/15	S80E 90SW	-	Coarse grained sandstone	Discontinuous	Another joint set	Cross cuts horizontal joints
42	2cc	9/25/15	S80E 90SW	1.23	Coarse grained sandstone	Discontinuous	-	-
43	2CC	9/25/15	N30E 80SE	0.91	Coarse grained sandstone	Continuous	-	Cuts straight back into the outcrop
44	2CC	9/25/15	S80E 90SW	1.23	Coarse grained sandstone	Discontinuous	-	-
45	2CC	9/25/15	S80E 90SW	1.23	Coarse grained sandstone	Discontinuous	-	-
46	2CC	9/25/15	S75E 90SW	-	Coarse grained sandstone	Continuous	-	-
47	2CC	9/25/15	S65E 90SW	-	Coarse grained sandstone	Continuous	-	-
48	2CC	9/25/15	N30E 80SE	-	Coarse grained sandstone	Continuous	-	Runs perpendicular to joint 47 and 48
49	2CC	9/25/15	S65E 80SW	-	Coarse grained sandstone	Discontinuous	-	-
50	2CC	10/2/15	N65W 3NE	3.66	Medium grained sandstone	Continuous	-	Horizontal Joint that cross cuts all the vertical joints

51	2CC	10/2/15	N65W 3NE	3.66	Medium grained sandstone	Continuous	-	Horizontal Joint that cross cuts all the vertical joints
52	2CC	10/2/15	N65W 3NE	3.66	Medium grained sandstone	Continuous	-	Horizontal Joint that cross cuts all the vertical joints
53	2CC	10/2/15	N65W 3NE	3.66	Medium grained sandstone	Continuous	-	Horizontal Joint that cross cuts all the vertical joints
54	2CC	10/2/15	N65W 3NE	3.66	Medium grained sandstone	Continuous	-	Horizontal Joint that cross cuts all the vertical joints
55	2CC	10/2/15	N65W 3NE	3.66	Medium grained sandstone	Continuous	-	Horizontal Joint that cross cuts all the vertical joints
56	2CC	10/2/15	N65W 3NE	3.66	Medium grained sandstone	Continuous	-	Horizontal Joint that cross cuts all the vertical joints
57	3	10/2/15	N12E 75SE	5.5	Coarse grained sandstone	Continuous	-	Irregular joint direction changes each time it meets a new bedding plane
58	3	10/2/15	N70W 83NE	0.2032	Coarse grained sandstone	Discontinuous	-	Highly eroded
59	3	10/2/15	N70W 83NE	0.2032	Coarse grained sandstone	Discontinuous	-	Highly eroded
60	3	10/2/15	N70W 83NE	0.2032	Coarse grained sandstone	Discontinuous	-	Highly eroded
61	3	10/2/15	N70W 83NE	0.2032	Coarse grained sandstone	Discontinuous	-	Highly eroded
62	3	10/2/15	N20E 75SE	2.44	Coarse grained sandstone	Continuous	-	-
63	3	10/2/15	N5E 80SE	3.66	Coarse grained sandstone	Continuous	-	-
64	3	10/2/15	N85W 90NE	0.8128	Coarse grained sandstone	Discontinuous	-	-
65	3	10/2/15	W 90	0.4064	Coarse grained sandstone	Discontinuous	-	-
66	3	10/2/15	N75W 90NE	1.6256	Coarse grained sandstone	Discontinuous	-	Curved like a "c"
67	4	10/2/15	N80E 90SE	5.5	Medium grained sandstone	Continuous	-	Contains another possible joint set with an orientation of S80E 85
68	4	10/2/15	N80E 90SE	5.5	Medium grained sandstone	Continuous	-	-
69	4	10/2/15	N80E 90SE	5.5	Medium grained sandstone	Continuous	-	-
70	4	10/2/15	N85E 80SE	1.52	Medium grained sandstone	Continuous	-	-
71	4	10/2/15	N75E 50SE	1.016	Medium grained sandstone	Discontinuous	Hole	-
72	4	10/2/15	S80E 87SW	2.032	Medium grained sandstone	Discontinuous	Bedding plane	-
73	4	10/2/15	N45E 65SE	7.32	Coarse grained sandstone	Continuous	-	-
74	4	10/2/15	N80E 65SE	9.14	Coarse grained sandstone	Continuous	-	-
75	4	10/2/15	N85E 80SE	9.14	Coarse grained sandstone	Continuous	-	Wide crack on bottom and thins towards the top
76	4	10/2/15	N80E 80SE	3.66	Medium grained sandstone	Discontinuous	Bedding plane	-
77	4	10/2/15	E 90	1.6256	Medium grained sandstone	Discontinuous	-	-
78	4	10/2/15	N80E 80SE	7.32	Medium grained sandstone	Discontinuous	Bedding plane	-
79	4	10/2/15	N80E 80SE	1.016	Medium grained sandstone	Discontinuous	Bedding plane	-
80	4	10/8/15	N75W 90NE	1.016	Coarse grained sandstone	Discontinuous	-	-
81	4	10/8/15	N65W 90NE	2.44	Coarse grained sandstone	Discontinuous	-	-
82	4	10/8/15	N60W 90NE	2.44	Coarse grained sandstone	Discontinuous	-	-
83	4	10/8/15	S80W 75NW	2.8448	Medium grained sandstone	Discontinuous	Another joint set	-
84	5	10/8/15	S45E 90SW	3.66	Medium grained sandstone	Continuous	-	-
85	5	10/8/15	N5W 80NE	1.2192	Medium grained sandstone	Discontinuous	-	-
86	5	10/8/15	N5W 80NE	1.2192	Medium grained sandstone	Discontinuous	-	-
87	5	10/8/15	S35E 85SW	4.88	Medium grained sandstone	Continuous	-	-
88	5	10/8/15	E-W 90	8.84	Medium grained sandstone	Continuous	-	Large seperated joint
89	5	10/8/15	S 75	2.44	Medium grained sandstone	Discontinuous	Bedding plane	Bedding planes control the shape of this joint
90	5	10/8/15	S 75	2.44	Medium grained sandstone	Discontinuous	Bedding plane	Bedding planes control the shape of this joint
91	5	10/8/15	S30E 75SW	1.8	Medium grained sandstone	Continuous	-	-
92	5	10/8/15	S40W 90NW	1.8	Medium grained sandstone	Continuous	-	Curved portion of joint 88
93	5	10/8/15	N30E 90SE	1.8	Medium grained sandstone	Discontinuous	-	-
94	5	10/8/15	E-W 90	5.5	Medium grained sandstone	Continuous	-	Large seperated joint
95	5	10/8/15	S15E 87SW	1.23	Medium grained sandstone	Discontinuous	-	-
96	5	10/8/15	N30E 90	6.06	Medium grained sandstone	Continuous	-	Forms a normal angle withjoint 94
97	5	10/8/15	N-S 90	0.6096	Medium grained sandstone	Discontinuous	Bedding plane	-
98	5	10/8/15	N-S 90	0.6096	Medium grained sandstone	Discontinuous	Bedding plane	-
99	5	10/8/15	N-S 90	0.6096	Medium grained sandstone	Discontinuous	Bedding plane	-
100	5	10/8/15	N-S 90	0.6096	Medium grained sandstone	Discontinuous	Bedding plane	-
101	5	10/8/15	N-S 90	0.6096	Medium grained sandstone	Discontinuous	Bedding plane	-
102	5	10/8/15	E-W 90	2.4	Medium grained sandstone	Continuous	-	Joint is curved. Orientaion of curved portion is S70W 90
103	5	10/8/15	N30E 65SE	2.4	Medium grained sandstone	Continuous	-	-

Appendix A: Joint Data

Table 2: Joint Data from Hocking Hills State Park, Logan, Ohio

Joint Number	Outcrop Number	Date observed	Orientation	Joint Length (m)	Rock Description	Continuous or Discontinuous	Reason for Termination	Other notes
1	1	12/23/15	N80W 90	3		Continuous	-	-
2	1	12/23/15	N10E 85	8		Continuous	-	-
3	1	12/23/15	S25W 90	12		Continuous	-	-
4	1	12/23/15	S45E 90	20		Continuous	-	-
5	1	12/23/15	S20E 90	12		Discontinuous	Bedding	-
6	1	12/23/15	S40W 90	20		Continuous	-	-
7	1	12/23/15	S35E 90	12		Discontinuous	Bedding	-
8	1	12/23/15	S40E 80	1		Discontinuous	Bedding	-
9	1	12/23/15	S15E 90	9		Continuous	-	-
10	1	12/23/15	S80E 85	8		Discontinuous	Bedding	-
11	1	12/23/15	N75W 85	9		Continuous	-	-
12	1	12/23/15	N40W 85	6		Discontinuous	Bedding	-
13	1	12/23/15	N75W 80	10		Discontinuous	Unknown	Might be discontinous looking due to erosion
14	1	12/23/15	South	5		Discontinuous	Unknown	-
15	1	12/23/15	S40W 87	5		Discontinuous	Unknown	-
16	1	12/23/15	N40E 65	5		Discontinuous	Unknown	-
17	1	12/23/15	N70E 65	1		Discontinuous	Unknown	-
18	1	12/23/15	N80E 90	10		Continuous	-	-
19	1	12/23/15	N55E 75	0.5		Discontinuous	Unknown	-
20	1	12/23/15	N75E 75	0.5		Discontinuous	Unknown	-
21	1	12/23/15	N40E 80	0.5		Discontinuous	Unknown	-
22	1	12/23/15	N30W 90	5		Discontinuous	Unknown	-
23	1	12/23/15	N45E 85	3		Discontinuous	Unknown	-
24	2	12/24/15	S55E 80	2		Discontinuous	Unknown	-
25	2	12/24/15	S55E 80	2		Discontinuous	Unknown	-
26	2	12/24/15	S55E 80	2		Discontinuous	Unknown	-
27	2	12/24/15	S55E 80	2		Discontinuous	Unknown	-
28	2	12/24/15	S55E 80	2		Discontinuous	Unknown	-
29	2	12/24/15	S55E 80	2		Discontinuous	Unknown	-
30	2	12/24/15	S45E 65	30		Continuous	-	-
31	2	12/24/15	N70E 70	4		Discontinuous	Bedding	-
32	2	12/24/15	N70E 70	4		Discontinuous	Bedding	-
33	2	12/24/15	N70E 70	4		Discontinuous	Bedding	-
34	2	12/24/15	N70E 70	4		Discontinuous	Bedding	-
35	2	12/24/15	S50E 50	1		Discontinuous	Unknown	-
36	2	12/24/15	S50E 50	1		Discontinuous	Unknown	-
37	2	12/24/15	S50E 50	1		Discontinuous	Unknown	-
38	2	12/24/15	N5E 50	1		Discontinuous	Unknown	-
39	2	12/24/15	N5E 50	1		Discontinuous	Unknown	-
40	2	12/24/15	N5E 50	1		Discontinuous	Unknown	-
41	2	12/25/15	N55E 80	9		Discontinuous	Unknown	-
42	2	12/26/15	N55E 80	9		Discontinuous	Unknown	-