THE INFLUENCE OF FRACTURE CHARACTERISTICS ON GROUNDWATER FLOW SYSTEMS IN FRACTURED IGNEOUS AND METAMORPHIC ROCKS OF NORTH CAROLINA (USA)

By

Justin E. Nixon

May, 2013

Director of Thesis: Dr. Alex K. Manda

Major Department: Geological Sciences

The yield of water wells drilled in crystalline rock aquifers is determined by the occurrence and interaction of open, saturated fractures which decrease with increased depth, outside of the influence of large-scale features such as fault zones. These trends suggest that in the shallow subsurface, (i) fluid flow is controlled by specific fracture types, and (ii) there is a bounding depth below which groundwater flow is significantly reduced. These hypotheses are tested in this paper. The analysis of fracture properties identified in boreholes offers an approach to investigate the depth evolution of groundwater systems in crystalline rocks. Optical televiewer, caliper and heat pulse flow meter logs are utilized to investigate the attributes, distributions, orientations, and the contribution to flow of 570 fractures that intersect 26 bedrock wells drilled in crystalline rocks of North Carolina. Results indicate that the dominant fracture types are foliation parallel fractures (FPFs) (42%), other fractures (32%) and sheet joints (26%). The boreholes are drilled into five lithologic terranes and intersect seven major lithologic and rock fabric types, consisting of: (1) felsic gneiss, (2) andesitic to basaltic flows, (3) diorite, (4) mafic gneiss, (5) gneiss and amphibolite, (6) gneiss and mylonite and (7) schist. The dominant fracture type in the upper 40 m is sheet joints. Rocks with sub-horizontal planar fabric prefer to develop FPFs instead of sheet joints. Fractures with the largest apertures are mostly restricted to

shallow depths, where sheet joints dominate. However, some sheet joints and FPFs with large apertures are observed at depths greater than 40 m. Flow intervals identified from borehole logs reveal that sheet joints and FPFs are the dominant fracture type where the majority of flow is observed and are therefore likely to control most of the flow in the shallow subsurface. In contrast, FPFs and other fractures are the dominant conduits for channeling flow at greater depths. Fracture and flow analyses indicate that the majority of flow (> 80%) occurs at depths shallower than 75 m, suggesting the existence of a bounding depth in the shallow subsurface below which permeabilities of fractured crystalline rocks are significantly reduced.

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Justin E. Nixon

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Justin E. Nixon

APPROVED BY:

DIRECTOR OF THESIS: ______________________________
Dr. Alex K. Manda

COMMITTEE MEMBER: ______________________________
Dr. Eric Horsman

COMMITTEE MEMBER: ______________________________
Dr. Richard K. Spruill

COMMITTEE MEMBER: ______________________________
Dr. Cheryl Waters-Tormey

CHAIR OF THE DEPARTMENT OF
GEOLOGICAL SCIENCES ______________________________
Stephen J. Culver

DEAN OF THE GRADUATE SCHOOL ______________________________
Dr. Paul J. Gemperline

DEDICATION

This research is dedicated to my mom, dad and my two sisters. Thank you for always being there when I needed you and for providing for me during difficult times. Without your encouragement, love and patience, this would not have been possible. Thank you so much for the opportunity to gain this tremendous education and the necessary tools to succeed in life.

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LIST OF SYMBOLS/ABBREVIATIONS

BF- Brevard Fault

CPS- Central Piedmont Suture

CPSZ- Central Piedmont Shear Zone

FLT- Falls Lake Terrane

FPF- Foliation Parallel Fracture

GHSZ- Gold Hill Shear Zone

lpm- Liters per minute

LT- Langtree Peninsula

MT- Milton Terrane

OPC- Older Plutonic Complex

OTV- Optical Televiewer

PMREP- Piedmont and Mountains Resource Evaluation Program

RB- Rolesville Batholith

RT- Raleigh Terrane

SMW- Sauratown Mountains Window

SOP- Standard Operating Procedure

SRA- Smith River Allochthon

TT- Tugaloo Terrane

VFD- Variable Frequency Drive

CHAPTER I: INTRODUCTION

Overview

This thesis is prepared in four parts: Chapter 1 (this section) provides an outline of this document as well as objectives of this study, Chapter 2 is the main body of this thesis work, and thus will be submitted for publication, Chapter 3 reviews previous work and provides recommendations for future work related to this study, and the Appendices comprise the supporting data and information used in this study.

Objectives

The goal of this study is to assess the occurrence, separation, types and properties of fractures intersecting bedrock wells and the resulting influence on groundwater flow within crystalline rock aquifers in North Carolina. Specific questions that will be addressed in this study are as follows:

Is there a dominance of a certain fracture type where the majority of flow is derived?

How do fracture intensities and apertures affect groundwater flow regimes in crystalline rocks outside of the influence of large scale structures such as fault zones?

To what degree do sheet joints in the shallow subsurface in crystalline rocks control groundwater flow?

Hypothesis:

The hypothesis that will be tested is that there is a bounding depth in crystalline rocks of North Carolina below which groundwater flow is greatly diminished.

CHAPTER II: THE INFLUENCE OF FRACTURE CHARACTERISTICS ON GROUNDWATER FLOW SYSTEMS IN FRACTURED IGNEOUS AND METAMORPHIC ROCKS OF NORTH CAROLINA (USA)

Abstract

The yield of water wells drilled in crystalline rock aquifers is determined by the occurrence and interaction of open, saturated fractures which decrease with increased depth, outside of the influence of large-scale features such as fault zones. These trends suggest that in the shallow subsurface, (i) fluid flow is controlled by specific fracture types, and (ii) there is a bounding depth below which groundwater flow is significantly reduced. These hypotheses are tested in this paper. The analysis of fracture properties identified in boreholes offers an approach to investigate the depth evolution of groundwater systems in crystalline rocks. Optical televiewer, caliper and heat pulse flow meter logs are utilized to investigate the attributes, distributions, orientations, and the contribution to flow of 570 fractures that intersect 26 bedrock wells drilled in crystalline rocks of North Carolina. Results indicate that the dominant fracture types are foliation parallel fractures (FPFs) (42%), other fractures (32%) and sheet joints (26%). The boreholes are drilled into five lithologic terranes and intersect seven major lithologic and rock fabric types, consisting of: (1) felsic gneiss, (2) andesitic to basaltic flows, (3) diorite, (4) mafic gneiss, (5) gneiss and amphibolite, (6) gneiss and mylonite and (7) schist. The dominant fracture type in the upper 40 m is sheet joints. Rocks with sub-horizontal planar fabric prefer to develop FPFs instead of sheet joints. Fractures with the largest apertures are mostly restricted to shallow depths, where sheet joints dominate. However, some sheet joints and FPFs with large apertures are observed at depths greater than 40 m. Flow intervals identified from borehole logs reveal that sheet joints and FPFs are the dominant fracture type where the majority of flow is observed and are therefore likely to control most of the flow in the shallow subsurface. In contrast, FPFs and other fractures are the dominant conduits for channeling flow at greater depths. Fracture and flow analyses indicate that the majority of flow (> 80%) occurs at depths shallower than 75 m, suggesting the existence of a bounding depth in the shallow subsurface below which permeabilities of fractured crystalline rocks are significantly reduced.

Keywords: Fracture, Fractured rocks, Bounding depth, Crystalline rocks, USA

2.1 Introduction

Crystalline rock aquifers are increasingly sought to serve as potable sources of water where unconsolidated aquifers and surface water bodies fail to meet demand. Because crystalline rocks have negligible matrix permeability, the degree to which this demand is met is dependent on boreholes intersecting highly conductive fractures in the subsurface. Fracture lengths, orientations, apertures, connectivities and spacings therefore influence the productivity of boreholes drilled in crystalline rocks. However, although the relationship among states of stress, lithology, geologic history, fracture types and permeability varies spatially and ranges over several orders of magnitude (NRC 1996), investigators working in various regions have been able to demonstrate sharp decreases of permeability with depth.

Numerous workers (e.g., Snow, 1968; Rutqvist and Stephansson, 2003; Maréchal et al., 2004) have shown that the densities and apertures of fractures decrease with increasing depth and contribute to the declines in porosity and permeability at depth. It is generally accepted that the density of hydraulically significant fractures is low in relation to the total fracture density, i.e. there may be many fractures within a well, but only a few contribute to flow (Snow 1968; Shapiro and Hsieh, 1991; Shapiro and Hsieh, 1994; Mazurek et al., 2003). These trends have been observed in crystalline rocks where the density of hydraulically significant fractures is low in relation to the total fracture density (Shapiro and Hsieh, 1991; Shapiro and Hsieh, 1994; Mazurek et al., 2003). Working in igneous and metamorphic rocks at the Mirror Lake Research Station in New Hampshire, USA, Shapiro and Hsieh (1998) found that the most transmissive fractures in boreholes ranging in depth from 20-70 m were observed in the upper 50 m of boreholes. In a study of bedrock wells in South Korea, Cho et al., (2003) determined that the maximum specific capacity in granitic rocks is encountered at 80 m depth. Cumulative airlift flow rates derived from boreholes drilled in granitic rocks of Andhra Pradesh, India reach maximum flow rates at depths ranging from 20 to 30 m depth (Maréchal et al., 2004). In Zimbabwe, fractures located in the top 15-20 m of bedrock were found to be major contributors to flow into wells drilled in granitic gneisses and lower grade metamorphic rocks (Chilton and Foster, 1995; Houston and Lewis, 1988). Such observations have led other workers to hypothesize that the networks of hydraulically active fractures are primarily maintained within the upper 100-150 m of the land surface where most of the flow in crystalline rocks is confined (e.g., Legrand, 1954, 1967; Davis and Turk, 1964; Boutt et al., 2010). This hypothesis is tested in the current study.

The objectives of this study are to (i) assess the influence of fracture attributes on the hydraulic properties of fractured crystalline rock aquifers, and (ii) estimate a bounding depth of groundwater flow in the shallow subsurface of crystalline rocks in North Carolina. Suites of borehole logs and heat pulse flow meter measurements acquired from groundwater monitoring and research stations across five terranes in North Carolina are utilized to characterize fractures and derive relative interval transmissivity logs. Several wells are used at each research station in order to derive statistically meaningful results from each terrane and to generate simplified conceptual descriptions that may be transferable to other regions. The conceptual frameworks derived here may provide important information that may be useful to practicing hydrologists, water managers and well drillers working in fractured crystalline rocks.

2.2 Structural and hydrogeologic setting

Crystalline rocks of North Carolina are part of the Southern Appalachian Mountains, and are part of one of three realms based on their proximity to the Late Proterozoic Laurentian and Gondwanan continents, or rocks sandwiched in between relating to the Iapetan ocean (Hibbard et al., 2012) (detailed description can be found in Appendix A). These rocks are composed of moderately-deformed intrusives to highly deformed metamorphics (Hibbard et al., 2006). The study boreholes are drilled in five litho-tectonic terranes, consisting of the Raleigh Terrane, Carolina Terrane, Charlotte Terrane, Milton Terrane and the Tugaloo Terrane, from east to west respectively (Fig. 1). The boreholes intersect seven major lithologic and rock fabric types, consisting of: (1) felsic gneiss, (2) andesitic to basaltic flows, (3) diorite, (4) mafic gneiss, (5) gneiss and amphibolite, (6) gneiss and mylonite and (7) schist (Table 1).

Table 1. Rock units, degree of penetrative fabric development, and ages of formations and rock types in North Carolina

Terrane	Formation	Dominant Rock Type(s)	* Foliation Development	Age of Crystallization or Deformation
Raleigh	Raleigh Formation	Felsic gneiss	Well developed	[1]Precambrian
Carolina	Virgilina Sequence	Volcanic Flows, Granodiorite	Weak - Massive	[2]Precambrian
Charlotte	Older Plutonic Complex	Quartz Diorite	Weak - Massive	[3]Cambrian
Milton		Felsic Gneiss, Mafic Gneiss, Amphibolite, Mylonite	Moderate - Well developed	[4]Ordovician
Tugaloo	Ashe Metamorphic Suite	Interlayered schist and metagraywacke	Well developed	[5]Ordovician

*Foliation development determined by the USGS (Stoddard et al., 2001; Bradley et al., 2006; Chapman et al., 2005; Chapman et al., 2007; Pippin et al., 2008; Campbell, 2009).
[1]Raleigh Gneiss Formation (age of crystalization) – 560 ± 2Ma (Owens and Buchwaldt, 2009).
[2]Vergilina Sequence (age of crystalization) – 630-610 Ma (Samson et al., 1995; Wortman et al., 2000; Bradley et al., 2006).
[3]Older Plutonic Complex (age of crystalization) – (Goldsmith et al., 1988)
[4]Milton Terrane (age of crystalization) – (Wortman et al., 1995)
[5]Ashe Metamorphic Suite (age of metamorphism) – (Trupe et al., 2004); likely age of latest penetrative deformation is Devonian (Waters-Tormey and Stewart, 2010).

The Raleigh Gneiss is composed of amphibolite-facies, felsic gneiss, portraying migmatitic compositional banding, which often produces black gray and white intervals (Fig. 2) (Horton and Stern, 1994; Goldberg, 1994; Chapman et al., 2005). Foliation near the boreholes, as reported by Heller (1996), strikes N-5^o-E and has a subvertical dip. Local variations of foliation are possible from folding (Heller, 1996).

Crystalline rocks of the Virgilina Sequence, part of the Carolina Terrane, are of greenschist facies and are composed of andesitic - basaltic volcanic flows, as well as ranges of intrusive diorites (Fig. 3) (Bradley et al., 2004). Extrusive flows lack foliation, however, diorites in this area may possess weak fabrics. Regional metamorphism has produced folding of the strata into km-scale folds, trending NE-SW and are inclined to the WNW.

The Older Plutonic Complex (OPC) of the Charlotte Terrane is composed of metamorphosed quartz diorite (Fig. 4) (Goldsmith et al., 1988). Two foliations are identified near the drill site and average N-12^o-E and dip 60^o both to the SE (dominant) and NW (secondary). Granitic dikes intersect all boreholes at various depths, except 17 (Table 2), and range in thickness from 0.5 – 15 m. The contacts of these intrusions with the overall rock mass are sometimes accentuated by the presence of fractures (Pippin et al., 2008). These dikes are generally oriented N-20^o-W and dip 66^o to the west.

The Milton Terrane (MT) is composed of interlayered mica gneiss and schist, felsic gneiss, amphibolite, and mylonitic mica schist and gneiss (Fig. 5) (Horton and Geddes, 2006). The foliation in this area dips moderately to the south and southeast.

The Ashe Metamorphic Suite (AMS), within the Tugaloo Terrane, consists of Ordovician amphibolite facies mica-schists with inter-layered, weakly foliated meta-greywacke, well-foliated gneiss. Kilometer-scale mafic amphibolite and ultramafic bodies also occur locally (Fig.

6) (Table 2) (Abbott and Raymond, 1984; Hatcher and Goldberg, 1991; Willard and Adams, 1994; Merschat and Carter, 2002; Trupe et al., 2003; Campbell, 2009). Foliations generally strike to the NE, with moderate to steep dips in NW or SE directions (Merschat and Carter, 2002).

The groundwater system in the studied rocks is generally composed of two parts: shallow weathered regolith and the deeper un-weathered bedrock (Heath, 1984; Harned and Daniel, 1992). The regolith is composed of sand, silt and clays that are derived from the in-situ weathering of the underlying bedrock. This shallow aquifer system provides the bulk of groundwater storage and typically retains directional flow properties that mimic the bedrock. The bedrock is broken and displaced by numerous faults and zones of shearing, some of which are many kilometers in length. Fracture sets are ubiquitous, commonly oriented in one or more preferred directions. All rocks have been subjected to uplift, weathering, and erosion, which have resulted in the widening of fractures as well as the formation of new fractures.

Table 2. Physical characteristics of bedrock wells and lithologic types derived from all study sites in North Carolina. All boreholes are 15.24 cm in diameter. masl = meters above mean sea level. NR = Not Reported.

Well Number	Well ID	Year Drilled	Land Surface Elevation (masl)	Dominant Rock Type	Total Depth (m)	Geologic Terrane
1	RT-1D	2001	247.65	Felsic Gneiss	92.05	Raleigh
2	RT-2D	2001	109.66	Felsic Gneiss	183.18	Raleigh
3	RT-3D	2001	114.71	Felsic Gneiss	91.15	Raleigh
4	RT-PW-1	2001	109.14	Felsic Gneiss	92.05	Raleigh
5	RT-A	2010	NR	Felsic Gneiss	91.70	Raleigh
6	RT-B	2010	NR	Felsic Gneiss	121.06	Raleigh
7	DF-2Dgs	2005	NR	Andesitic / Basaltic Lava Flow	85.65	Carolina
8	DF-2Dpvc	2005	NR	Andesitic / Basaltic Lava Flow	81.99	Carolina
9	DF-4D	2005	NR	Granodiorite	121.92	Carolina
10	MT-N1D	2002	204.98	Gneiss and Amphibolite	91.44	Milton
11	MT-N2D	2002	204.79	Mafic Gneiss	91.44	Milton
12	MT-N3D	2002	234.77	Gneiss and Mylonite	79.24	Milton
13	MT-N4D	2002	256.09	Gneiss and Mylonite	91.44	Milton
14	MT-S3D	2002	215.03	Felsic Gneiss	133.50	Milton
15	MT-S4D	2002	201.03	Gneiss and Amphibolite	115.82	Milton
16	LT-1D	2000	247.65	Diorite	183.49	Charlotte
17	LT-2D	2000	244.66	Diorite	121.92	Charlotte
18	LT-4D	2001	244.40	Diorite	121.92	Charlotte
19	LT-5D	2001	239.18	Diorite	121.92	Charlotte
20	LT-6D	2001	233.43	Diorite	121.92	Charlotte
21	TT-1D	2002	671.10	Schist	67.11	Tugaloo
22	TT-2D	2002	667.56	Schist	86.92	Tugaloo
23	TT-3D	2002	673.32	Schist	91.14	Tugaloo
24	TT-4D	2002	688.40	Schist	152.71	Tugaloo
25	TT-5D	2002	702.52	Schist	86.87	Tugaloo
26	TT-7D	2002	722.34	Schist	86.87	Tugaloo

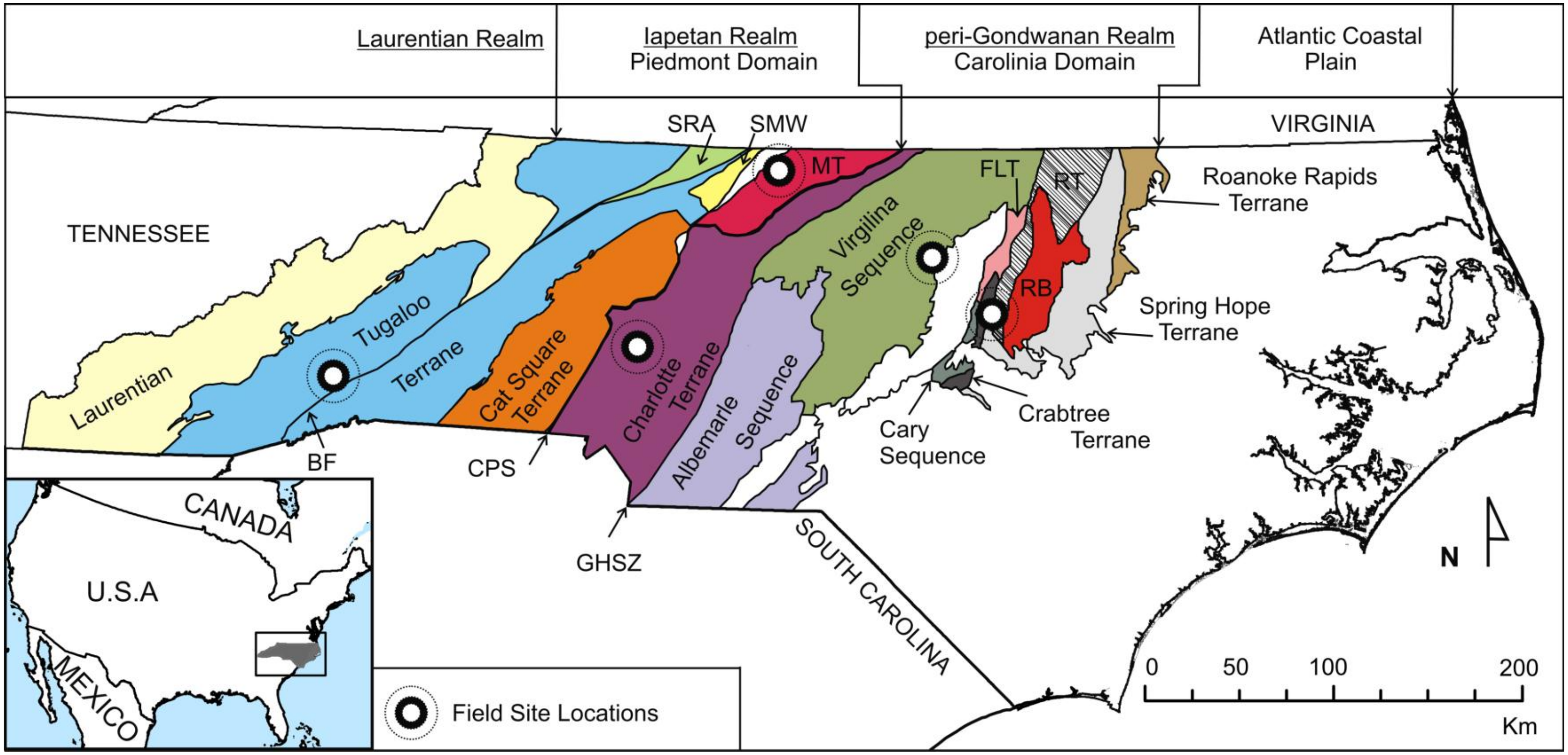


Figure 1: Simplified geologic map of North Carolina showing geologic divisions. BF-Brevard Fault zone, SRA-Smith River allochthon, SMW-Sauratown Mountains Window, MT-Milton Terrane, CPS-Central Piedmont Suture, GHSZ- Gold Hill Shear Zone, FLT-Falls Lake Terrane, RT-Raleigh Terrane, RB-Rolesville Batholith. Modified from Hibbard, (1998); Hibbard et al., (2002); Hatcher (2005).

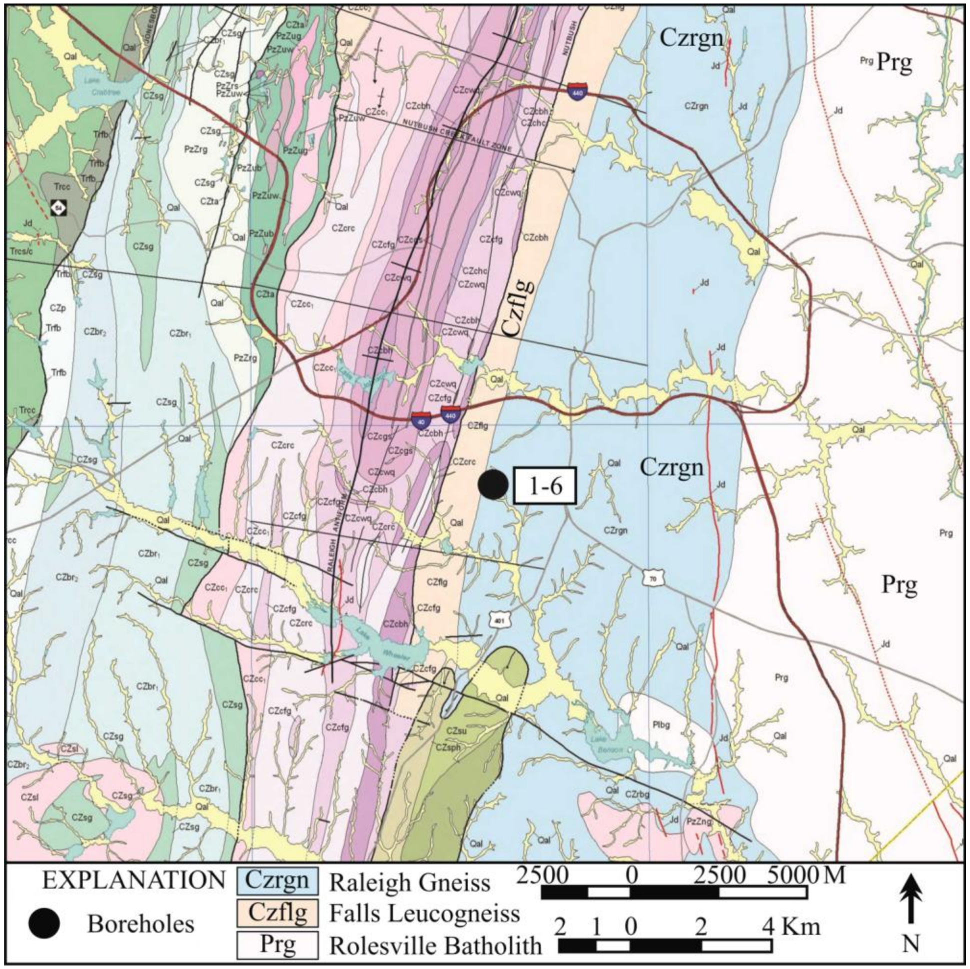


Figure 2: Geologic map showing the location of Lake Wheeler Research Station site within the Raleigh Gneiss of the Raleigh Terrane (Modified from Clark et al., 2004).

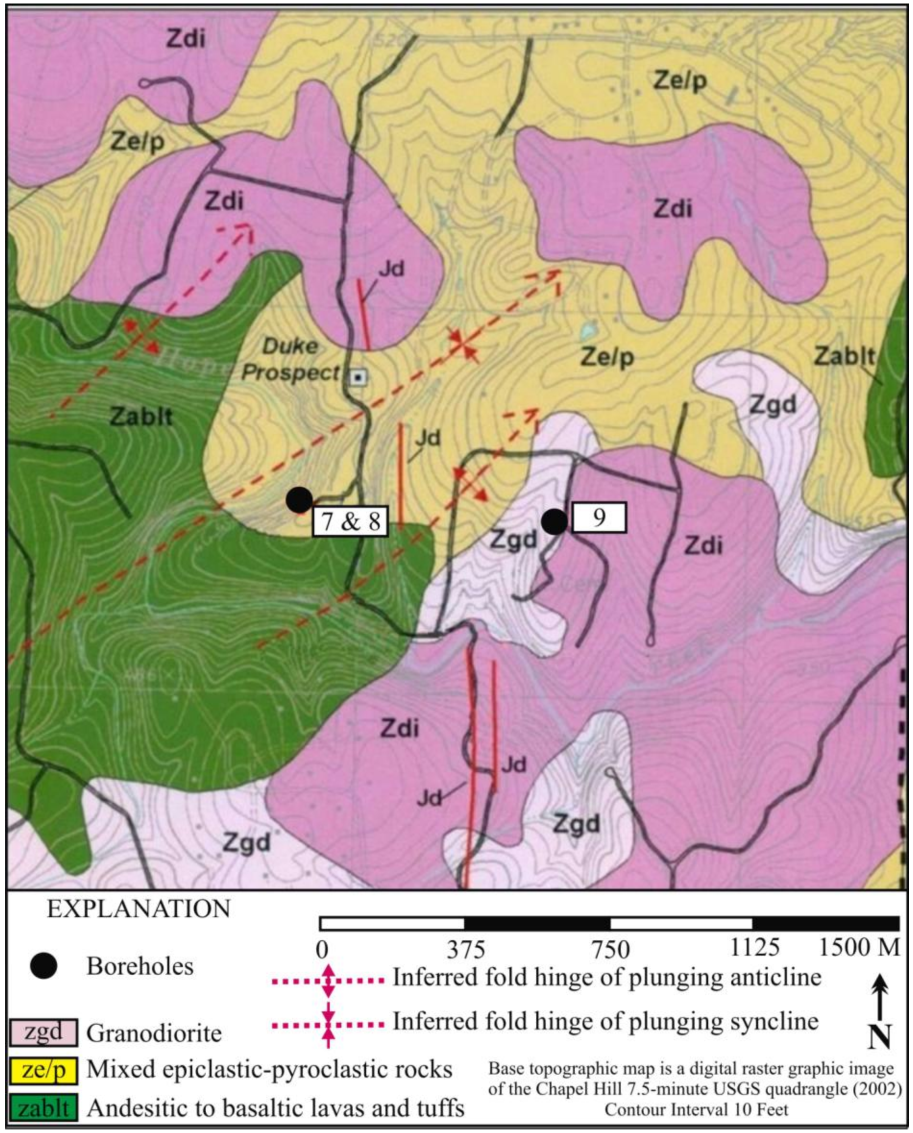


Figure 3: Geologic map showing the location of the Duke Forest Groundwater Research Station site within the Virgilina Sequence of the Carolina Terrane (Modified from Bradley et al., 2004).

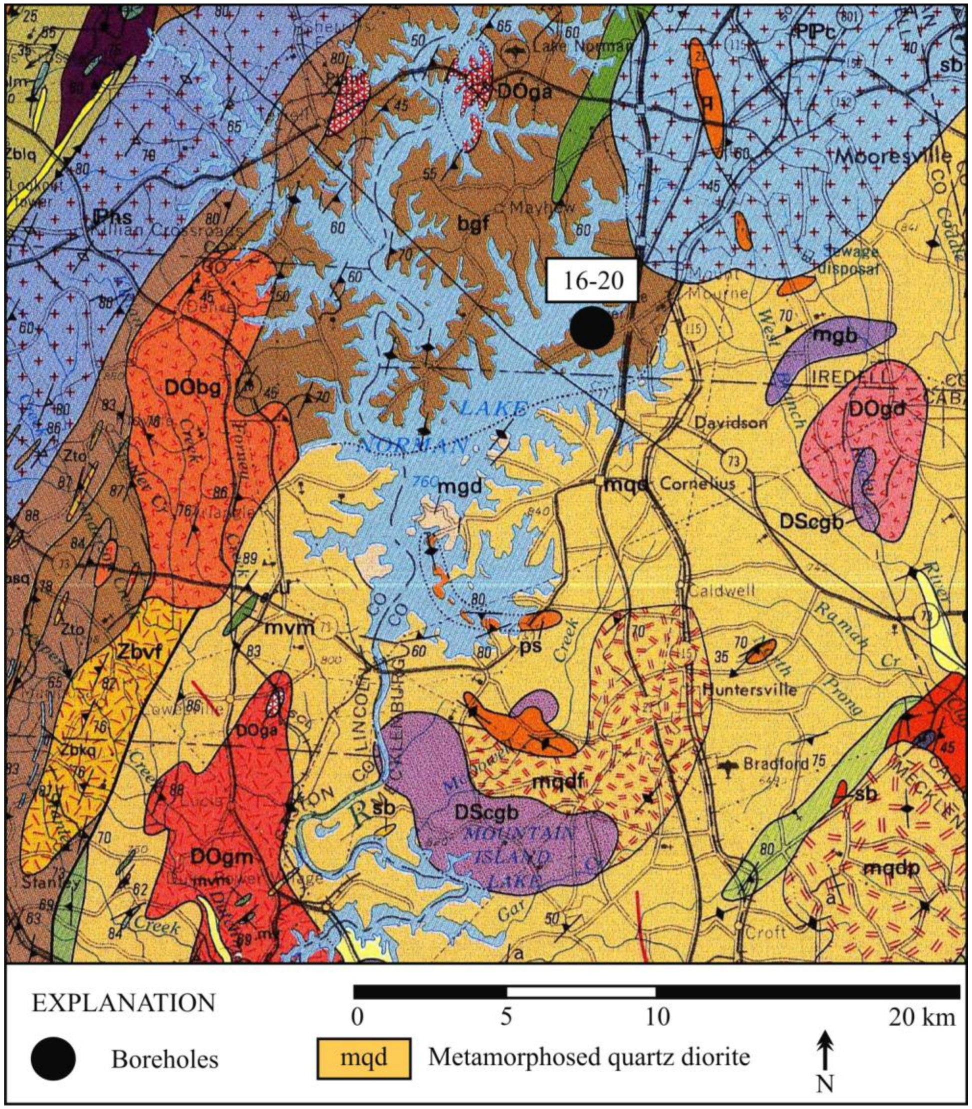


Figure 4: Geologic map showing the location of the Langtree Peninsula site within the Older Plutonic Complex, Charlotte Terrane (Modified from Goldsmith et al., 1988).

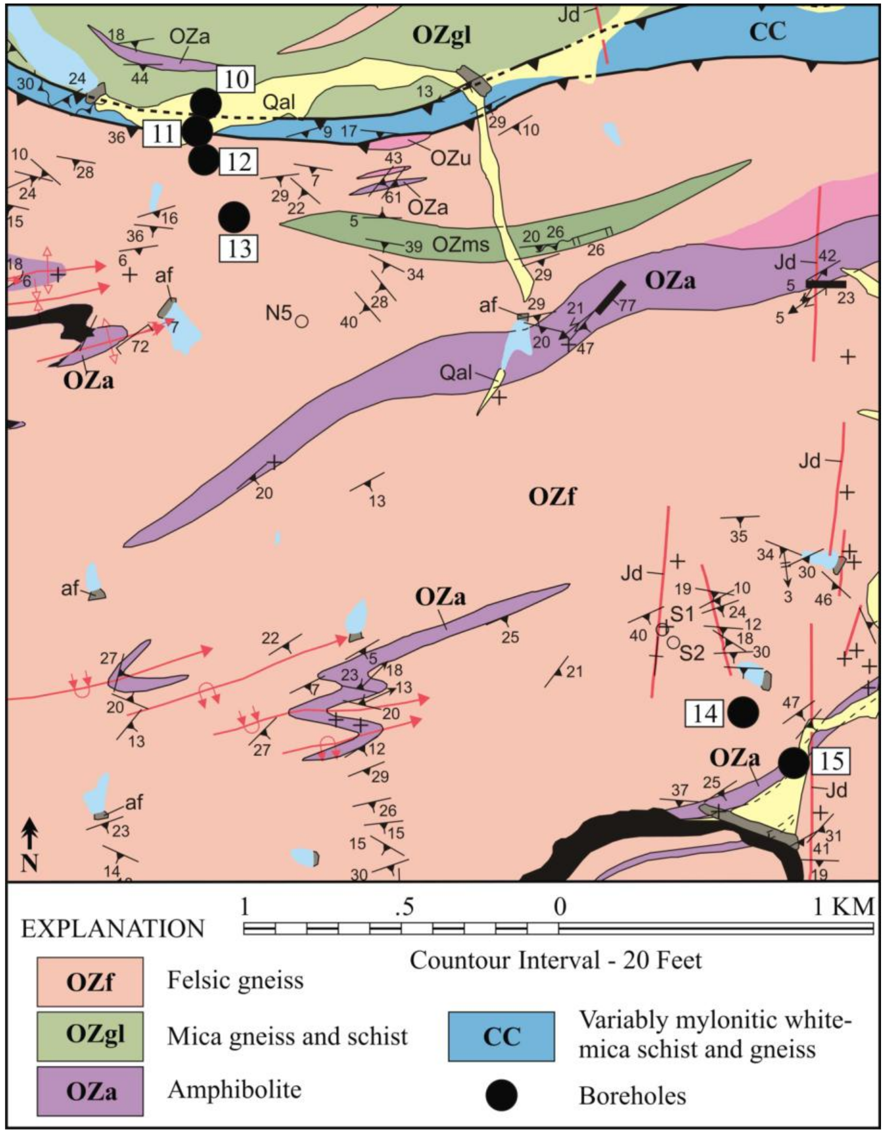


Figure 5: Geologic map showing the location of the Upper Piedmont Research Station site within the Milton Terrane (Modified from Horton and Geddes, 2006).

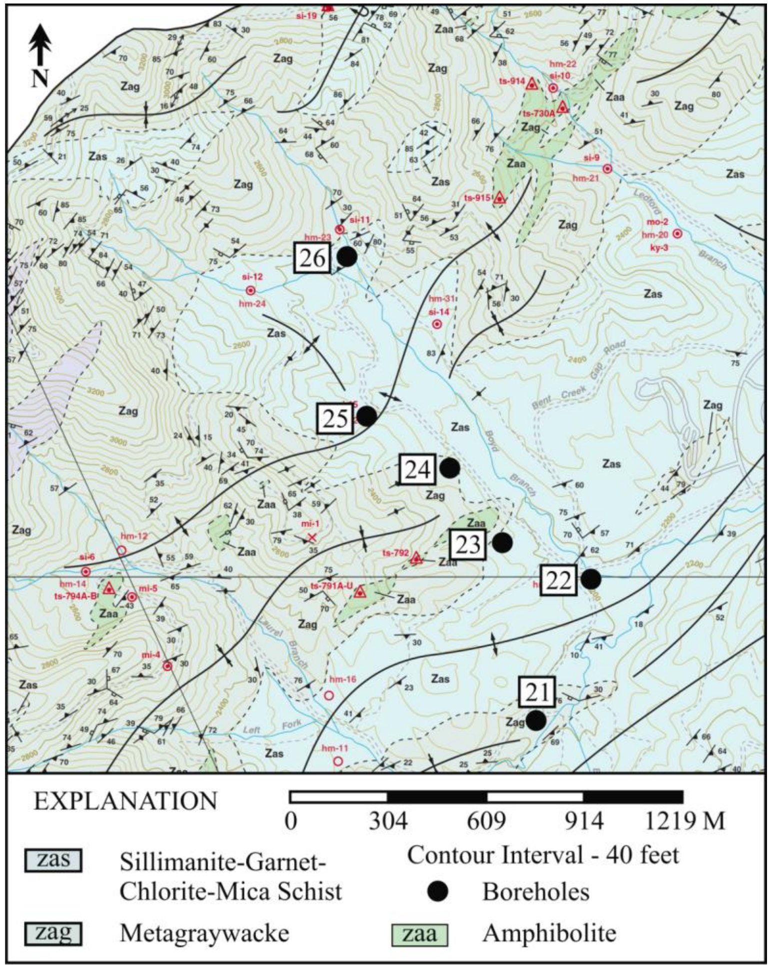


Figure 6: Geologic map showing the location of the Bent Creek Research Station site within the Ashe Metamorphic Suite of the Tugaloo Terrane (Modified from Merschat and Carter, 2002).

2.3 Methods

2.3.1 Borehole logging

Borehole logs were acquired from the Piedmont and Mountains Resource Evaluation Program (PMREP). Borehole logs had previously been interpreted for fractures and foliation, however, inconsistencies in the number of logs used to identify fractures intersecting boreholes may have caused bias for comparison purposes. In some cases, USGS workers utilized six logs to investigate a single borehole, and in other cases only utilized two. If the same criteria are not used to identify fractures intersecting each borehole, comparison of fractures intersecting multiple boreholes may be questionable. By re-analyzing the borehole logs, using the same type of logs for each borehole, a more accurate comparison of fracture characteristics in rocks with similar lithologies and foliation can be established.

For this study, a complete suite of borehole logs consists of optical televiewer (OTV), caliper and heat pulse flow meter logs. Video logs were also acquired to aid in the identification of fractures for boreholes 1-9 (Table 2). In addition to the borehole logs previously acquired by the USGS scientists, 20 more logs were acquired for boreholes drilled in the Raleigh Terrane and the Carolina Terrane (Table 3). Despite these efforts, some heat pulse flow meter and video logs were unavailable for this study (Table 2).

Borehole logs were used to characterize fracture attributes, distributions as well as the hydraulic properties of fractures in the shallow subsurface. Each tool that was used to acquire the logs was mounted to a winch system and suspended over the borehole with a tripod pulley system. Log depth was adjusted in the logging software for each tool before acquisition to account for the length of casing above the land surface as well as different lengths of each probe. The data were saved, and could be viewed as they were collected using the programs MSLog, MSHeat and WellCAD. The winch, computers and submersible pump was powered by a generator in the field.

The OTV, R-Cam1000 and caliper tools were used to identify appropriate intervals for flow logging. The OTV is a magnetically oriented camera that takes a 360-degree continuous image of the borehole wall (Fig. 7). Whereas the OTV offers a still image of the borehole wall, the R-Cam1000 provides real time video of the borehole. The R-Cam1000 has a down-looking as well as a side-looking camera that can be toggled between the two views to investigate the borehole wall in more detail. The caliper tool is a three-armed device that is used to measure the diameter of the borehole wall in its entire length. The heat pulse flow meter measures vertical flow in the borehole and is operated with a deformable disk to block flow in the annulus around the cylindrical measurement section of the probe. The single largest source of error is associated with in-effective blocking of the annulus of the borehole (Pallet, 1998). Therefore, the OTV, R-Cam1000 and caliper tools were used to identify appropriate intervals of borehole where the deformable disk would have maximum annulus blockage.

The aquifer was stressed using a 1/2 horsepower variable frequency drive (VFD) Grundfos submersible pump. After quasi-steady state was achieved, heat pulse measurements were acquired. Quasi-steady state is when minimal change in hydraulic head is observed in the pumping well. It may be impossible to achieve steady state in a reasonable amount of time, so quasi-steady state is assumed. The standard operating procedures (SOP) were followed for the Piedmont and Mountains Resource Evaluation Program (PMREP) to avoid well contamination (NCDENR, 2002).

Table 3. Logs that were collected by the USGS – ✗ and logs that were collected by Nixon - ✓. N/A indicates that the log has not yet been collected.

Terrane	Site	Well	OTV	Caliper	Video	Heat Pulse
Raleigh	Lake Wheeler	1	✗	✗	✓	✗
		2	✗	✗	✓	✗
		3	✗	✗	✓	✗
		4	✗	✗	✓	N/A
		5	✓	✓	✓	N/A
Carolina	Duke Forest	6	✓	✓	✓	N/A
		7	✓	✓	✓	✓
		8	✓	✓	✓	N/A
		9	✓	✓	✓	N/A
Milton	Upper Piedmont Research Station	10	✗	✗	N/A	✗
		11	✗	✗	N/A	✗
		12	✗	✗	N/A	✗
		13	✗	✗	N/A	✗
		14	✗	✗	N/A	✗
		15	✗	✗	N/A	✗
Charlotte	Langtree Peninsula	16	✗	✗	N/A	✗
		17	✗	✗	N/A	✗
		18	✗	✗	N/A	✗
		19	✗	✗	N/A	✗
		20	✗	✗	N/A	✗
Tugaloo	Bent Creek	21	✗	✗	N/A	✗
		22	✗	✗	N/A	✗
		23	✗	✗	N/A	✗
		24	✗	✗	N/A	✗
		25	✗	✗	N/A	✗
		26	✗	✗	N/A	✗

2.3.2 Processing and interpreting borehole logs

The software program WellCAD was used in the acquisition and analysis of borehole logs in this study. Logs from each well were imported into the program and were depth calibrated using a known marker, such as the bottom of the casing. Once the logs were calibrated, fractures were identified in the borehole logs.

Fractures traces were then created from the fractures that were identified in the OTV images in WellCAD. The fracture traces appear as sinusoids with varying amplitudes and phase shifts in the structure logs (Fig. 7). Since the OTV image is magnetically oriented, fracture azimuth was easily calculated by using the dip direction of the fracture. The amplitude of the fracture trace was used to compute the dip of the fracture. Dip directions were converted to strike using the right hand rule convention, providing strike and dip data for the construction of lower-hemisphere equal-area stereonet plots. Fracture aperture was measured by adjusting the width of the fracture trace as observed in the OTV image.

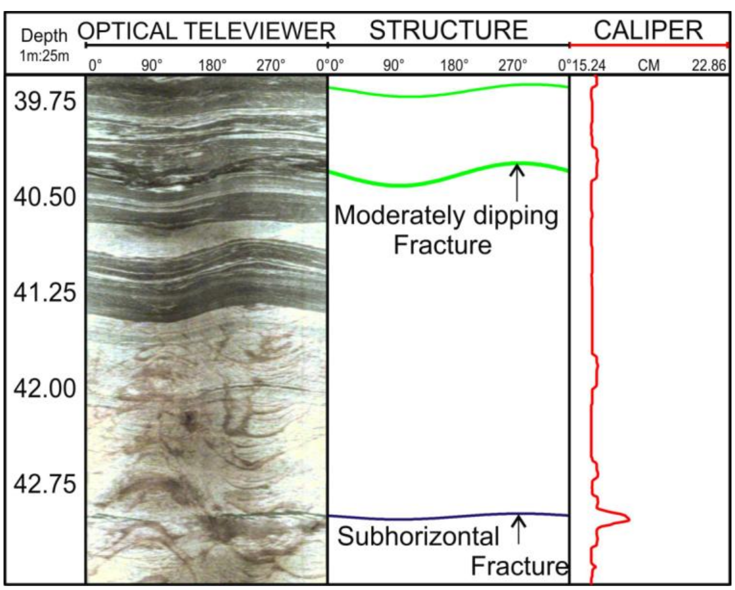


Figure 7: Example of 4-m section of optical televiewer (OTV), structure and caliper log.

Fractures were classified into three categories: foliation parallel fractures (FPFs), sheet joints or other fractures. Fractures that appear to be parallel to the dominant foliation in OTV images were classified as FPFs. Fractures that have dips less than 25 degrees and do not appear to be parallel to foliation were assumed to be sheet joints, whereas fractures that have dips greater than 25 degrees and are not parallel to foliation were labeled other fractures. Other fractures may include joints and faults because there is no way to verify from visual inspection that these features are actually small scale faults.

Foliation parallel fractures and dark foliation bands could easily be confused due to small color contrasts between dark foliation bands and open fractures. To distinguish FPFs from foliation bands, the caliper log was used to verify the presence of a fracture identified in the OTV image. However, hairline FPFs were typically not detected by the caliper tool. Therefore, fractures were recorded as such only when they were confirmed in multiple logs of the same well (Fig. 7).

The poles of fracture attitudes were plotted in lower-hemisphere equal-area stereonets to distinguish major fracture sets such as gently and steeply dipping fractures. The orientation of fractures within a producing interval was visually assessed. When stereonet plots of productive intervals are paired with fracture intensity plots, the type and attitude of fractures, through which fluid is flowing, is evident.

Fracture intensities were calculated by dividing the total number of fractures intersecting a wellbore by the length of open borehole. However, the cumulative intensity for a group of wells was computed by first dividing the borehole into 15 m intervals. Then, the sum of fractures within corresponding 15 m intervals was divided by the sum of the lengths of the overlapping intervals.

Heat pulse flow meter logs were used to estimate relative interval transmissivity, which is the proportion of total flow within a borehole that is contributed by specific intervals in the borehole (Paillet, 1998). This approach assumes that the flow rate is proportional to the transmissivity of flowing intervals under quasi-steady state conditions. This technique is semi-quantitative because the exact depth of the interval is given precisely but the transmissivity is given qualitatively. Flow logs, collected using the heat pulse flow meter during pumping by researchers from the United States Geological Survey (USGS), were used to develop flow intervals. Flow interval boundaries were interpreted where appreciable shifts in flow magnitude were observed. The flow interval boundary is placed at the measurement depth below the measurement that showed an appreciable change in flow magnitude. Borehole flow magnitude was calculated by taking the average of flow measurements within each interval. The contribution to the total flow from each individual interval was determined by taking the difference in flow from adjacent flow intervals. Flow from each interval is assumed to originate from fractures identified in OTV and caliper logs intersecting the length of borehole between flow measurements.

Flow intervals represent a group of fractures intersecting the length of borehole between heat pulse flow measurements and are either contributing to or taking away from flow during pumping within the borehole. Relative interval transmissivity refers to the transmissivity of each flow interval based on flow rate from other intervals within the same borehole. By dividing the contribution of flow from each interval by the pumping rate, and multiplying the result by 100, the relative interval transmissivity is given in percent (Pallet, 1998). This analysis allows for a preliminary hydraulic analysis of individual boreholes by utilizing borehole flow measurements.

Note that the flow measurements collected by workers from the USGS were most likely taken where the deformable disk would have had a maximum annulus blockage. Ideally, fractures should be targeted individually to investigate their contribution to borehole flow.

However, the selective procedure in which flow measurements were taken provides little insight about the hydraulic character of individual fractures. The only distinction that can be made is how much flow is attained or lost from each group of fractures intersecting the borehole between flow measurements.

2.3.3 Limitations

Limitations to the techniques applied in this study include the following: (1) vertical fracture sets are not observed because boreholes are vertical. If vertical fracture sets do exist, sampling outcrops near the boreholes may help aid in the identification of these sets. (2) If appreciable flow originates from all depths of a borehole, a bounding depth of flow cannot be determined from that borehole. This may be a factor of the borehole not being deep enough to yield a bounding depth of groundwater flow or the presence of a fault in the vicinity of the borehole. (3) The depth that flow measurements are taken is heavily relied upon in determining the boundaries of flow intervals. By taking flow measurements closer to individual fractures, more accurate depths of flow interval boundaries may be determined. In the face of these limitations, this technique provides a quick and inexpensive method to analyze the general hydraulic properties of bedrock wells using data that is easily collected if not already available.

This study specifically investigates fractures in the absence of faults. It is known that features such as fault zones may alter the natural fracturing of crystalline rock with depth. Steeply dipping faults have been known to connect isolated fracture clusters at depth to shallow aquifer systems. However, the boreholes investigated in this study were not drilled in the vicinity of such structural features. Therefore, the natural fracturing of rock with depth is investigated outside of the influence of faults.

2.4 Results

2.4.1 Fractures

There were 570 fractures identified and measured in 26 bedrock wells investigated in this study. A total of 2,288 m of borehole were analyzed with an average fracture density of 0.25 fractures per meter. Sheet joints consist of 26%, FPF's comprise 42%, and other fractures are 32% of all fractures. The number of fractures intersecting boreholes ranges from 8 to 64 fractures per well. The average depth of the studied wells is 108 m, ranging in depth from 67 m for the shallowest borehole to 183 m for the deepest borehole (Table 1). The depth of casing extending from the land surface to open borehole ranged from 12 to 31 m below the land surface, averaging 20 m.

The majority of fractures observed intersecting boreholes drilled into andesitic-basaltic volcanic flows are classified as other fractures, comprising 87% of the total. Sheet joints comprise the remaining 13%. Fractures classified as other generally strike NW-SE and dip to the SW and NE (Fig. 8).

The dominant fracture type identified intersecting boreholes drilled in diorite rocks is other fractures, consisting of 67% of the total. Sheet joints comprised 26% and FPFs accounted for the remaining 7%.

The most common fracture type observed in the felsic gneiss rock type is sheet joints, consisting of 46% of the total fractures identified. FPFs are the second most common fracture observed, consisting of 41% of the total. The remaining 13% are other fractures. FPFs strike NE-SW and dip to the SE, generally consistent with the orientation of the foliation (Fig. 8).

Boreholes drilled into Gneiss and Amphibolite rock types yielded similar fracture occurrences as the gneiss and mylonite rock type. FPFs consisted of 81% and the remaining

19% are classified as other fractures.

The dominant fracture type intersecting boreholes drilled in Gneiss and Mylonite are FPFs, consisting of 92% of the total. The remaining 8% are classified as other fractures. A mylonitic shear zone is interpreted to intersect boreholes MT-N3D and MT-N4D as evidenced by the increase in fracture intensity at an approximate depth of 45-55 and 60-70 m respectively. FPFs are the dominant fracture type in Mafic Gneiss, accounting for 84% of the total. Sheet joints account for the remaining 16%.

FPFs are the dominant fracture type identified in schistose rocks, consisting of 57% of the total. Fractures classified as other account for 33% and the remaining 9% are sheet joints. Two dominant fracture sets are observed in the schist rock type. Stereonets show that FPFs are clustered and strike NE-SW, moderately dipping to the SE and NW (Fig. 8).

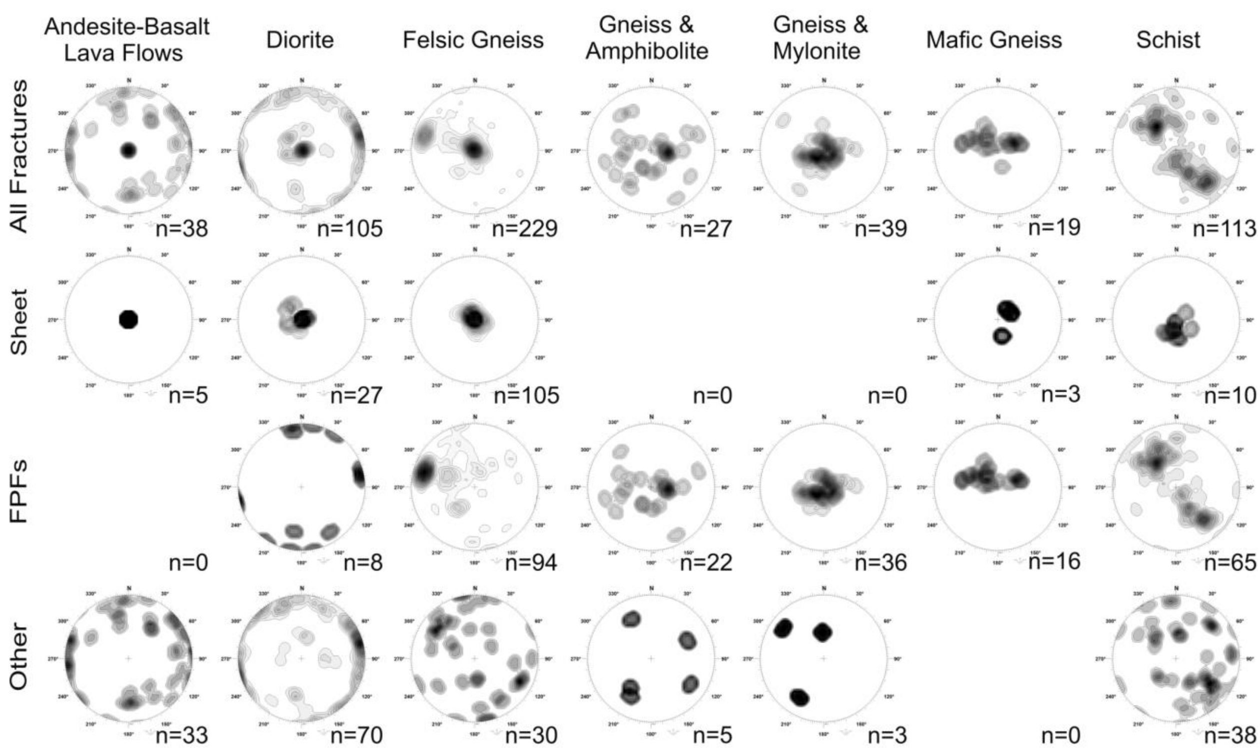


Figure 8: Lower-hemisphere equal-area stereonet of poles to fracture planes identified from OTV logs. Contour interval = 1%.

2.4.2 Distribution of fractures with depth

One of the major goals of this study is to determine fracture occurrence, type and separation with depth. The data presented here demonstrate that the occurrence of fractures decreases with increasing depth into the subsurface of these crystalline rocks (Fig. 9).

Fracture spacing is the perpendicular distance between fractures of the same set (e.g. have similar orientations). However, fracture separation is the distance between any two adjacent fractures, regardless of its orientation. Fracture separation in boreholes is equivalent to the slope of the depth versus fracture intensity curve. The slope of the curve for all fractures in the cumulative fracture intensity versus depth plot is gentle in the upper parts of most boreholes but steepens with depth beginning at ~40 m, suggesting that fracture separation increases with depth (Fig. 9).

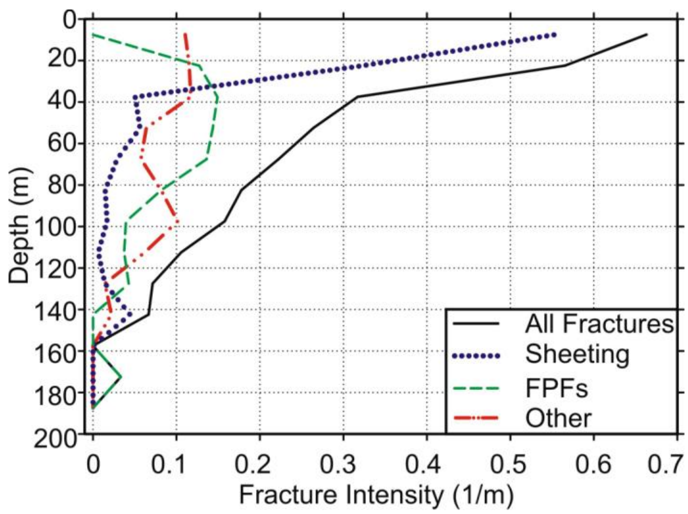


Figure 9: Composite plot of normalized fracture intensity for the different fracture types identified in the study area. In general, the normalized intensity for all fracture types decreases with depth.

When the occurrence of fractures is considered in terms of fracture type, the results indicate that sheet joints are the most common fracture type in the upper 40 m of the shallow subsurface. FPFs dominate between 40 and 80 m, whereas other fractures are the most common fractures identified from 80 to 120 m. Below 120 m, all fracture types appear to be present but at very low intensities (<0.05 m^{-1}).

2.4.3 Distribution of fracture apertures

The largest fracture apertures for sheet joints and FPFs are generally confined to depths <60 m (Fig. 10). In general, FPFs have the largest fracture apertures. These apertures are as wide as ~170 mm, whereas the largest apertures for sheet joints are <120 mm. The largest apertures of other fractures are less than 50 mm, and the peaks in fracture aperture are not restricted to depths shallower than 60 m. Even though FPFs possess the widest fractures, sheet joints have the widest fractures at depths shallower than ~40 m.

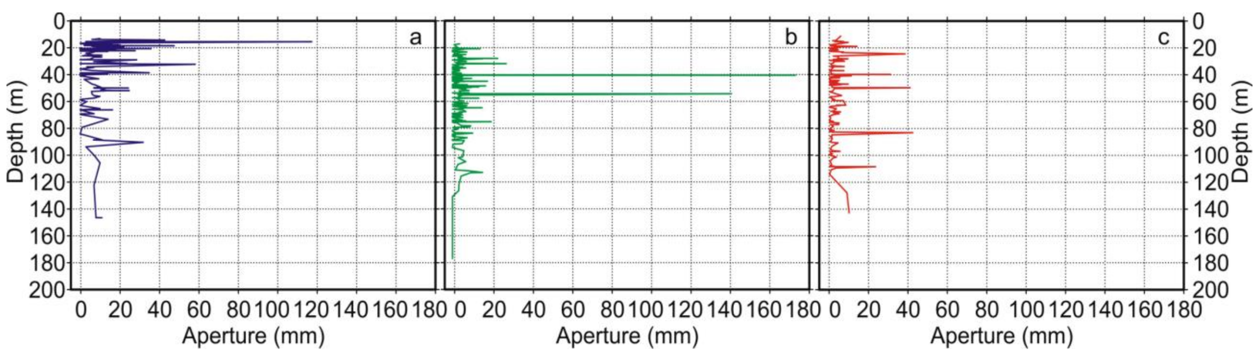


Figure 10: Fracture aperture distributions with depth of (a) sheet joints, (b) FPFs, and (c) other fractures.

2.4.4 Groundwater flow

Flow measurements obtained from boreholes drilled in the felsic gneiss, wells 1-3 (Table 2), suggest that more than 90% of flow is derived from a depth interval of 0 - 70 meters (Fig. 11). Flow interval analysis for well 7, (Table 2), indicates that flow is derived from various locations throughout the borehole (Fig. 12). More than 50% of flow was derived from the bottom half of this well, at depth ranges of approximately 59 - 86 m. Flow measurements taken in the upper section of the well were discarded due to large measurement errors, attributing to the presence of a breakout in the borehole. Mafic Gneissic rock types derive flow from a depth shallower than 65 m. Gneissic and Mylonitic rocks derive all flow from a depth shallower than 75 m. Flow measurements of boreholes installed in Gneissic and Amphibolitic rock types suggest that more than 90% of flow is attained from a depth shallower than 50 m (Fig. 13). Over 90% of flow from boreholes installed in the diorite rock type derives flow from a depth less than 180 m. However, more than 80% of flow originates from a depth shallower than 70 m (Fig. 14).

Flow intervals developed for schistose rock types indicate that five out of six boreholes derive more than 90% of flow from a depth shallower than 50 m. The remaining borehole, TT-2D, attains 75% of flow from a depth shallower than 25 m and the remaining 25% from fractures at or near the bottom of the well bore (Fig. 15).

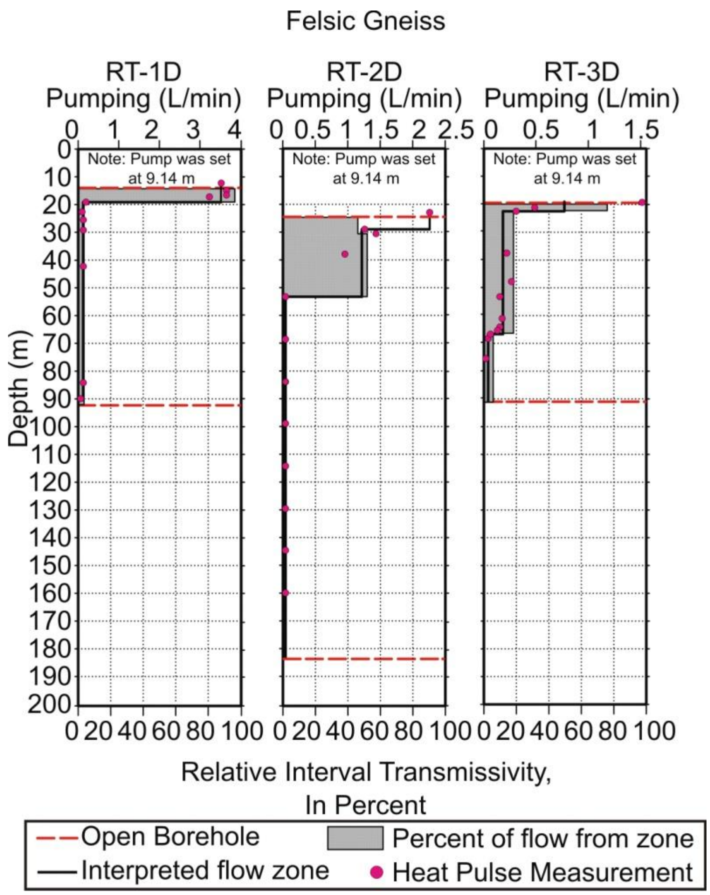


Figure 11: Pumping flow measurements and relative interval transmissivity in percent of interpreted flow intervals in boreholes drilled in felsic gneiss rocks of the Raleigh Gneiss, Raleigh Terrane.

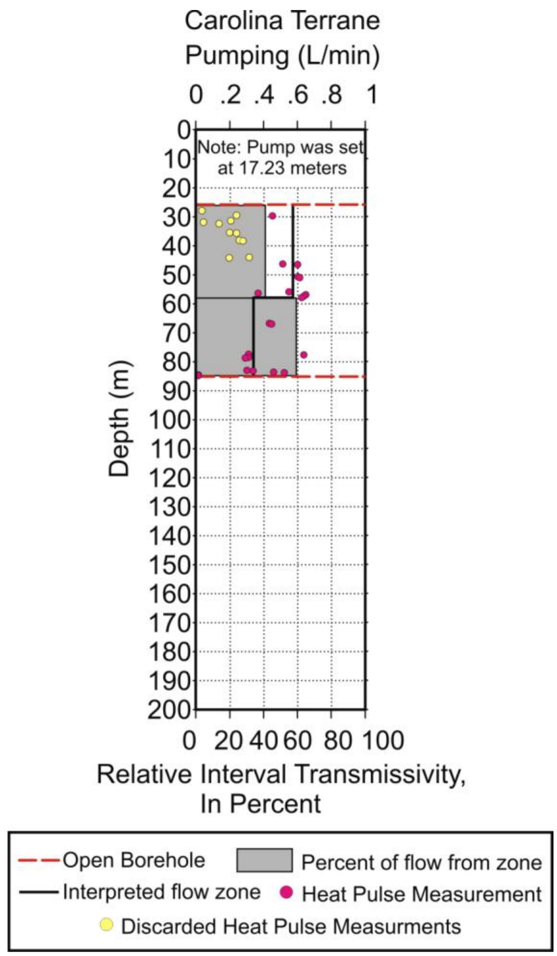


Figure 12: Pumping flow measurements and relative interval transmissivity in percent of interpreted flow intervals in boreholes drilled in intermediate-mafic volcanic flows within the Virgilina sequence, Carolina Terrane.

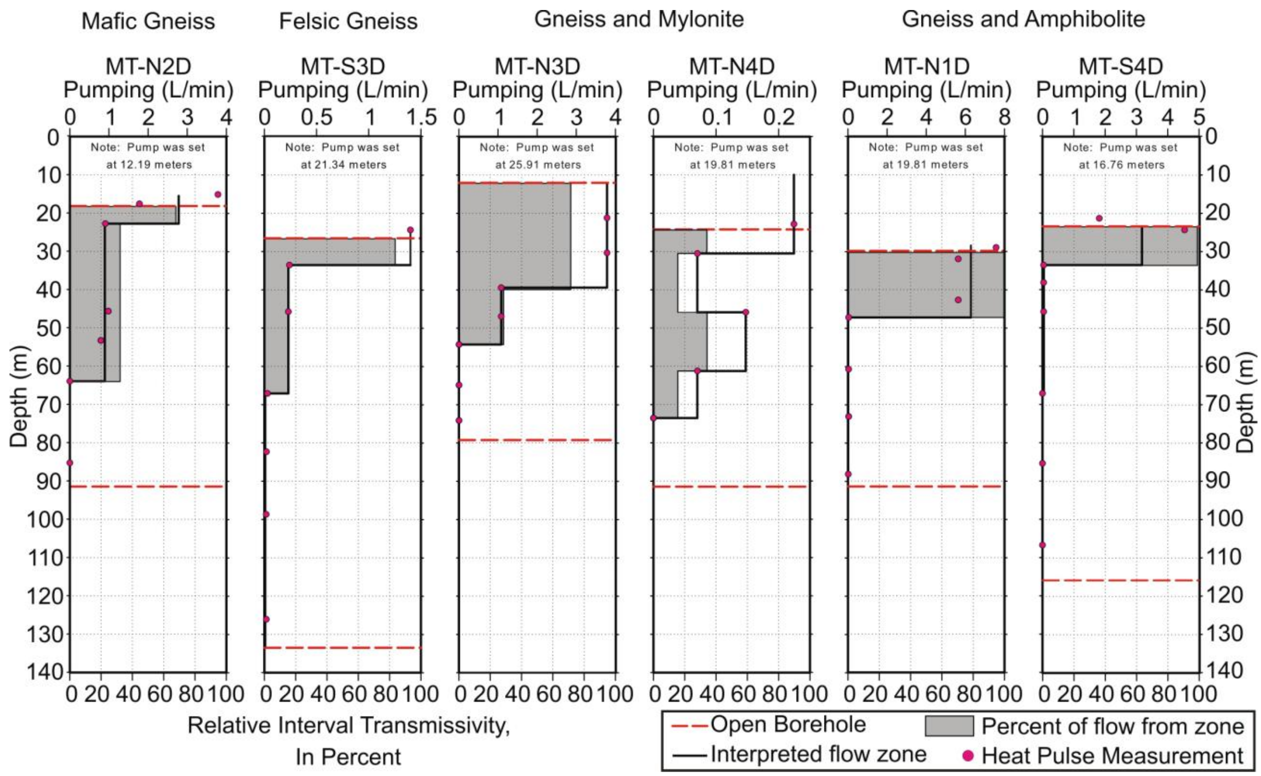


Figure 13: Pumping flow measurements and relative interval transmissivity in percent of interpreted flow intervals in boreholes drilled in mafic gneiss, felsic gneiss, gneiss and mylonite, and gneiss and amphibolite rock types within the Milton Terrane.

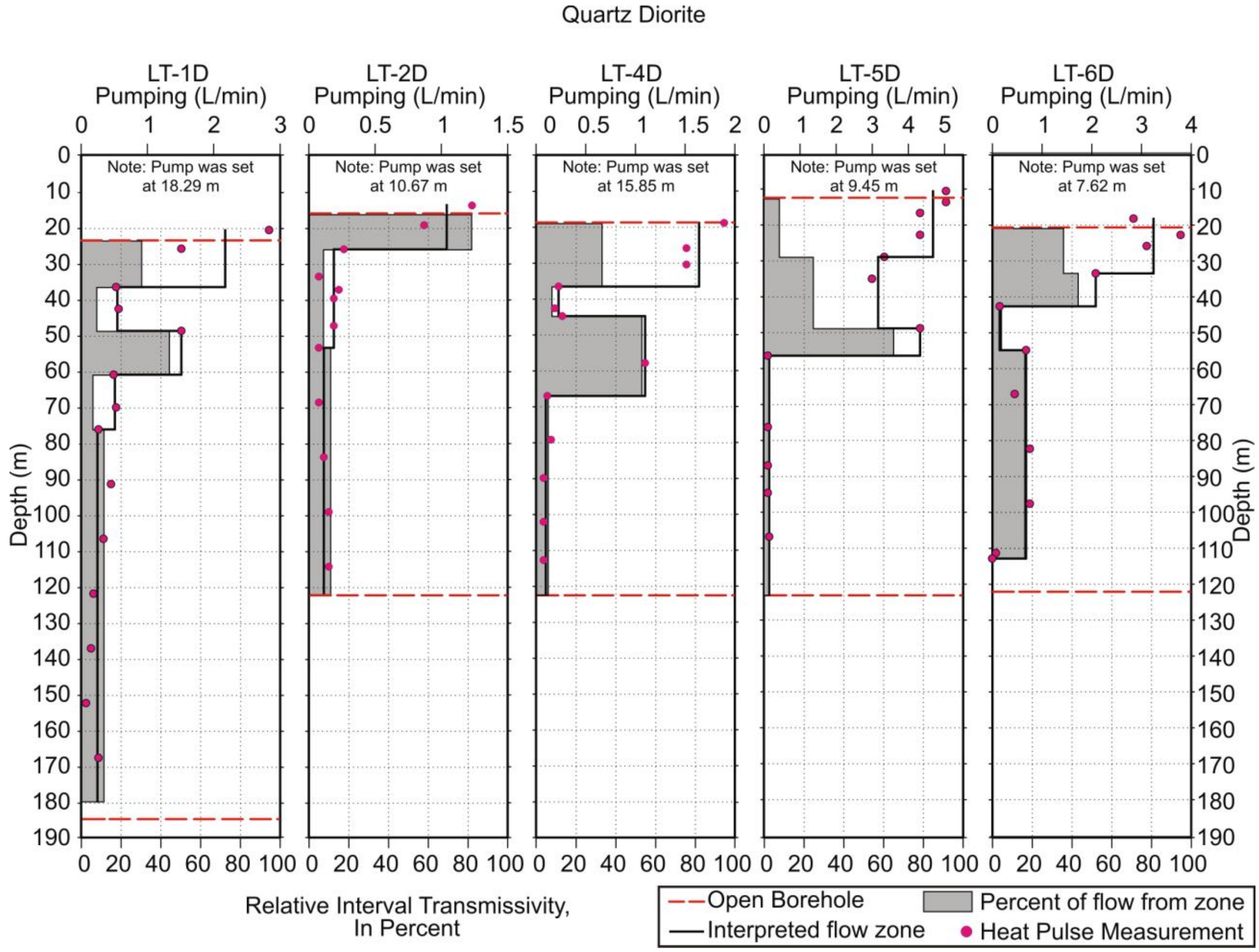


Figure 14: Pumping flow measurements and relative interval transmissivity in percent of interpreted flow intervals in boreholes drilled in quartz diorite rock type in the Older Plutonic Complex within the Charlotte Terrane.

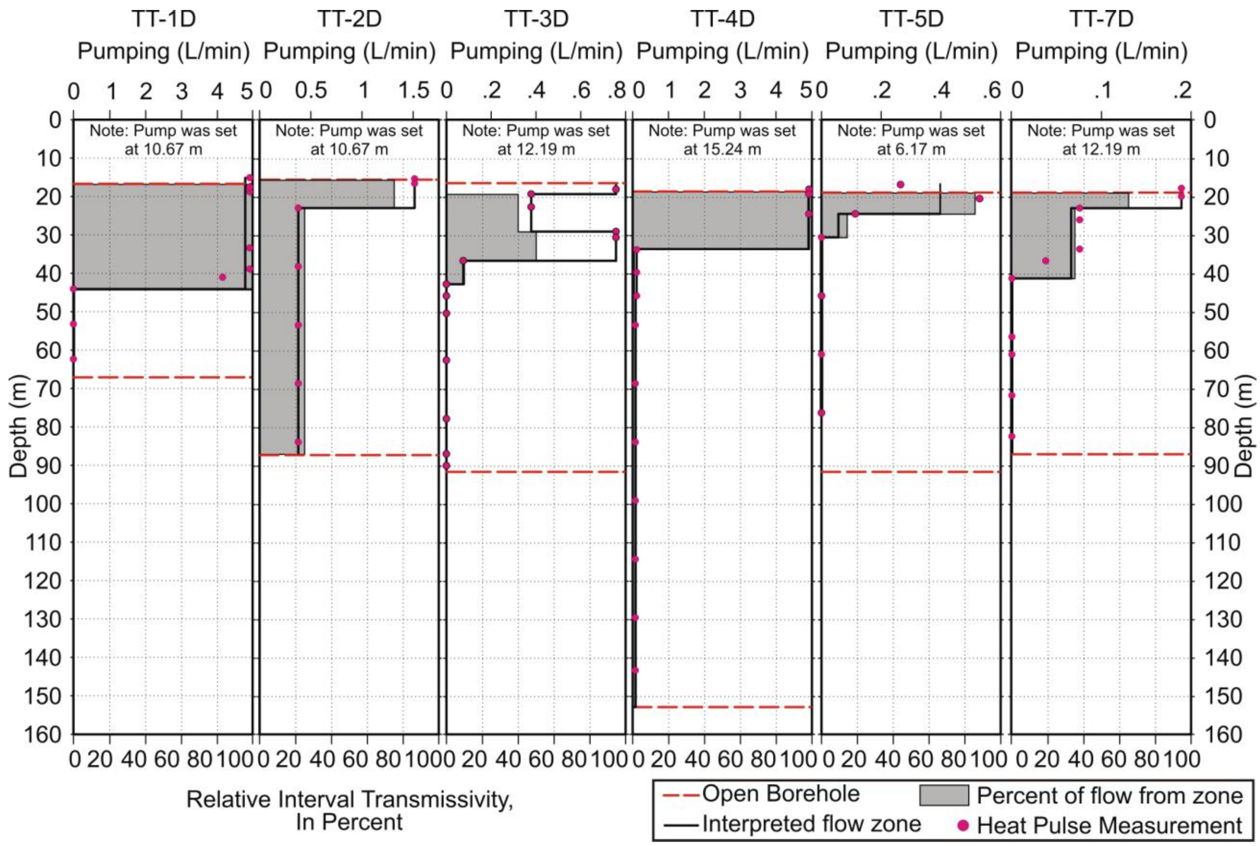


Figure 15: Pumping flow measurements and relative interval transmissivity in percent of interpreted flow intervals in boreholes drilled in the schistose rocks of the Ashe Metamorphic Suite, Tugaloo Terrane.

The majority of flow (80%) is acquired from fractures shallower than 75 meters for all rock types (Figs 11-15). This interval corresponds to the depths where fractures were the most abundant as well as where fracture apertures were the widest for sheet joints and foliation parallel fractures. All boreholes installed in the felsic gneiss rock type attain more than 90% of flow from a depth shallower than 70 m (Figs. 11 & 13). All flow from a borehole installed in mafic gneiss (well 11) is acquired from depths shallower than 65 m (Fig. 13). Over 90% of flow is derived from a depth shallower than 50 m from boreholes drilled in the gneiss and amphibolite rock type and less than 75 m from boreholes drilled in the gneiss and mylonite rock type (Fig. 13). More than 90% of flow is attained from fractures intersecting boreholes installed in the diorite rock type from a depth less than180 m. However, more than 80% of flow originates from a depth shallower than 70 m (Fig. 14). Boreholes installed in schist rock types attain 90% of flow from a depth shallower than 50 m. However, one borehole, TT-2D, gains up to 90% of flow from a depth shallower than 87 m (Fig. 15).

2.5 Discussion

The migration of groundwater in crystalline rocks depends on the existence and interaction of open fractures. Potential fluid pathways were recognized by measuring the occurrence and aperture of fractures. The presence of fault zones have been known to alter fracture occurrence with depth and by doing so, altering the hydraulic properties of wells near these features (Barton et al., 1995; Seaton and Burbey, 2005). Boreholes investigated in this study are not in the vicinity of known faults and therefore should reveal the natural fracturing of rock with depth. This in turn should give insight to how groundwater migrates within fractured bedrock aquifers outside the influence of these features.

The dominant fracture type that controls flow in the shallow subsurface depends in part on the geologic history, and the degree of development and orientation of planar fabric. Due to most of these rocks possessing planar fabric, it is not surprising that FPFs are an important fracture type in channeling flow. Although FPFs are the most abundant fractures overall, sheet joints appear where the majority of flow is observed, and therefore most likely play a large role in controlling fluid flow. However, where foliation is oriented sub-horizontal to the land surface, FPFs prefer to develop along these planes of weakness and in turn play a large role in controlling the groundwater flow regime. This was found to be true in a field study conducted in crystalline rock aquifers of Massachusetts (Boutt et al., 2010). Rocks possessing foliation that is steeply dipping may develop steeply dipping FPFs as well as shallow dipping sheet joints. The fracture type that controls flow in the shallow subsurface of these rocks may therefore be a combination of the two fracture types. Manda et al., (2008) suggests that fractures with long trace lengths (such as sheet joints) and closely spaced fractures (such as FPFs) may form well connected networks of fractures that influence the permeability of fracture rock aquifers. Massive rocks do not have strong penetrative fabrics and therefore do not develop FPFs. Instead, sheet joints or other fractures are likely to dominate groundwater flow in such rocks.

A high intensity of fractures is observed in the upper 80 m of boreholes, suggesting that these fractures are closely spaced and may therefore enhance the connectivity of fracture networks at shallow depths more so than networks below 80 m, where the fracture intensity decreases (Fig. 9). Sheet joints are the most common fracture type observed in the upper 40 m of boreholes. Below 40 m, FPFs and other fractures are the most common and thus are probably responsible for controlling flow below 40 m. Where FPFs and other fractures dominate, these fractures tend to have larger spacing. Large separation distances suggest that fractures may be poorly connected to other fractures in the network.

Fractures must have non-zero apertures in order to transmit fluids in the subsurface. However, as suggested by the fracture aperture versus depth plots (Fig. 10), this ability appears to generally diminish with increasing depth. This is especially true for sheet joints. Interestingly, there are fractures with appreciable aperture that are observed in deeper sections of boreholes and may indicate that these fractures are critically stressed (Barton et al., 1995). Just because a fracture has an aperture does not mean it is hydraulically active and there is no way of discerning whether a fracture is hydraulically active from OTV images. Therefore, fracture apertures reported are mechanical fracture apertures, not hydraulic apertures.

The majority of flow (80%) is derived from the upper 75 m of all studied boreholes under pumping conditions, where the highest fracture intensities and largest apertures are observed. A study investigating the depth evolution of groundwater flow in fractured crystalline rocks in Massachusetts suggested that the number of hydraulically active fractures in boreholes is proportional to the number of fractures present (Boutt et al., 2010). Therefore, the interval where the highest fracture intensities and largest fracture apertures are observed is the interval where one should expect to observe the highest flow rates, which in this case is the 0-75 m depth interval.

The suggestion of a bounding depth does not mean that water supply wells should only be drilled to 75 m in crystalline rock aquifers. If sufficient yields cannot be obtained from wells that are shallower than 75 m, drilling deeper could still be useful as additional well storage would be provided to meet demand. Furthermore, depending on the Geology, it is possible that a water bearing feature (e.g. a fault or shear zone) may be intersected at depth that would improve the yield of a well. It should also be noted that the bounding depth of 75 m as suggested in this research may not be universally applied in other regions with different rock types and geologic histories. Additional research would therefore have to be conducted to determine the bounding depths in crystalline rock aquifers elsewhere.

2.6 Summary and Conclusions

The distributions, characteristics and contribution to borehole flow of 570 fractures intersecting 26 bedrock wells in North Carolina were determined using optical televiewer (OTV), caliper and heat pulse flow meter logs. The boreholes are located in five litho-tectonic terranes, intersecting seven major plutonic, volcanic and metamorphic rocks. Multiple sites were utilized to investigate the natural fracturing of rock with depth in order to increase confidence in the results obtained from the study.

Three major fracture types, consisting of sheet joints, foliation parallel fractures (FPFs), and other fractures, have been recognized to contribute to the hydraulic properties of crystalline rock aquifers in North Carolina. FPFs represent the majority of fractures observed in these rocks, accounting for 42% of the total. Sheet joints account for 26% and the remaining 32% are classified as other fractures.

The major conclusions derived from this work are as follows.

- Sheet joints are the most common fracture type where the highest flow is observed and are probably responsible for controlling flow in the shallow subsurface.
- Overall, fracture intensity and aperture decrease with increasing depth and as a result, the relative interval transmissivity decreases with depth.
- Fracture separation increases with well depth, suggesting a decrease in fracture connectivity with depth.
- Borehole flow logs during pumping suggest that the majority of flow (80%) is attained from a depth shallower than 75 m.

The presence of sheet joints, fractures with high intensity, and fractures with large apertures in the shallow subsurface suggests that fracture networks in this zone not only have high connectivity but have higher relative transmissivity than networks at depth. This does not go to say that fractures at depth could not be significant contributors to groundwater flow, however, data from this study support this interpretation.

CHAPTER III: PREVIOUS AND FUTURE WORK

3.1 Previous work

Fracturing is a general term used to describe the brittle deformation of a rock mass. Extension fractures occur when a rock mass experiences stresses greater than the tensile strength of the grains or crystals that compose the rock. Fractures can range in scale from microfractures, with dimensions of microns, to lineaments, with dimensions on the order of kilometers (Seeburger, 1982). Factors that influence fracturing include, but are not limited to, rock type, lithology, metamorphic grade, degree of foliation, foliation orientation, grain or crystal size, competency contrast between adjacent layers, and folding and faulting. In light of these factors, fracture intensity and aperture are still thought to follow the general trend, decreasing with increasing depth (Snow, 1968).

Dilation strain causes rocks to fracture and is called jointing (Pollard and Ayden, 1988). Joints produce no appreciable offset between opposing rock faces. Massive rocks, such as granitic plutons, act in a brittle way near the surface of the earth, where temperatures and pressures are much lower than where these rocks cool and crystallize. Horizontal jointing near the surface is attributed to rock expansion in response to erosional unloading. This type of jointing is known as unloading or sheet jointing. Sheet joints are likely to be concentrated near the surface and tend to be spaced much wider apart as depth increases (Jahns, 1943).

One of the first observations of joint structures in relation to depth in crystalline rock was pointed out by Crosby (1881). Crosby noted that vein miners commonly noticed the jointed structure of the rock would fade away and disappear in the deeper parts of mines. Crosby theorized that weathering was the primary reason for open joint structures near the surface. He suggested that the structure of the rock at depth may still be just as traversed by joints, but because no force had made them apparent, the faces of the blocks adhered as if no structure existed. Another early study, by Meinzer (1923), pointed out that wells drilled into crystalline basement rocks yielded less water than shallower wells placed in sandstones and other surficial aquifers. Meinzer suggested that this was due to the type of material as well as the stress state. He proposed that wells drilled into crystalline rock would have lower permeability values as depth increased. He attributed this decrease in well yield to increasing weight (i.e. stresses) of the overburden material. Data from later studies confirm this depth dependent permeability proposition. Legrand, 1954; Davis and Turk, 1964; Legrand, 1967; Snow, 1968, suggested that open joints contributing to groundwater flow was predominately found in the upper 100 to 150 meters of crust. It was also proposed that the existence of significant fractures are primarily controlled by geologic structure and weathering (Davis and Turk, 1964). Snow (1969) suggested a reason for decreasing well yields with depth; as depth increased, fracture occurrence decreased. Fracture aperture also was suggested to decrease in size; this was also attributed to increasing stress state with increasing depth.

After this groundwork was formed, focus began to shift to determine the factors that controlled flow within single fractures. Results obtained from laboratory studies showed that permeability values of fractures were sensitive to stress state. If a stress was applied to an open fracture parallel to the fracture orientation, the fracture would dilate, increasing the permeability. Also, if a stress was applied to the fracture perpendicular to the fracture orientation, the fracture would close, decreasing its permeability. Stresses of less than 10 MPa have the most effect on fracture closure (Bandis et al., 1983; Brown and Scholz, 1986; Hillis, 1998). These studies showed that fractures needed very little stress to begin to close, but as stresses were increased, closure slowed. This suggests that fracture stiffness increases as stress is applied. If stress can open or close a fracture based on its orientation to the dominant stress direction, knowledge of fracture orientation should enable quantitative assessment of permeability (Renshaw and Pollard, 1994).

It is necessary to quantify fracture location, direction and genesis in order to fully understand flow systems in fractured rock aquifers because these systems depend on secondary porosity, or fracturing, to permit flow (Pollard and Aydin, 1988). Fracture patterns in sandstones can be predicted to a certain degree of certainty; however, this has proven inadequate for crystalline rock as the fracture orientation and aperture are anisotropic (Zhang and Sanderson, 1995).

A field study characterizing fractures in outcrops attempted to provide upper bound estimates of the yield of a fracture network (Caine and Tomusiak, 2003). These methods can be fallible because fractures at the surface are not subject to the same stress conditions as those at depth (Vermilye and Scholz, 1995). Fractures in outcrops are also subject to more intensive weathering, which may give a false perception of fracture attributes at depth. To further complicate the outcrop mapping technique, Banks et al. (1992) conducted a fracture mapping study at an outcrop in a crystalline rock unit and compared them to fractures in a recently dug tunnel in the same unit. Banks found that flowing fractures at the surface were not present or contributing to flow in the subsurface.

A 20 year study was conducted by the USGS at Mirror Lake in New Hampshire to explore groundwater flow in a bedrock setting. This study focused on identifying fractures and fracture properties in outcrops (Barton, 1996), subsurface structure and hydrogeology using borehole geophysics (Johnson and Dunstan, 1998; Paillet, 1985; Paillet and Kapucu, 1989); and hydraulic and transport properties of fractures by means of hydraulic testing (Hsieh, 1996; Hsieh and Shapiro, 1996; Tiedeman and Hsieh, 2001). Fracture orientations mapped in outcrops were present in the same orientation in the subsurface. Hydraulic testing showed that crystalline rock aquifers cannot be compared to porous medium. They proposed that flow in these aquifers occurs in highly transmissive clusters, connected by less conductive fractures.

Overburden, topography and fracture anisotropy were found to have the greatest influence on groundwater flow in a modeling study conducted in crystalline rock (Harte and Winter, 1995). A study conducted in California showed that fracture mineralization can cause significant reductions in the overall permeability of a fracture network (Mabee and Hardcastle, 1997).

The studies mentioned above focus on fracture occurrence, fracture attributes and flow within fractures in the shallow crust and would not apply to the stress and temperature conditions found at greater depths.

3.2 Future work

Six additional field sites are available via the PMREP. These include:

- Pasour Mountain Groundwater Monitoring and Research Station - Gaston County, NC
- Allison Woods Groundwater Monitoring and Research Station - Iredell County, NC
- Morgan Mill Groundwater Monitoring and Research Station - Union County, NC
- NC Zoo Groundwater Monitoring and Research Station - Randolph County, NC
- Tater Hill Groundwater Monitoring and Research Station - Watauga County, NC
- Coweeta Groundwater Monitoring and Research Station - Macon County, NC

It would be beneficial to study the character of fractures in these crystalline rocks in order to add to this data set. The analysis of boreholes that do intersect major geologic features (i.e. fault zones) may be of interest to better evaluate their importance.

APPENDIX A: Southern Appalachian Geology

The Appalachian orogen is the northeast-trending belt of Mesoproterozic to Paleozoic rocks in eastern North American that was deformed during the Paleozoic (Fig. 1) (Rodgers, 1970). The structural grain of the orogen is surprisingly consistent, defining a series of harmonically curved promontories and embayments (Fig.1) (Hibbard, 2007). Lithotectonic divisions are used to distinguish rock affiliations that were either formed or deposited in a common tectonic setting during a finite time span (Hibbard, 2004). These divisions are scale dependent, reliant on the scale of the tectonic process considered. Lithotectonic divisions consist of the realm at orogen scale and the domain at the scale of two or less embayments (Hibbard, 2007). At yet smaller scale, terranes are recognized as regional subdivisions of a domain.

Crystalline rocks in North Carolina are part of the Southern Appalachians, defined as the rocks lying south of the New York promontory (Fig. 16). The Laurentian, Iapetan and peri-Gondwanan realms are represented here, all of which obtained their defining geologic character before the Late Ordovician (Hibbard, 2006). Neoproterozoic-Paleozoic rocks, native to Laurentia, define the western-most realm. The eastern margin is characterized by Neoproterozoic-early Paleozoic rocks of the peri-Gondwanan realm, which formed adjacent to Gondwana. Paleozoic Terranes of predominately oceanic and volcanic-arc affinity characterize the Iapetan realm and were caught between the Laurentian and peri-Gondwanan realms during Appalachian orogenesis (Fig. 16).

The Carolinia and Piedmont domains are present in North Carolina (Fig. 16). The surface exposure of the Carolinia domain extends from the Central Piedmont Shear Zone (CPSZ) to the fall line (Fig. 1), where it is onlapped by Cretaceous to Tertiary sediments of the Atlantic Coastal Plain to the east (Hibbard et al., 1998; Hibbard et al., 2002). The Piedmont domain begins at the

CPSZ and is tectonically severed from Laurentian rocks to the west along a series of faults termed the Hollins Line-Pleasant Grove fault system, named for the faults anchoring either end of the system. In terms of lithotectonic evolution, the Piedmont domain is one of the least understood of the Appalachian domains (Hibbard, 2007).

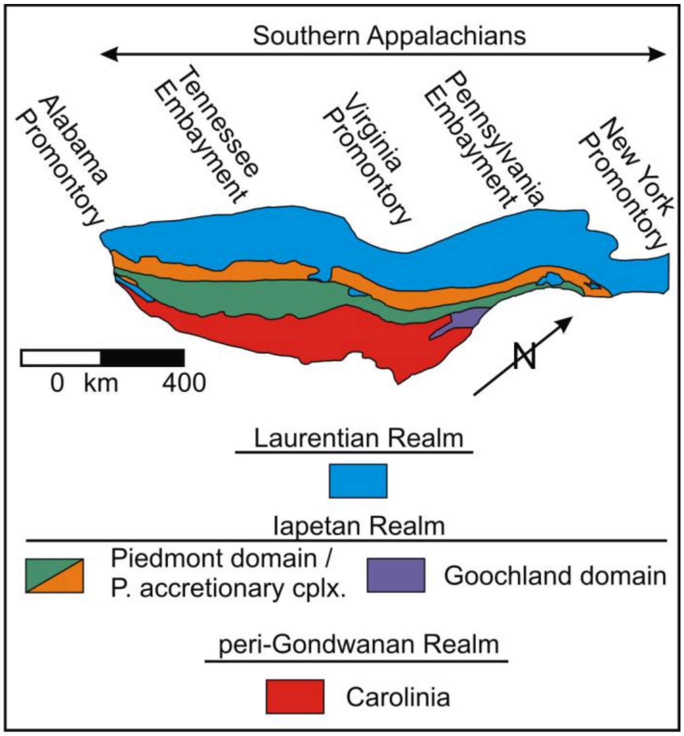


Figure 16. General geologic map depicting realms of the Appalachian orogen. Modified from Hibbard et al., (2006); Hibbard et al., (2009).

The Raleigh, Carolina and Charlotte Terranes are within the Carolinia domain while the Milton and Tugaloo Terranes are within the Piedmont domain (Hibbard et al., 2002; Hibbard, 2007). Rocks that compose these terranes range from weakly to moderately-foliated intrusives to granulite- to greenschist-grade, moderately- to well-foliated rocks and are representative of many crystalline bedrock aquifers throughout the world. Lithologic contacts and foliation are generally oriented in a northeast-southwest fashion, the result of the accretion of rocks and deformation during the Ordovician Taconic orogeny, the Silurian-Devonian Acadian orogeny, and the Carboniferous-Permian Alleghenian orogeny (e.g., Miller et al., 2006). Structures were modified and potentially reactivated by extension in the Triassic Period through opening of the present day Atlantic Ocean. One of the best known features resulting from rifting is the Mesozoic sedimentary basins, the largest forming along the eastern margin of the Carolina Terrane.

The Raleigh Terrane is composed primarily of Proterozoic rocks of amphibolite-facies, felsic schists and gneisses deformed during the early Paleozoic (Hibbard, 2002). Deformation fabrics in the Raleigh Terrane are consistent throughout the terrane, oriented to the NE-SW, moderately dipping towards the south-east (Chapman et al., 2007). The Raleigh Terrane is separated from the Crabtree and Falls Lake Terranes to the northwest by the Nutbush Creek fault zone and from the Spring Hope Terrane to the south and southeast by the Macon fault zone (Fig. 1). The Raleigh Terrane was metamorphosed and intruded by numerous granitic plutons, such as the Rolesville batholith, during the late Paleozoic Alleghanian Orogeny (Stoddard et al., 1991).

The Carolina Terrane is Proterozoic to early Cambrian in age and consists of mostly greenschist-facies metamorphic rocks, separated from the Raleigh Terrane by the Nutbush Creek fault zone (Horton et al., 1986; Hibbard et al., 2002). The Carolina Terrane is composed of thick sequences of intermediate to mafic volcanic and volcanogenic sedimentary rocks and intrusive plutonic rocks and in North Carolina encompasses the Virgilina, Albemarle and Cary sequences. The Carolina Terrane is separated from the Charlotte Terrane by the Gold Hill shear zone (Hibbard et al., 2012).

The Charlotte Terrane is positioned to the west of the Carolina Terrane and is dominantly plutonic, ranging in composition from granite to gabbro. These plutons intrude a suite of mainly metaigneous rocks and minor metasedimentary rocks (Hibbard et al., 2002). The contact between the Charlotte Terrane and the Cat Square Terrane is the Central Piedmont Suture (CPS) (Fig. 1).

The Ordovician aged Milton Terrane is an amalgamation of intermediate to high grade metamorphic rocks consisting of strongly deformed and metamorphosed, interlayered mafic and felsic metavolcanic schists and gneisses, with minor pelitic schist, marble and quartzite (Coler et al., 2000). The Milton Terrane is situated east of the Dan River Triassic basin and is separated from the Carolina Terrane by the Hyco shear zone, a northern extension of the Central Piedmont Suture (CPS) (Hibbard et al., 1998).

It has generally been accepted that accretion of the Tugaloo Terrane to Laurentia occurred during Ordovician Taconian orogenesis (e.g., Hatcher, 1989; Horton et al., 1989). The Tugaloo Terrane is within the Piedmont domain, which was overthrust onto central Blue Ridge Terranes along the Alleghanian, Chattahoochee-Holland Mountain fault (Hatcher, 2005). The Ashe Metamorphic Suite (AMS) is positioned within the Fries thrust sheet, which is the highest structural position in the Blue Ridge thrust complex (Boyer and Elliott, 1982; Trupe et al., 2003). The Ashe Metamorphic Suite has been interpreted as a combination of metamorphosed oceanic crust and sediments formed east of the Laurentian margin, possibly as an accretionary mélange containing fragments of dismembered ophiolite (Hatcher, 1978; Abbott and Raymond, 1984; Hatcher et al., 1984; Horton et al., 1989; Raymond et al., 1989; Misra and Conte, 1991; Adams et al., 1995). Within the Tugaloo, the AMS is bound to the northwest by the Burnsville fault zone and to the southeast by the Brevard fault zone (Trupe et al., 2004). The AMS consists of Ordovician amphibolite facies felsic and mafic schists and gneisses intercalated with metasandstone, as well as felsic Siluro-Devonian intrusives (Abbott and Raymond, 1984; Hatcher and Goldberg, 1991; Willard and Adams, 1994; Trupe et al., 2003).

Extension and compression, resulting from the collision and breakup of continents fractured the crystalline rocks of North Carolina; however, fractures that were created were filled with diabase. Isostatic rebound in combination with erosional unloading has had the greatest effect on these rocks, causing the rock mass to expand vertically and horizontally. Stress is concentrated around flaws or weaknesses acting as points of origin for fractures. The weakness, most commonly in the case of these rocks, is foliation planes but may also include mylonite planes, bedding planes or the contacts between rock types.

APPENDIX B: Stress and Fractures

Fractures

The fracturing of rock is a brittle response to stress and originates when stress exceeds the rock strength. Fractures may be tensile (Mode I), or shear with components parallel (Mode II) or perpendicular (Mode III) to the direction of propagation of the fracture front (Pollard and Aydin 1988). Tensile fractures that show no offset are referred to as joints. Shear fractures are commonly referred to as faults when they have significant displacement.

Fracture orientations relative to principal stress orientations

The principal stresses describe the stress at a point in three mutually perpendicular directions: The maximum (σ_1), the intermediate (σ_2), and the minimum (σ_3).

The following theory applies for isotropic rocks or rocks without fabric. The propagation front of a joint develops perpendicular to σ_3 axis and parallel to σ_1 axis (Fig. 17). Conjugate pairs of shear fractures are common. Shear fractures typically develop at a 20-30 degree angle to σ_1 (Fig. 17).

The proximity of the ground surface influences stress orientations as well. The surface of the earth is a free surface on which the shear stress is zero, the principal stresses are therefore perpendicular and parallel to the surface, or approximately vertical or horizontal in areas without topographic relief.

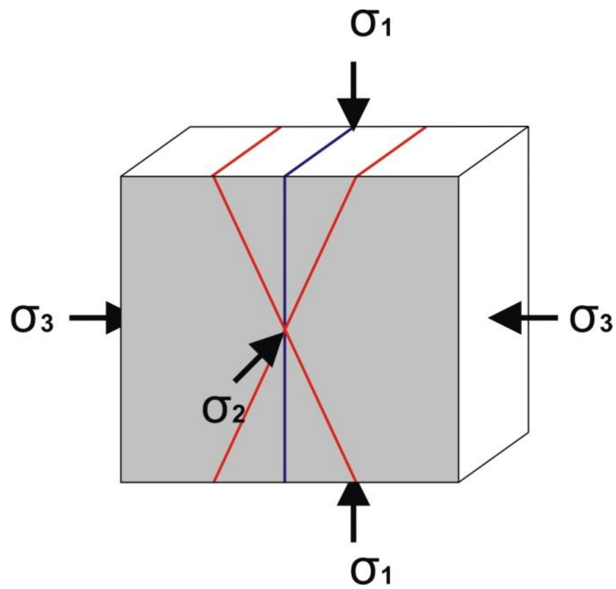


Figure 17: Generalized figure depicting the orientation of natural fractures in relation to the dominant stress directions. Blue line – joint, Red line – conjugate shear fractures.

Rock fabric and fracturing

Rocks that have strong fabrics fracture differently from those lacking fabrics. Fabrics are easily used as preferential fracture planes even at large angles to principal stresses. Therefore, it is difficult to infer stress directions from fractures that develop in anisotropic rock. It is expected that fractures will develop parallel to fabric.

Current Understanding of the Stress field in North Carolina

Though data are sparse in North Carolina, a stress map of North America (Zoback and Zoback 1980) suggests that the maximum principal stress (σ_1) is generally NW- SE. The intermediate principal stress (σ_2) is NE-SW and the minimum principal stress (σ_3) is vertical at the earth's surface (Fig. 18). It appears that these stress orientations near the land surface make it favorable for sheet joints to form. However, this stress regime changes with depth due to variables such as overburden weight, the poisson effect, and the thermal effect. Generally speaking, most joints are thought to form in the upper 500 m of the crust, with the highest intensities near the surface.

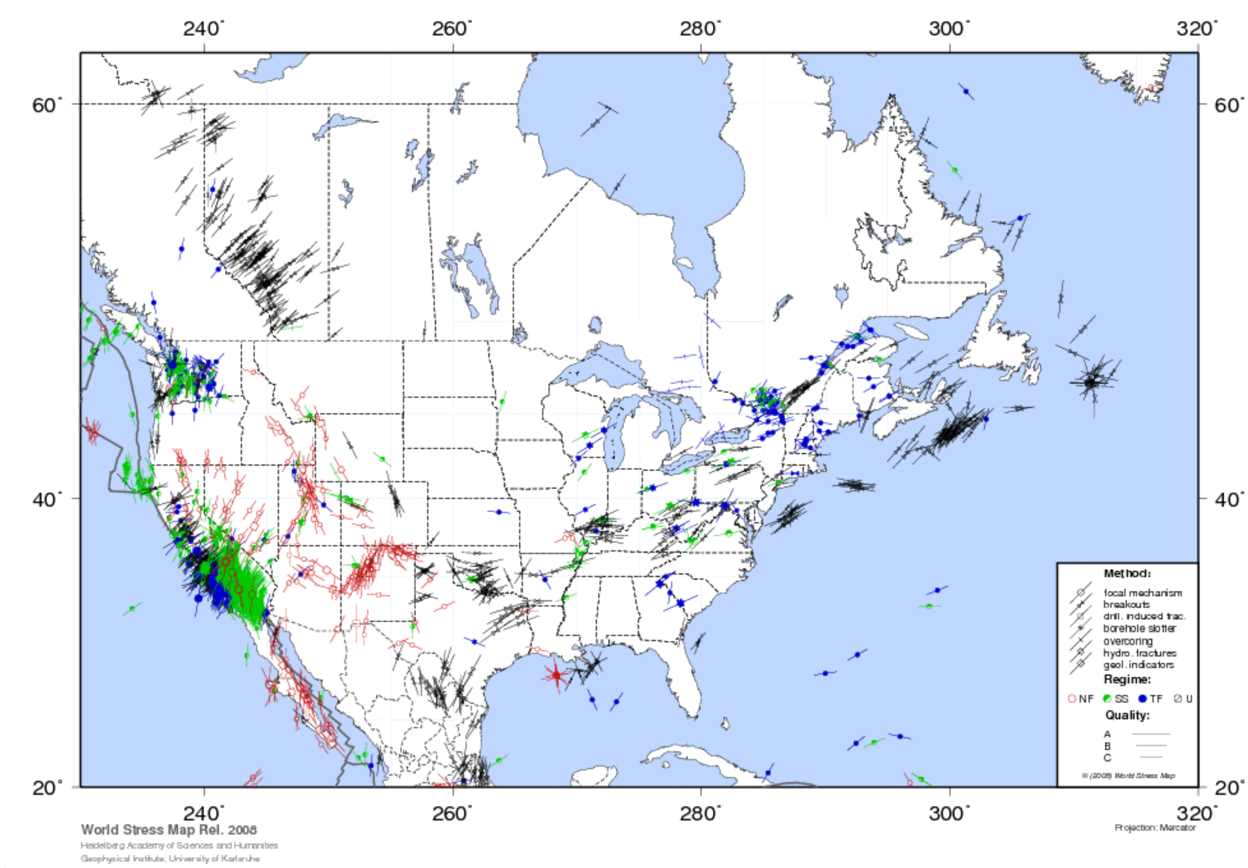


Figure 18: Stress map of North America (Modified from http://dc-app3-14.gfz-potsdam.de/pub/stress_data/stress_data_frame.html)

Discussion

Fractures observed in boreholes drilled in the crystalline rocks of North Carolina are classified into three categories: Sheet, Foliation Parallel Fractures (FPFs) and other fractures. Sheet joints are fractures that have a dip less than 25 degrees and are not parallel to rock fabric. FPFs are fractures that appear to be parallel to rock fabric in optical televiewer logs. Other fractures are fractures that have a dip greater than 25 degrees and do not appear to be parallel to foliation. Other fractures are expected to be mostly joints, but since it is impossible to distinguish between joints and meso-scale faults by visual means using the OTV, these are lumped together as other fractures.

Sheet joints, FPFs and fractures classified as other form under different stress regimes. The type of fracture that is the most common to form may give an indication of the principal stress regime at a specific location. In the crystalline rocks of North Carolina, the majority of fractures observed in boreholes are FPFs. The dominance of these features is not a strong indicator of principle stress directions, primarily due to the fact that FPFs can develop at large angles to principle stress directions. Though deriving principle stresses by recognizing dominant fracture types in North Carolina, the current understanding of principle stresses in North America is illustrated in figure 18.

APPENDIX C: Site descriptions, Fracture characteristics, Fracture depth distribution, Borehole logs, Fracture intensity plots, Fracture aperture plots, Stereonet plots

Appendix C-1. Location, physical characteristics, borehole logs and interpreted structures for RT-1D.

RT-1D is located on Chi road in Raleigh, North Carolina. The PMREP constructed the well in 2001 to investigate ambient groundwater flow and quality in a felsic gneiss unit. The well was drilled to 92.05 meters and cased 14.33 meters below the land surface. The well is 103.21 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of hornblende-biotite gneiss and characterized by migmatitic banding, producing white, gray and black intervals.

A total of 64 fractures were measured. Of the total number of fractures, 38 are sheet joints and 26 are foliation parallel fractures (FPF).

Appendix C-2. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from RT-1D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	RT-1D
Location:	Lake Wheeler Research Station Site, Wake County, NC
Elevation:	103.21 m
Rock Type:	Felsic Gneiss
Depth of casing:	14.33 m
Depth of well:	92.05 m

Fracture Characteristics

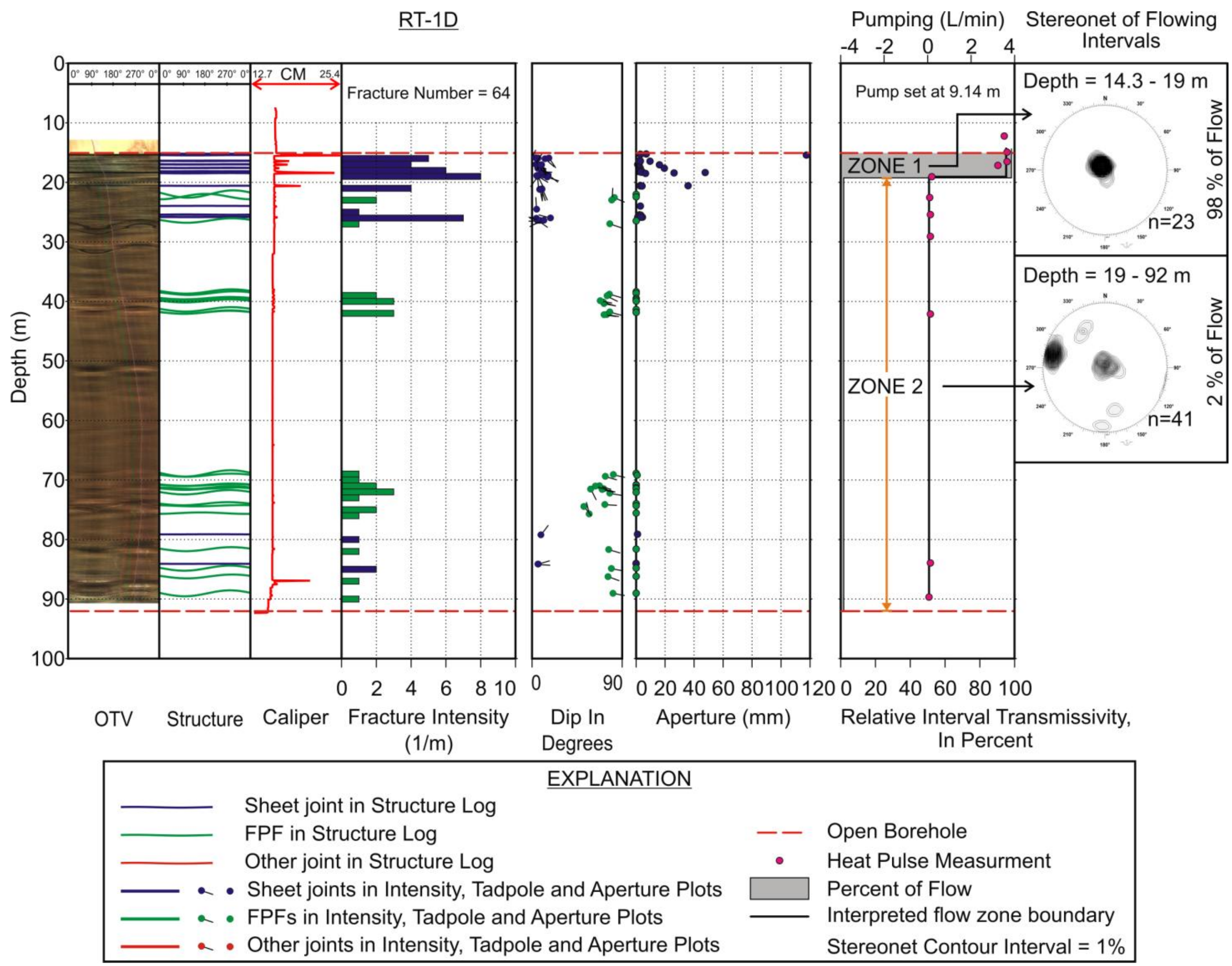
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	15.29	7	295.23	0	s
2	15.32	2.99	76.96	3.87	s
3	15.36	2.91	55.42	17.17	s
4	15.37	2.98	96.52	6.42	s
5	15.48	117.47	41.24	13.03	s
6	16.45	3	302.03	4.27	s
7	16.47	2.07	28.96	6.57	s
8	16.49	2.97	51.73	8.94	s
9	16.51	9.63	68.74	9.91	s
10	17.05	1.19	40.87	8.57	s
11	17.06	2.08	38.13	7.02	s
12	17.08	2.08	51.17	8.52	s
13	17.1	16.18	26.5	5.99	s
14	17.65	2.94	4.3	11.39	s
15	17.69	19.53	33.4	9.88	s
16	18.23	4.11	258.09	11.68	s
17	18.24	2.01	37.56	16.44	s
18	18.3	3.28	85.18	5.5	s
19	18.32	3.29	63.07	4.9	s
20	18.35	3.88	6.94	6.33	s
21	18.4	47.66	31.04	5.76	s
22	18.48	26.2	125.53	5.68	s
23	18.56	6.55	16.49	15.43	s
24	20.58	2.95	88.87	10.01	s
25	20.62	35.91	70.91	9.45	s
26	20.66	2.95	66.19	10.26	s
27	20.67	4.16	78.09	8	s
28	22.05	0	23.1	82.57	p
29	22.48	0	273.12	79.94	p
30	24.04	2.99	266.6	4.91	s

31	25.5	2.27	194.88	18.82	s
32	25.55	3.29	186.66	4.5	s
33	25.88	2.08	188.65	7.24	s
34	25.89	1.17	157.75	12.07	s
35	25.89	2.38	177.97	6.91	s
36	25.91	4.45	152.08	8.31	s
37	25.92	3.28	34.44	5.66	s
38	26.5	0	18	77.91	p
39	38.4	0	16.02	77.65	p
40	38.68	0	25.28	75.27	p
41	39.52	0	9.4	68.21	p
42	39.75	0	17.34	71.65	p
43	39.99	0	9.78	72.36	p
44	41.4	0	13.94	77.97	p
45	41.86	0	8.08	74.97	p
46	41.89	0	6.94	72.23	p
47	68.93	0	12.05	81.5	p
48	69.23	0.68	15.26	73.44	p
49	70.82	0	13.94	67.76	p
50	70.89	0	16.2	63.56	p
51	71.33	0	14.69	71.7	p
52	71.4	0	64.02	58.83	p
53	71.47	0	10.72	70.09	p
54	72.09	0	8.65	77.93	p
55	74.01	0	2.79	73.06	p
56	74.35	0	51.35	52.17	p
57	75.6	0	256.02	57.36	p
58	79.15	0.98	306.57	8.99	s
59	81.64	0	15.07	76.69	p
60	84.05	0	344.27	6.53	s
61	84.1	0	3.26	6.16	s
62	84.83	0	9.21	79.58	p
63	86.22	0	19.13	76.27	p
64	89.05	0	9.97	81.12	p

Appendix C-3. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: RT-1D	#	%
Total Fractures:	64.0	100.00
Total above 90 m:	64.0	100.00
Total above 60 m:	46.0	71.88
Total above 30 m:	38.0	59.38
FPFs:	26.0	40.63
Sheet:	38.0	59.38
Other:	0.0	0.00

Appendix C-4. Interpreted features for RT-1D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-5. Location, physical characteristics, borehole logs and interpreted structures for RT-2D.

LWRSS-MW-2D is located on Chi road in Raleigh, North Carolina. The PMREP constructed the well in 2001 to investigate ambient groundwater flow and quality in a felsic gneiss unit. The well was drilled to 183.18 meters and cased 24.68 meters below the land surface. Well yield is 56.78 lpm. The well is 109.66 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of hornblende-biotite gneiss and characterized by migmatitic banding, producing white, gray and black intervals.

A total of 27 fractures were measured. Of the total number of fractures, 2 are sheet joints, 6 are foliation parallel fractures and 1 is classified as an “other” joint.

Appendix C-6. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from RT-2D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	RT-2D
Location:	Lake Wheeler Research Station Site, Wake County, NC
Elevation:	109.66 m
Well Yield (l/min):	56.78
Rock Type:	Felsic Gneiss
Depth of casing:	24.68 m
Depth of well:	183.18 m

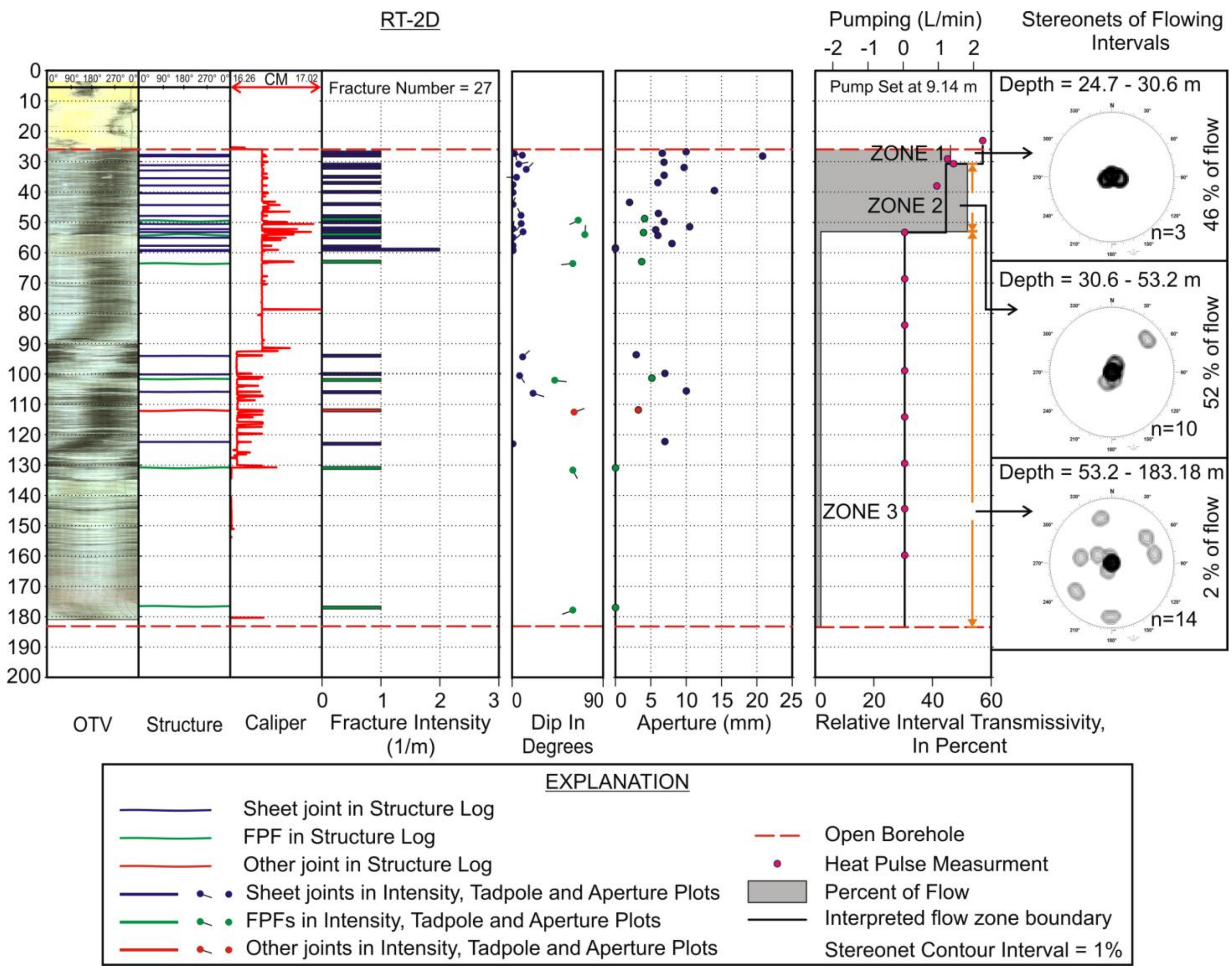
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	26.75	10	82.25	2.76	s
2	27.26	6.64	191.24	10.26	s
3	30.23	6.88	339.17	6.91	s
4	31.94	9.72	296.57	14.26	s
5	34.53	6.89	180.57	4.83	s
6	36.95	6	271.13	0	s
7	39.55	14	278.79	0	s
8	43.46	2	282.97	0	s
9	47.07	6.08	255.12	9.26	s
10	48.76	4.12	138.83	65.64	p
11	49.78	6.89	110.98	9.32	s
12	51.48	10.5	275.1	0	s
13	52.49	5.7	120.44	11.23	s
14	53.39	3.97	270.89	72.34	p
15	54.35	6	275.49	0	s
16	57	8	279.75	0	s
17	58.44	0	275.81	0	s
18	58.72	0	270.71	0	s
19	62.94	3.71	168.84	60.16	p
20	93.67	2.95	299.47	10.57	s
21	99.83	7	70.28	7.68	s
22	101.35	5.15	10.14	42.6	p
23	105.63	10.04	29.3	20.91	s
24	111.84	3.26	322.52	61.62	t
25	122.27	7	268.01	0	s
26	130.91	0	75.11	60.22	p
27	176.99	0	145.18	57.88	p

Appendix C-7. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: RT-2D	#	%
Total Fractures:	27	100.00
Total above 90 m:	19	70.37
Total above 60 m:	18	66.67
Total above 30 m:	2	7.41
FPF:	6	22.22
Sheet:	20	74.07
Other:	1	3.70

Appendix C-8. Interpreted features for RT-2D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-9. Location, physical characteristics, borehole logs and interpreted structures for RT-3D.

RT-3D is located on Chi road in Raleigh, North Carolina. The PMREP constructed the well in 2001 to investigate ambient groundwater flow and quality in a felsic gneiss unit. The well was drilled to 91.15 meters and cased 19.88 meters below the land surface. Well yield is 7.57 lpm. The well is 114.71 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of hornblende-biotite gneiss and characterized by migmatitic banding, producing white, gray and black intervals.

A total of 41 fractures were measured. Of the total number of fractures, 14 are sheet joints, 26 are foliation parallel fractures and 1 is classified as “other” joint.

Appendix C-10. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from RT-3D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	RT-3D
Location:	Lake Wheeler Research Station Site, Wake County, NC
Elevation:	114.71 m
Well Yield (l/min):	7.57
Rock Type:	Felsic Gneiss
Depth of casing:	19.88 m
Depth of well:	91.15 m

Fracture Characteristics

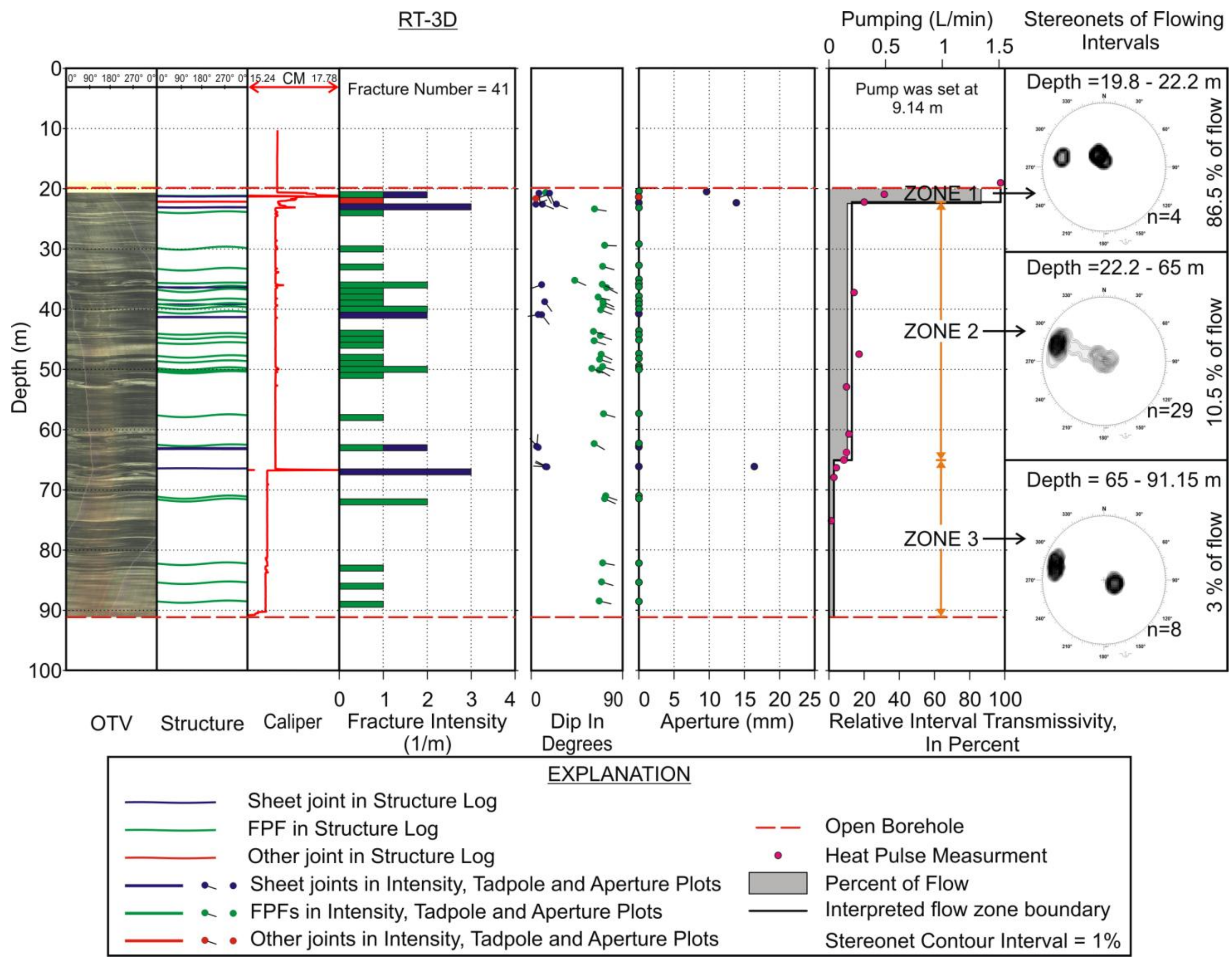
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	20.42	0	61.84	14.71	p
2	20.51	0	67.13	18.5	s
3	20.52	9.63	86.03	8.05	s
4	21.41	13.86	12.57	58.93	t
5	22.35	0	20.2	24.92	s
6	22.37	13.86	338.03	4.82	s
7	22.37	0	21.34	11.29	s
8	23.17	0	8.38	62.53	p
9	29.21	0	2.26	72.59	p
10	32.74	0	16.13	70.48	p
11	35.06	0	23.83	43.18	p
12	35.74	0	22.22	70.23	p
13	35.8	0	161.73	10.41	s
14	36.31	0	26.45	74.51	p
15	37.85	0	12.9	66.26	p
16	38.64	0	54.04	13.68	s
17	38.65	0	24.52	70.81	p
18	39.21	0	20	71.29	p
19	39.98	0	20.69	68.7	p
20	40.76	0	171.61	7.11	s
21	40.81	0	51.83	10.41	s
22	43.6	0	12.9	61.57	p
23	44.28	0	19.03	68.15	p
24	45.14	0	18.06	62.36	p
25	47.39	0	25.48	69.14	p
26	48.23	0	17.42	67.56	p
27	49.43	0	16.99	70.57	p
28	49.77	0	20.97	60.1	p
29	50.04	0	29.25	67.23	p

30	57.34	0	16.13	71.5	p
31	62.3	0	29.96	62.37	p
32	62.77	0	274.48	5.71	s
33	62.93	0	227.11	7.11	s
34	66.15	0	183.14	14.36	s
35	66.17	16.42	206.79	15.69	s
36	66.18	0	201.66	15.41	s
37	71.01	0	19.03	73.7	p
38	71.49	0	23.23	72.67	p
39	82.19	0	9.59	70.73	p
40	85.38	0	15.71	69.47	p
41	88.56	0	12.58	67.29	p

Appendix C-11. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: RT-3D	#	%
Total Fractures:	41	100.00
Total above 90 m:	41	100.00
Total above 60 m:	30	73.17
Total above 30 m:	9	21.95
FPFs:	26	63.41
Sheet:	14	34.15
Other:	1	2.44

Appendix C-12. Interpreted features for RT-3D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-13. Location, physical characteristics, borehole logs and interpreted structures for RT-PW-1.

RT-PW-1 is located on Chi road in Raleigh, North Carolina. The PMREP constructed the well in 2001 to investigate ambient groundwater flow and quality. The well was drilled to 115.82 meters and cased 23.47 meters below the land surface. Well yield is 11.36 lpm. The well is 109.14 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of hornblende-biotite gneiss and characterized by migmatitic banding, producing white, gray and black intervals.

A total of 8 fractures were measured. Of the total number of fractures, 7 are sheet joints and 1 is classified as an “other” joint. Only ambient heat pulse flow meter data is available for this well.

Appendix C-14. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from RT-PW-1 (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	RT-PW-1
Location:	Lake Wheeler Research Station Site, Wake County, NC
Elevation:	109.14 m
Well Yield (l/min):	11.36
Rock Type:	Felsic Gneiss
Depth of casing:	19.05 m
Depth of well:	92.05 m

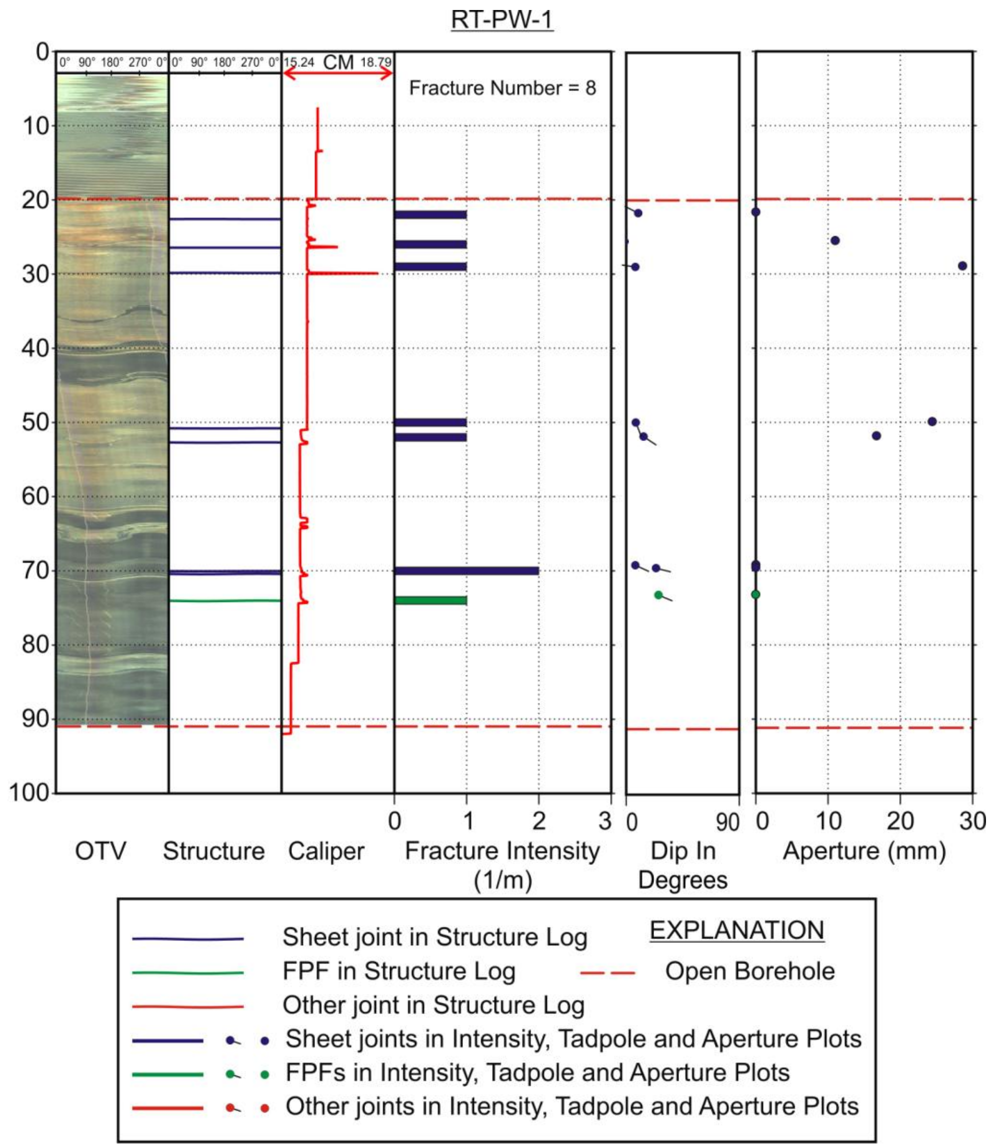
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	21.65	0	207.07	9.9	s
2	25.51	11	273.12	0	s
3	28.92	28.62	188.36	7.65	s
4	49.91	24.42	69.02	7.81	s
5	51.82	16.71	33.02	14	s
6	69.19	0	23.95	7.54	s
7	69.57	0	12.9	24.04	s
8	73.2	0	21.97	25.81	t

Appendix C-15. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: RT-PW-1	#	%
Total Fractures:	8	100.00
Total above 90 m:	8	100.00
Total above 60 m:	5	62.50
Total above 30 m:	3	37.50
FPFs:	0	0.00
Sheet:	7	87.50
Other:	1	12.50

Appendix C-16. Interpreted features for RT-PW-1. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, and fracture aperture plot.



Appendix C-17. Location, physical characteristics, borehole logs and interpreted structures for RT-A.

RT-A is located on Chi road in Raleigh, North Carolina. The PMREP constructed the well in 2010 to investigate ambient groundwater flow and quality. The well was drilled to 91.70 meters and cased 12.24 meters below the land surface.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of hornblende-biotite gneiss and characterized by migmatitic banding, producing white, gray and black intervals.

A total of 35 fractures were measured. Of the total number of fractures, 26 are sheet joints, 4 are FPFs and 5 are classified as other fractures.

Appendix C-18. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from RT-A (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	RT-A
Location:	Lake Wheeler Research Station Site, Wake County, NC
Rock Type:	Felsic Gneiss
Depth of casing:	12.24 m
Depth of well:	91.70 m

Fracture Characteristics

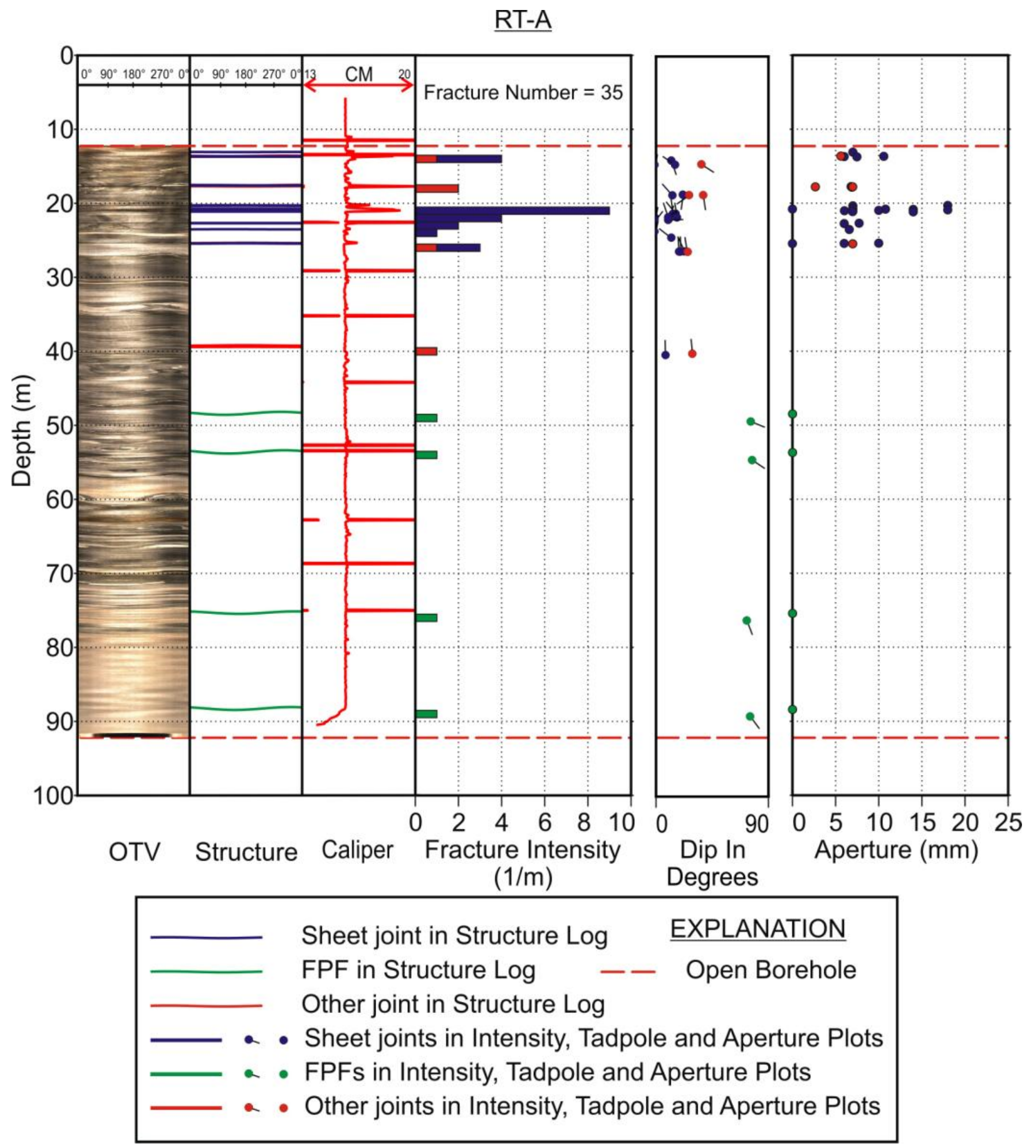
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	13.13	10	70.9	12.41	s
2	13.66	5.63	32.17	36.5	t
3	13.69	7	270	0	s
4	13.72	10.59	214.12	15.64	s
5	13.76	6	276.5	0	s
6	17.77	7.48	97.67	21.8	s
7	17.81	7	145.49	26.57	t
8	17.81	2.68	81.55	37.95	t
9	17.86	6.81	228.67	13.5	s
10	20.33	6.89	230.49	10.2	s
11	20.38	18	262.72	7.97	s
12	20.77	7	270	0	s
13	20.81	7	270	0	s
14	20.83	0	320.95	4	s
15	20.85	10.79	260.9	11.31	s
16	20.88	14	279.36	0	s
17	20.93	14	271.56	0	s
18	20.99	18	289.49	4.57	s
19	21.04	10	271.04	0	s
20	21.13	6.04	252.06	4.57	s
21	21.16	7	308.99	0	s
22	21.19	6.98	357.86	4	s
23	22.73	14	270	0	s
24	22.77	7.74	279.88	0	s
25	23.58	6	218.01	12.41	s
26	25.43	6.59	270	19.8	s
27	25.46	10	267.4	18.78	s
28	25.48	6	247.13	22.78	s
29	25.5	7	261.16	25.64	t
30	39.29	0	264.28	29.25	t
31	39.49	0	270	7.97	s

32	48.47	0	21.51	76.1	p
33	53.69	0	32.69	77.31	p
34	75.43	0	68.3	72.9	p
35	88.4	0	53.74	75.65	p

Appendix C-19. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: RT-A	#	%
Total Fractures:	35	100.00
Total above 90 m:	35	100.00
Total above 60 m:	33	94.29
Total above 30 m:	29	82.86
FPFs:	4	11.43
Sheet:	26	74.29
Other:	5	14.29

Appendix C-20. Interpreted features for RT-A. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, and fracture aperture plot.



Appendix C-21. Location, physical characteristics, borehole logs and interpreted structures for RT-B.

RT-B is located on Chi road in Raleigh, North Carolina. The PMREP constructed the well in 2010 to investigate ambient groundwater flow and quality. The well was drilled to 121.06 meters and cased 19.09 meters below the land surface.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of hornblende-biotite gneiss and characterized by migmatitic banding, producing white, gray and black intervals.

A total of 24 fractures were measured. Of the total number of fractures, 2 are FPFs and 22 are classified as other fractures.

Appendix C-22. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from RT-B (t = other fractures, s = sheet joints, p = foliation parallel fractures).

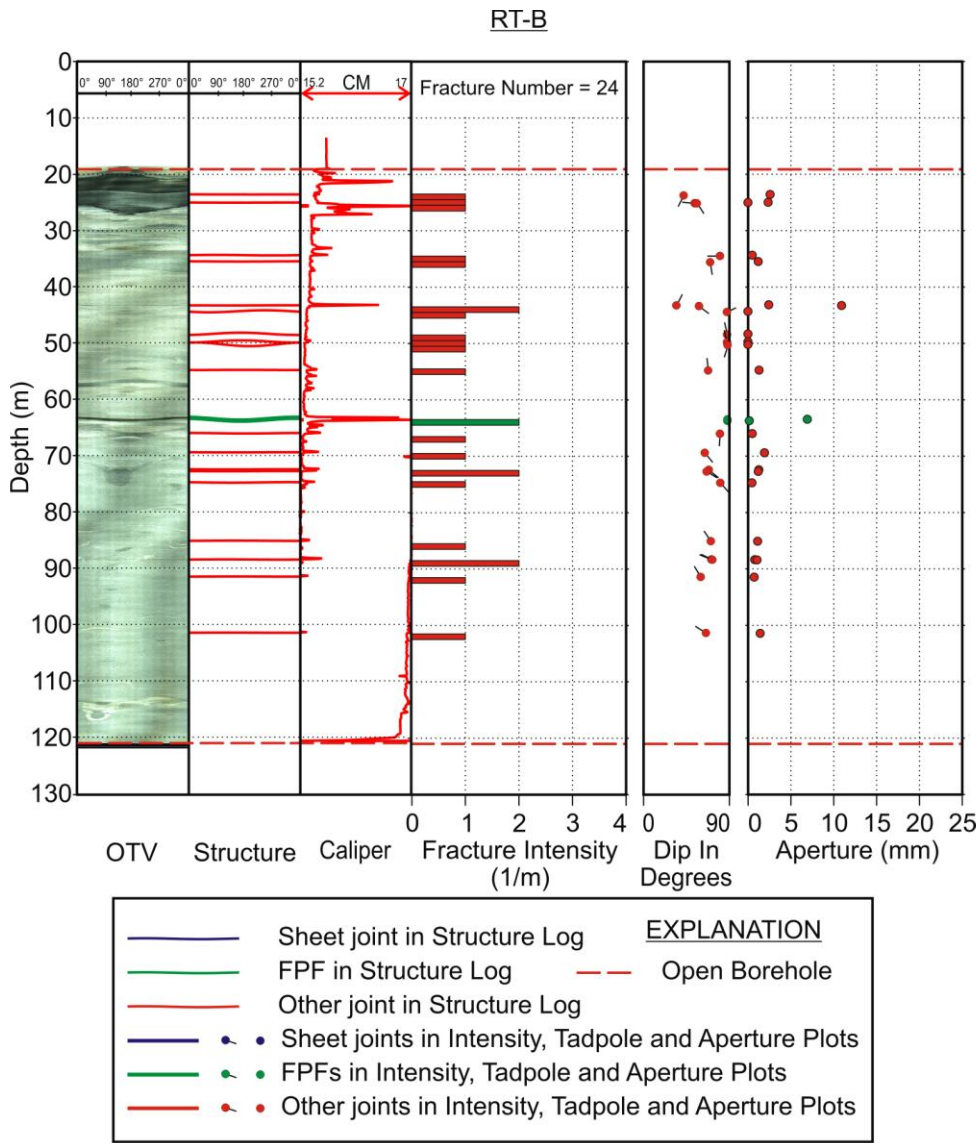
Well ID:	RT-B
Location:	Lake Wheeler Research Station Site, Wake County, NC
Rock Type:	Felsic Gneiss
Depth of casing:	19.09 m
Depth of well:	121.06 m

Fracture Characteristics					
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	23.6	2.59	116.24	42.24	t
2	24.99	2.37	186.31	53.65	t
3	25.03	0	57.23	56.1	t
4	34.37	0.51	180.35	80.22	t
5	35.49	1.2	80.21	69.91	t
6	43.18	2.43	296.95	34.6	t
7	43.3	10.93	36.24	58.45	t
8	44.34	0	334.96	87.54	t
9	48.35	0	258.09	87.83	t
10	49.71	0	259.5	87.82	t
11	50.21	0	106.31	88.68	t
12	54.76	1.31	263.48	68.07	t
13	63.44	6.9	75.39	88.21	p
14	63.7	0.13	77.09	88.17	p
15	66.01	0.5	94.11	80.4	t
16	69.4	1.94	50.14	64.57	t
17	72.43	1.28	39.08	68.61	t
18	72.73	1.2	30.28	66.5	t
19	74.74	0.48	49.01	80.86	t
20	85.1	1.14	237.09	70.94	t
21	88.36	0.79	202.2	71.27	t
22	88.42	1.06	206.45	72.45	t
23	91.46	0.74	239.08	60.24	t
24	101.43	1.44	212.13	65.71	t

Appendix C–23. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: RT-B	#	%
Total Fractures:	24	100.00
Total above 90 m:	22	91.67
Total above 60 m:	12	50.00
Total above 30 m:	3	12.50
FPFs:	2	8.33
Sheet:	0	0.00
Other:	22	91.67

Appendix C-24. Interpreted features for RT-B. Optical Televiewer (OTV), Structure, Caliper, fracture intensity plot, tadpole plot, and fracture aperture plot.



Appendix C-25. Location, physical characteristics, borehole logs and interpreted structures for DF-2Dgs.

DF-2Dgs is located on Mount Sinai road in Durham, North Carolina. The Resource Evaluation Program (REP) constructed the well in 2005 to investigate ambient groundwater flow and quality in the major rock types across Orange County. The well was drilled to 85.65 meters and cased 27.43 meters below the land surface.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of mixed epiclastics and andesitic lava flows.

A total of 17 fractures were measured. Of the total number of fractures, 5 are sheet joints and 12 are classified as other fractures.

Appendix C-26. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from DF-2Dgs (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	DF-2Dgs
Location:	Duke Forest Groundwater Research Station Site, Orange County, NC
Rock Type:	Andesitic to Basaltic Lavas and Tuffs
Depth of casing:	27.07 m
Depth of well:	85.68 m

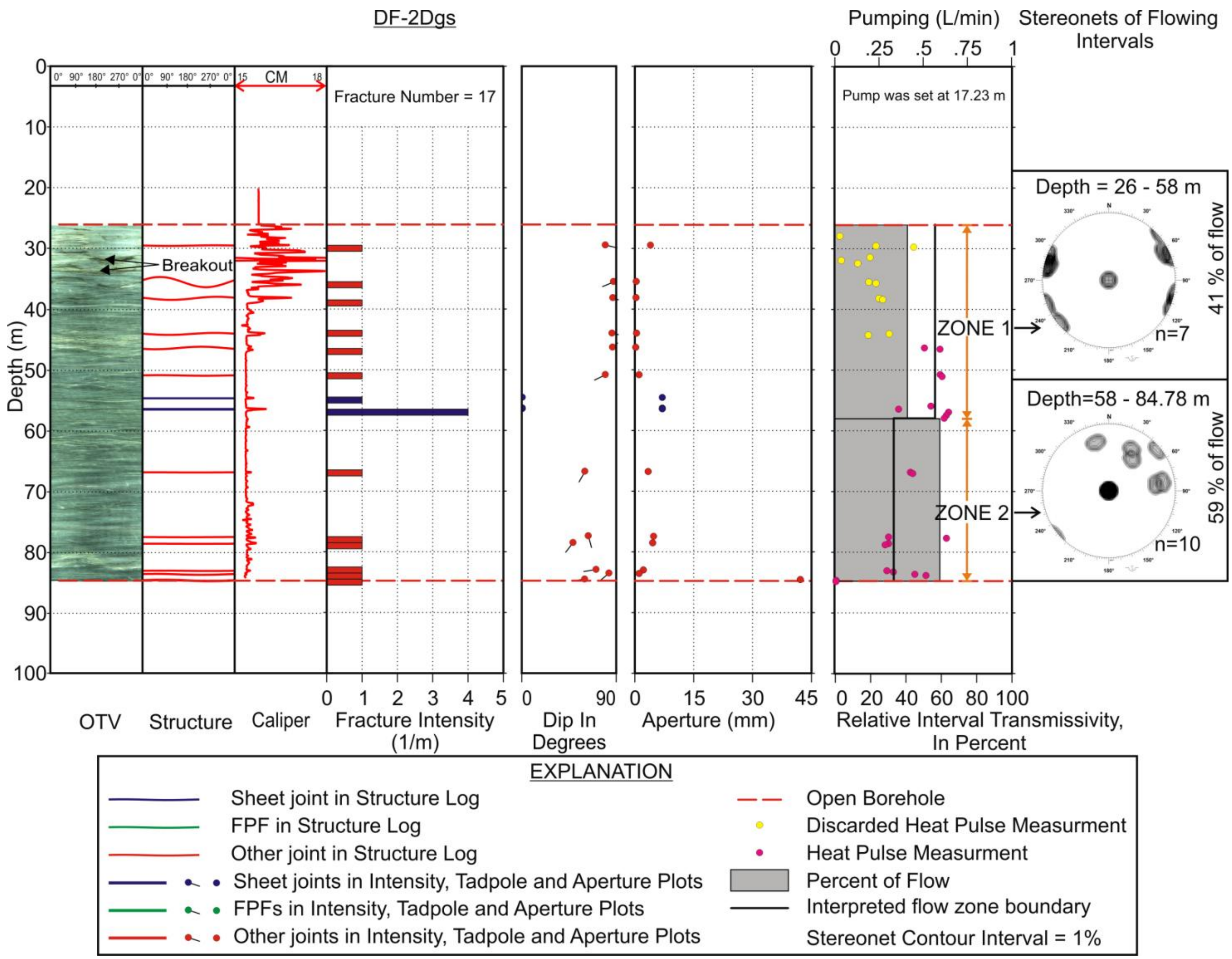
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	30.45	4.03	14.03	80.73	t
2	36.43	0.39	158.03	89.47	t
3	39.1	0.35	21.69	88.18	t
4	44.96	0.48	12.33	87.26	t
5	47.28	0.26	319.89	87.86	t
6	51.8	1.12	154.06	80.82	t
7	55.56	7	266.88	0	s
8	57.32	7	270	0	s
9	57.37	7	270	0	s
10	57.4	7	270	0	s
11	57.42	7	270	0	s
12	67.76	3.42	118.91	60.73	t
13	78.42	4.83	74.98	63.93	t
14	79.51	4.59	127.13	49.11	t
15	83.97	2.22	171.07	71.5	t
16	84.55	1.11	140.17	84.24	t
17	85.56	42.21	172.77	60.67	t

Appendix C-27. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: DF-2Dgs	#	%
Total Fractures:	17	100.00
Total above 90 m:	17	100.00
Total above 60 m:	11	64.71
Total above 30 m:	1	5.88
FPFs:	0	0.00
Sheet:	5	29.41
Other:	12	70.59

Appendix C-28. Interpreted features for DF-2Dgs. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-29. Location, borehole logs and physical characteristics of interpreted structures for DF-2Dpvc.

DF-2Dpvc is located on Mount Sinai road in Durham, North Carolina. The Resource Evaluation Program (REP) constructed the well in 2005 to investigate ambient groundwater flow and quality in the major rock types across Orange County. The well was drilled to 81.99 meters and cased 18.89 meters below the land surface.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of mixed epiclastics and andesitic lava flows.

A total of 21 fractures were measured. All fractures are classified as other fractures.

Appendix C-30. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from DF-2Dpvc (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	DF-2Dpvc
Location:	Duke Forest Groundwater Research Station Site, Orange County, NC
Rock Type:	Andesitic to Basaltic Lavas and Tuffs
Depth of casing:	19.82 m
Depth of well:	82.59 m

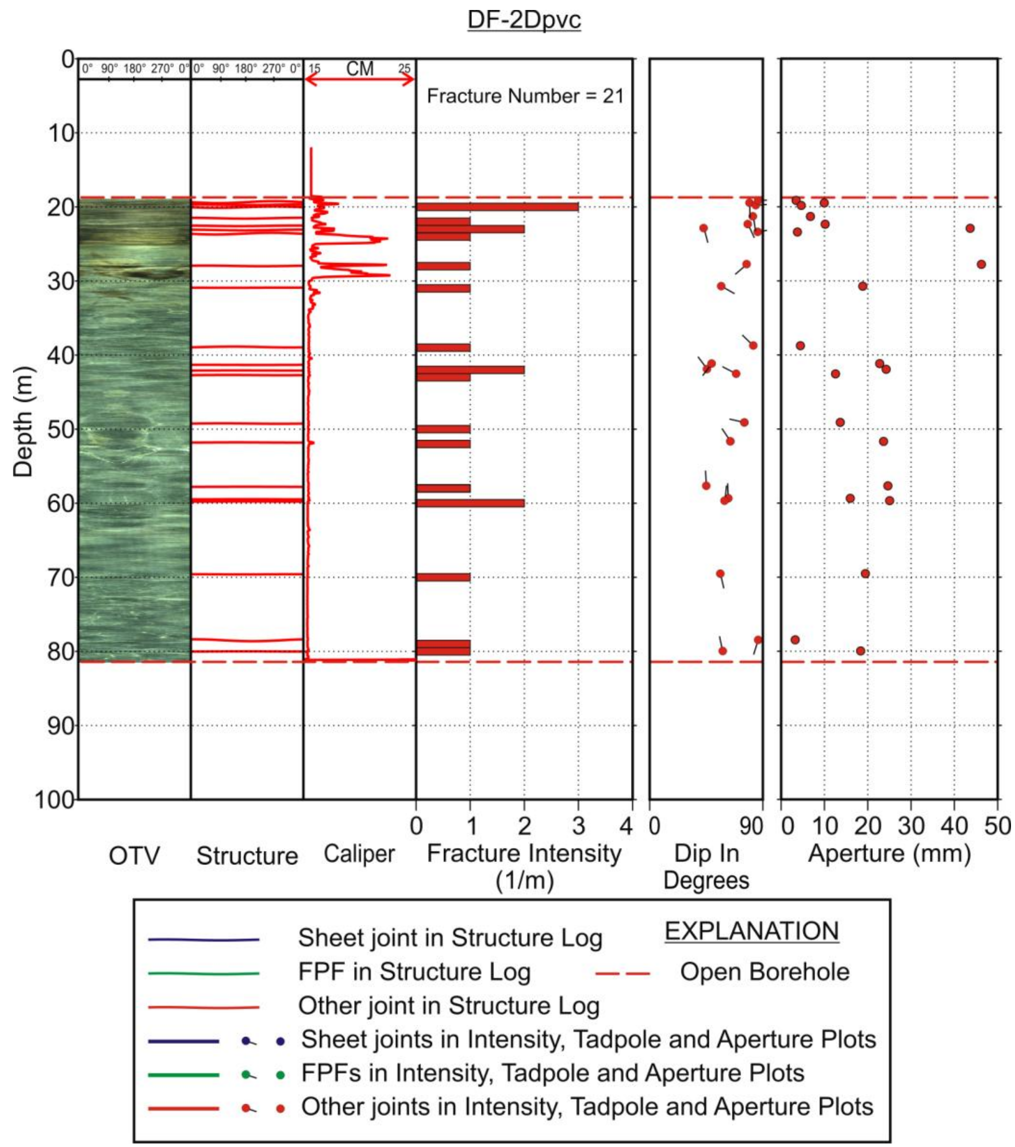
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	20.26	0.35	357.87	86.6	t
2	20.61	1	89.15	79.51	t
3	20.94	0.47	355.04	84.56	t
4	22.43	0.68	81.5	82.23	t
5	23.47	1.02	65.06	78.25	t
6	24.03	4.37	74.98	43.23	t
7	24.52	0.38	348.24	86.03	t
8	28.89	4.63	139.04	77.26	t
9	31.84	1.89	29.06	57.25	t
10	39.87	0.45	224.36	82.62	t
11	42.29	2.28	127.98	49.39	t
12	43.05	2.43	234	45.94	t
13	43.67	1.26	207.92	68.98	t
14	50.23	1.37	192.9	75.59	t
15	52.79	2.37	236.27	64.43	t
16	58.79	2.47	267.17	45.15	t
17	60.48	1.6	268.02	62.8	t
18	60.79	2.51	275.39	59.84	t
19	70.64	1.95	76.96	56.25	t
20	79.57	0.33	107.01	86.55	t
21	81.08	1.84	258.94	58.43	t

Appendix C-31. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: DF-2Dpvc	#	%
Total Fractures:	21	100.00
Total above 90 m:	21	100.00
Total above 60 m:	18	85.71
Total above 30 m:	8	38.10
FPFs:	0	0.00
Sheet:	0	0.00
Other:	21	100.00

Appendix C-32. Interpreted features for DF-2Dpvc. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, and fracture aperture plot.



Appendix C-33. Location, physical characteristics, borehole logs and interpreted structures for DF-4D.

DF-4D is located on Mount Sinai road in Durham, North Carolina. The Resource Evaluation Program (REP) constructed the well in 2005 to investigate ambient groundwater flow and quality in the major rock types across Orange County. The well was drilled to 121.92 meters and cased 28.04 meters below the land surface.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The bedrock is composed of Granodiorite.

A total of 38 fractures were measured. All are classified as other fractures.

Appendix C-34. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from DF-4D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	DF-4D
Location:	Duke Forest Groundwater Research Station Site, Orange County, NC
Rock Type:	Granodiorite
Depth of casing:	29.35 m
Depth of well:	122.75 m

Fracture Characteristics

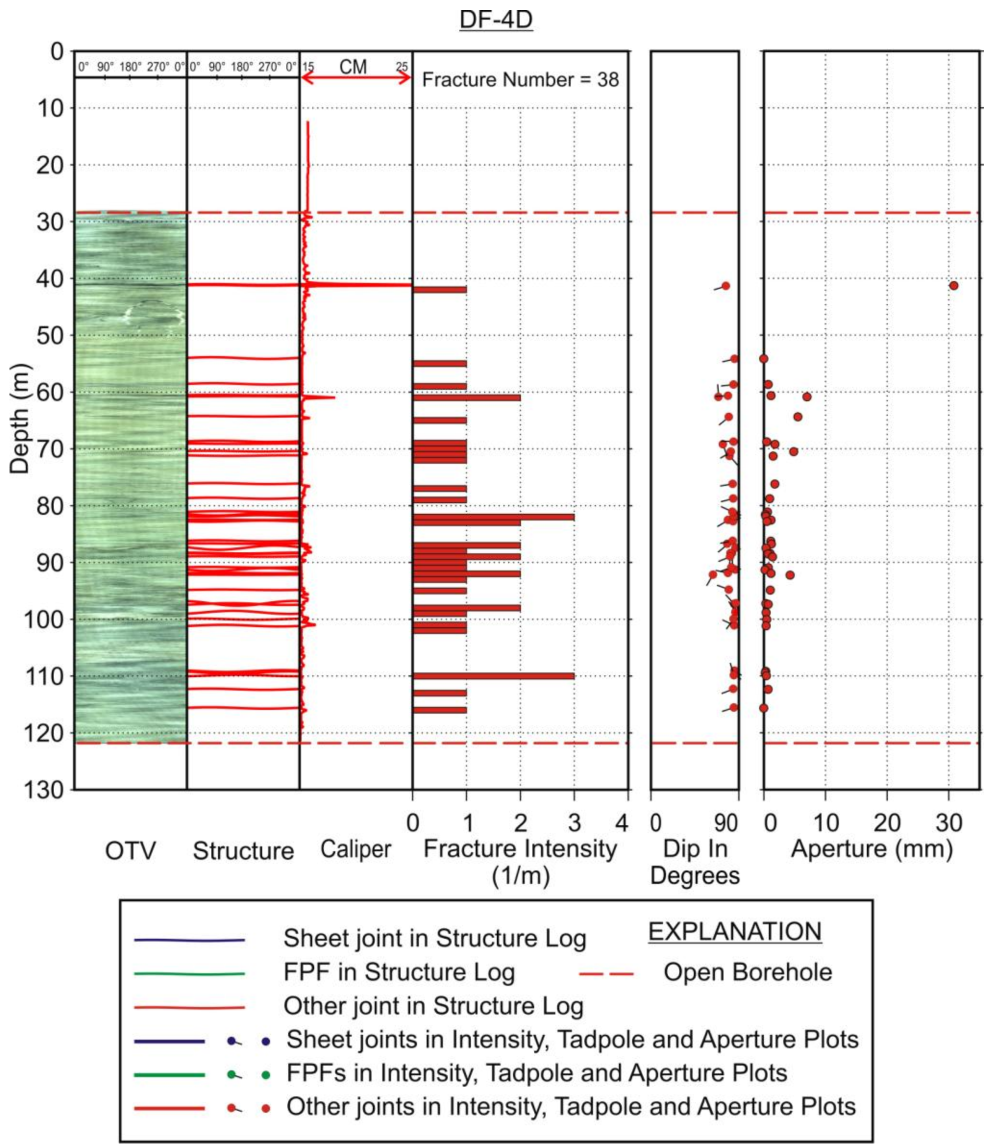
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	42.242	30.86	163.13	78.36	t
2	55.112	0	167.95	87.13	t
3	59.642	0.73	174.76	86.22	t
4	61.612	1.19	178.72	80.19	t
5	61.822	7.03	265.75	70.44	t
6	65.332	5.55	140.74	81.16	t
7	69.732	0.48	182.13	86.03	t
8	70.162	1.82	70.16	74.93	t
9	71.472	4.86	150.09	83.51	t
10	72.252	1.52	48.9	82.07	t
11	77.162	1.81	171.92	85.28	t
12	79.742	0.97	166.82	86.01	t
13	82.082	0.6	204.24	85.05	t
14	82.562	0.26	2.13	87.9	t
15	82.842	0.35	321.87	86.69	t
16	83.522	1.19	148.96	80.2	t
17	83.762	0.52	332.08	85.75	t
18	87.222	1.15	170.22	85.29	t
19	87.722	1.25	141.02	79.68	t
20	88.422	0.37	10.91	88.74	t
21	89.382	1.04	88.87	84.59	t
22	89.482	0.71	97.09	83.15	t
23	89.982	1.43	158.88	82.51	t
24	91.882	0.75	161.15	83.87	t
25	92.272	0.21	351.07	88.22	t
26	92.892	1.19	193.18	80.22	t
27	93.192	4.28	120.05	64.68	t
28	95.832	1.07	199.98	81.23	t
29	98.212	0.34	73.28	88.93	t
30	98.342	0.72	228.05	87.05	t
31	99.792	0.39	236.83	88.4	t

32	100.992	0.48	126.57	86.1	t
33	102.132	0.38	205.09	86.86	t
34	110.112	0.32	36.99	87.38	t
35	110.392	0.24	53.15	88.02	t
36	110.902	0.42	253.84	86.55	t
37	113.302	0.71	159.17	85.95	t
38	116.602	0	163.13	86.43	t

Appendix C-35. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: DF-4D	#	%
Total Fractures:	38	100.00
Total above 90 m:	23	60.53
Total above 60 m:	3	7.89
Total above 30 m:	0	0.00
FPFs:	0	0.00
Sheet:	0	0.00
Other:	38	100.00

Appendix C-36. Interpreted features for DF-4D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, and fracture aperture plot.



Appendix C-37. Location, physical characteristics, borehole logs and interpreted structures for LT-1D.

LT-1D is located at the Langtree Peninsula site, in Cornelius, North Carolina. The PMREP constructed the well in 2000 to investigate the effects of quartz diorite and massive (weakly foliated) biotite gneiss rock types with moderate to steeply dipping foliation on groundwater quality, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures. The well was drilled to 183.29 meters and cased 23.64 meters below the land surface. The well is 247.65 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. LT-1D intersects bedrock composed of quartz diorite.

A total of 13 fractures were measured. Of the total number of fractures, 7 are sheet joints, 3 are classified as other fractures and 3 are foliation parallel fractures.

Appendix C-38. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from LT-1D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	LT-1D
Location:	Langtree Research Station Site, Iredell County, NC
Elevation:	247.65 m
Rock Type:	Quartz Diorite
Depth of casing:	23.64 m
Depth of well:	183.49 m

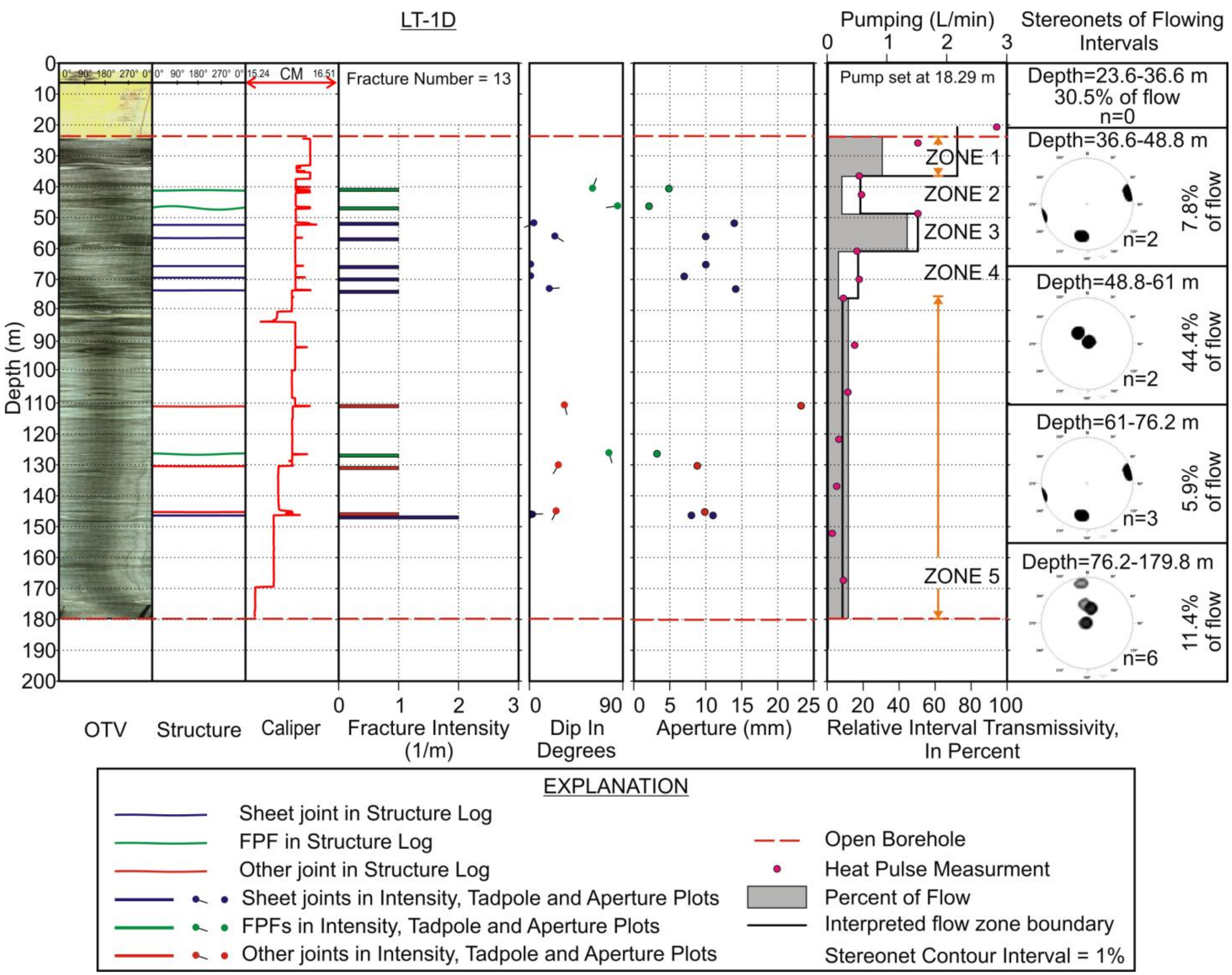
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	40.62	4.86	279.46	60.95	p
2	46.31	2.11	165.45	84.96	p
3	51.85	13.96	138.49	4.57	s
4	56.14	9.99	50.03	24.7	s
5	65.25	10	270	0	s
6	69.04	7	270	0	s
7	73.15	14.16	351.84	19.29	s
8	110.92	23.26	83.61	33.82	t
9	126.42	3.21	81.72	76.73	p
10	130.36	8.83	106.79	27.92	t
11	145.29	9.88	103.48	26.1	t
12	146.39	8	355.15	3.43	s
13	146.42	11	271.42	0	s

Appendix C-39. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: LT-1D	#	%
Total Fractures:	13	100.00
Total above 90 m:	7	53.85
Total above 60 m:	4	30.77
Total above 30 m:	0	0.00
FPFs:	3	23.08
Sheet:	7	53.85
Other:	3	23.08

Appendix C-40. Interpreted features for LT-1D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-41. Location, physical characteristics, borehole logs and interpreted structures for LT-2D.

LT-2D is located at the Langtree Peninsula site, in Cornelius, North Carolina. The PMREP constructed the well in 2000 to investigate the effects of quartz diorite and massive (weakly foliated) biotite gneiss rock types with moderate to steeply dipping foliation on groundwater quality, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures. The well was drilled to 121.92 meters and cased 16.15 meters below the land surface. The well is 244.66 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. LT-2D intersects bedrock composed of quartz diorite.

A total of 13 fractures were measured. Of the total number of fractures, 8 are sheet joints, 4 are classified as other fractures and 1 is a foliation parallel fracture.

Appendix C-42. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from LT-2D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

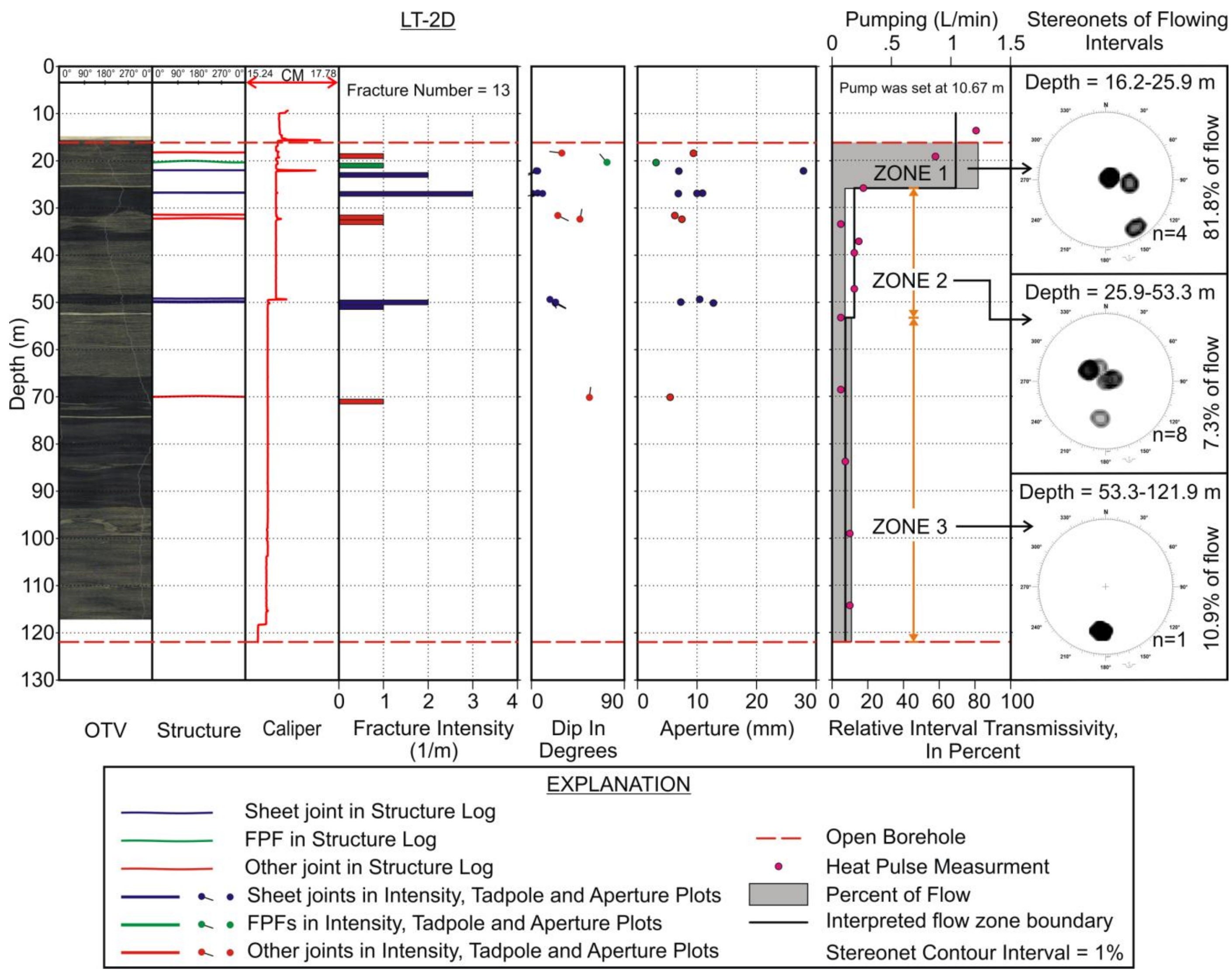
Well ID:	LT-2D
Location:	Langtree Research Station Site, Iredell County, NC
Elevation:	244.66 m
Rock Type:	Quartz Diorite
Depth to water:	
Depth of casing:	16.15 m
Depth of well:	121.92 m

Fracture Characteristics					
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	18.42	9.42	189.42	29.71	t
2	20.38	3.11	237.49	73.58	p
3	22.16	27.89	158.18	4.79	s
4	22.2	6.95	151.99	6.38	s
5	26.87	10.93	160.37	6.39	s
6	26.92	10	270	0	s
7	26.97	6.87	165.22	11.22	s
8	31.62	6.3	31.74	25.88	t
9	32.4	7.48	277.72	47.2	t
10	49.37	10.45	61.78	18.29	s
11	49.95	7.27	35.88	23.82	s
12	50.15	12.77	32.67	23.34	s
13	70.1	5.513	275.9	56.6	t

Appendix C-43. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: LT-2D	#	%
Total Fractures:	13	100.00
Total above 90 m:	13	100.00
Total above 60 m:	12	92.31
Total above 30 m:	7	53.85
FPFs:	1	7.69
Sheet:	8	61.54
Other:	4	30.77

Appendix C-44. Interpreted features for LT-2D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-45. Location, physical characteristics, borehole logs and interpreted structures for LT-4D.

LT-4D is located at the Langtree Peninsula site, in Cornelius, North Carolina. The PMREP constructed the well in 2001 to investigate the effects of quartz diorite and massive (weakly foliated) biotite gneiss rock types with moderate to steeply dipping foliation on groundwater quality, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures. The well was drilled to 121.92 meters and cased 16.15 meters below the land surface. The well was drilled to 121.92 meters and cased 21.03 meters below the land surface. The well is 244.40 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. LT-4D intersects bedrock composed of quartz diorite.

A total of 18 fractures were measured. Of the total number of fractures, 1 is a sheet joint, 16 are classified as other fractures and 1 is a foliation parallel fracture.

Appendix C-46. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from LT-4D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	LT-4D
Location:	Langtree Research Station Site, Iredell County, NC
Elevation:	244.40 m
Rock Type:	Quartz Diorite
Depth of casing:	21.03 m
Depth of well:	121.92 m

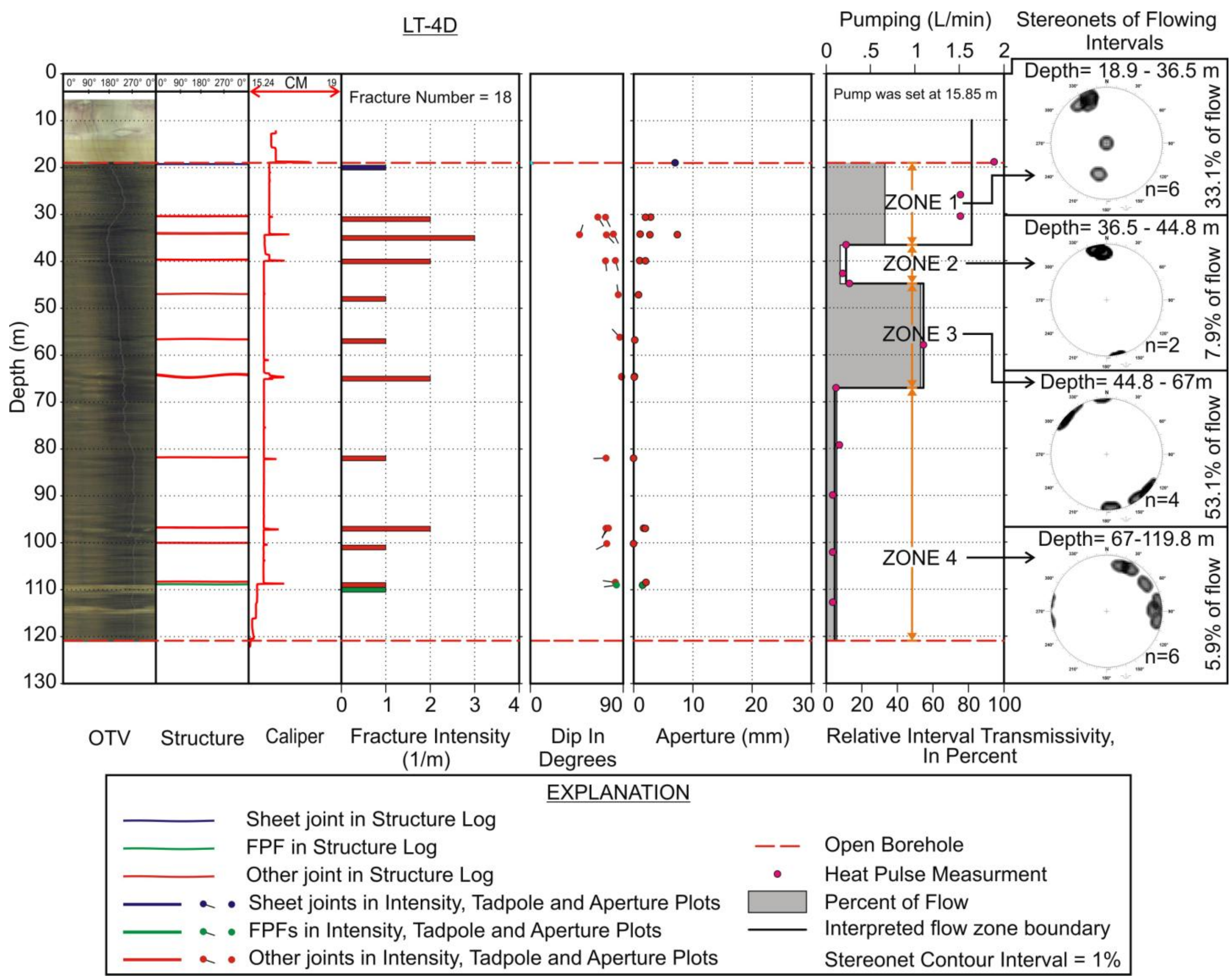
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	21.04	7	268.58	0	s
2	32.62	2.89	65.43	65.65	t
3	32.65	2.02	68.74	73.21	t
4	36.23	1.12	68.74	80.77	t
5	36.35	7.39	283.7	47.77	t
6	36.38	2.77	55.04	73.93	t
7	41.89	1.03	78.66	82.6	t
8	41.93	2.02	85.28	73.21	t
9	49.18	0.85	265.4	85.6	t
10	58.82	0.22	234.9	86.8	t
11	66.57	0.16	42.86	89.47	t
12	66.72	0.12	36.68	89.45	t
13	84.01	0	178.35	73.44	t
14	98.95	1.7	118.82	75.98	t
15	98.98	1.99	107.01	73.44	t
16	102.23	0	145.28	74.15	t
17	110.5	2.1	190.16	82.59	t
18	111.06	1.5	170.31	83.85	p

Appendix C-47. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: LT-4D	#	%
Total Fractures:	18	100.00
Total above 90 m:	13	72.22
Total above 60 m:	10	55.56
Total above 30 m:	1	5.56
FPFs:	1	5.56
Sheet:	1	5.56
Other:	16	88.89

Appendix C-48. Interpreted features for LT-4D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-49. Location, physical characteristics, borehole logs and interpreted structures for LT-5D.

LT-5D is located at the Langtree Peninsula site, in Cornelius, North Carolina. The PMREP constructed the well in 2001 to investigate the effects of quartz diorite and massive (weakly foliated) biotite gneiss rock types with moderate to steeply dipping foliation on groundwater quality, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures. The well was drilled to 121.92 meters and cased 16.15 meters below the land surface. The well was drilled to 121.92 meters and cased 12.19 meters below the land surface. The well is 239.18 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. LT-5D intersects bedrock composed of quartz diorite.

A total of 13 fractures were measured. Of the total number of fractures, 10 are sheet joints and 3 are classified as other fractures.

Appendix C-50. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from LT-5D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	LT-5D
Location:	Langtree Research Station Site, Iredell County, NC
Elevation:	239.18 m
Rock Type:	Quartz Diorite
Depth to water:	
Depth of casing:	12.19 m
Depth of well:	121.92 m

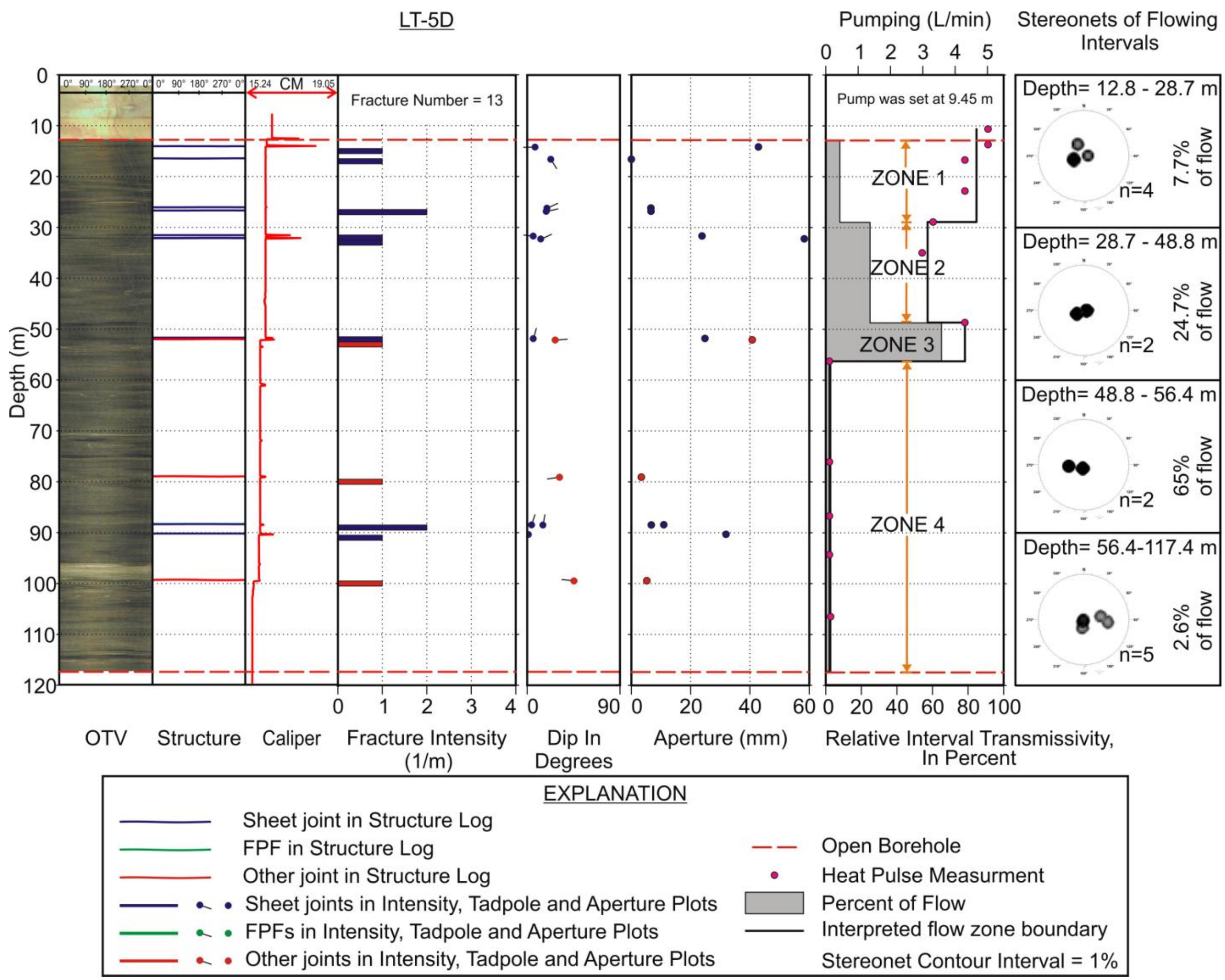
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	14.19	42.87	179.43	7.97	s
2	16.6	0	63.24	23.27	s
3	26.19	6.61	331.75	19.29	s
4	26.83	6.63	344.56	18.78	s
5	31.68	23.86	187.66	6.28	s
6	32.24	58.34	331.3	13.5	s
7	51.83	24.85	283.27	6.28	s
8	52.12	40.81	354.17	27.48	t
9	79.09	3.4	169.82	31.8	t
10	88.45	10.97	285.1	4.57	s
11	88.48	6.74	278.23	15.64	s
12	90.32	31.93	232.03	0	s
13	99.44	5.26	186.75	45.57	t

Appendix C-51. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: LT-5D	#	%
Total Fractures:	13	100.00
Total above 90 m:	11	84.62
Total above 60 m:	8	61.54
Total above 30 m:	4	30.77
FPFs:	0	0.00
Sheet:	10	76.92
Other:	3	23.08

Appendix C-52. Interpreted features for LT-5D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-53. Location, physical characteristics, borehole logs and interpreted structures for LT-6D.

LT-6D is located at the Langtree Peninsula site, in Cornelius, North Carolina. The PMREP constructed the well in 2001 to investigate the effects of quartz diorite and massive (weakly foliated) biotite gneiss rock types with moderate to steeply dipping foliation on groundwater quality, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures. The well was drilled to 121.92 meters and cased 16.15 meters below the land surface. The well was drilled to 121.92 meters and cased 21.03 meters below the land surface. The well is 233.43 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. LT-6D intersects bedrock composed of quartz diorite.

A total of 10 fractures were measured. Of the total number of fractures, 1 is a sheet joint, 6 are classified as other fractures, and 3 are foliation parallel fractures.

Appendix C-54. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from LT-6D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

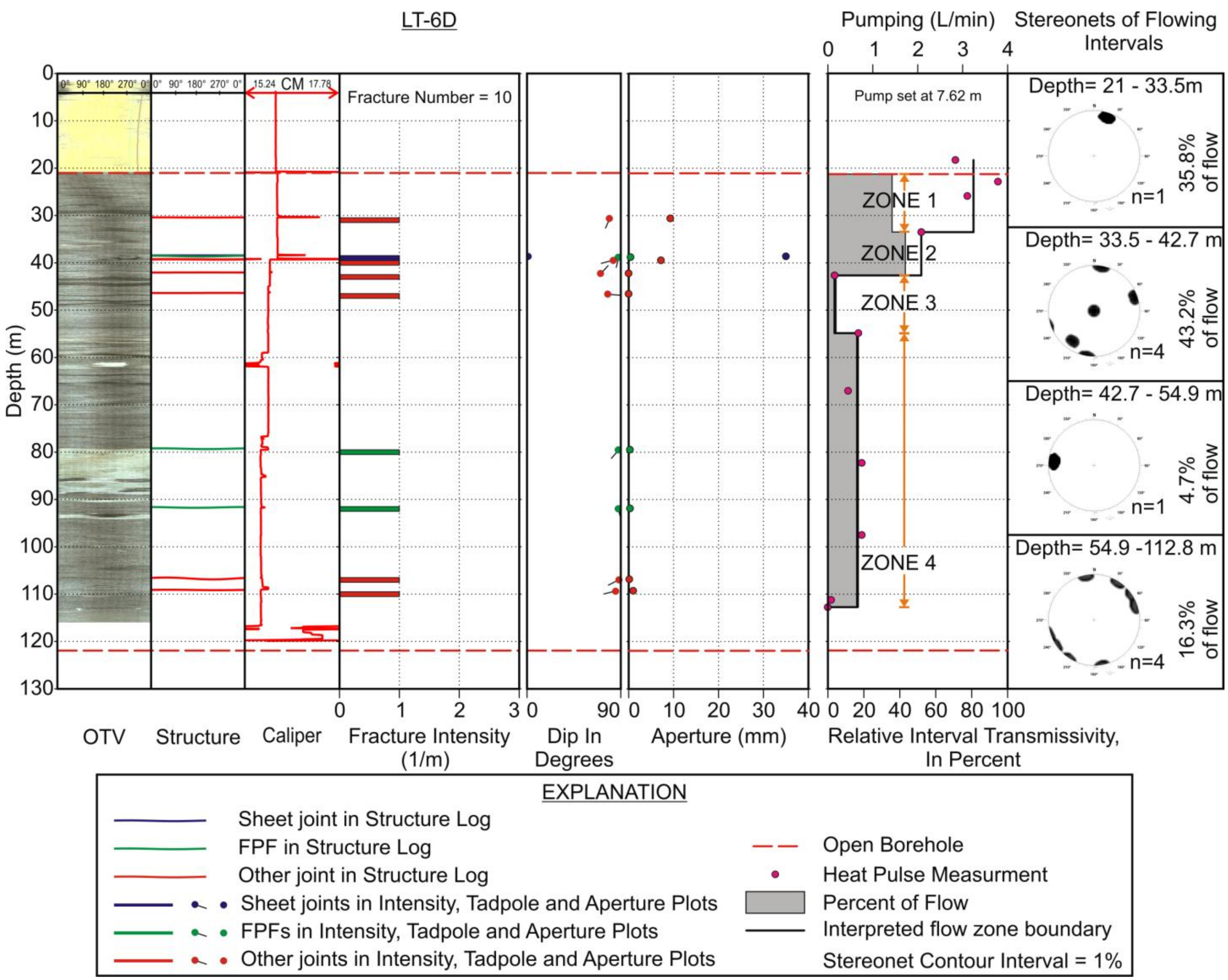
Well ID:	LT-6D
Location:	Langtree Research Station Site, Iredell County, NC
Elevation:	233.43 m
Rock Type:	Quartz Diorite
Depth of casing:	21.03 m
Depth of well:	121.92 m

Fracture Characteristics					
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	30.6	9.28	108.43	79.43	t
2	38.62	35	271.42	0	s
3	38.78	0.39	99.45	87.96	p
4	39.46	7.21	161.34	83.03	t
5	42.22	0	304.96	70.81	t
6	46.56	0	4.96	77.84	t
7	79.44	0.27	123.07	87.79	p
8	91.85	0.28	79.84	87.72	p
9	106.85	0.18	146.34	89.09	t
10	109.27	1.03	161.81	85.47	t

Appendix C-55. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: LT-6D	#	%
Total Fractures:	10	100.00
Total above 90 m:	7	70.00
Total above 60 m:	6	60.00
Total above 30 m:	0	0.00
FPFs:	3	30.00
Sheet:	1	10.00
Other:	6	60.00

Appendix C-56. Interpreted features for LT-6D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-57. Location, physical characteristics, borehole logs and interpreted structures for MT-N1D.

MT-N1D is located on Wentworth Street, Reidsville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Milton Terrane, a unit consisting of felsic and mafic gneiss. The well was drilled to 91.44 meters and cased 30.29 meters below the land surface. The well is 204.98 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. MT-N1D intersects bedrock composed of mafic gneiss with an interval of amphibolite from approximately 75 to 85 meters depth.

A total of 11 fractures were measured. All 11 are foliation parallel fractures.

Appendix C-58. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from MT-N1D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	MT-N1D
Location:	Upper Piedmont Research Station Site, Rockingham County, NC
Elevation:	204.98 m
Rock Type:	Gneiss and Amphibolite
Depth of casing:	30.29 m
Depth of well:	91.44 m

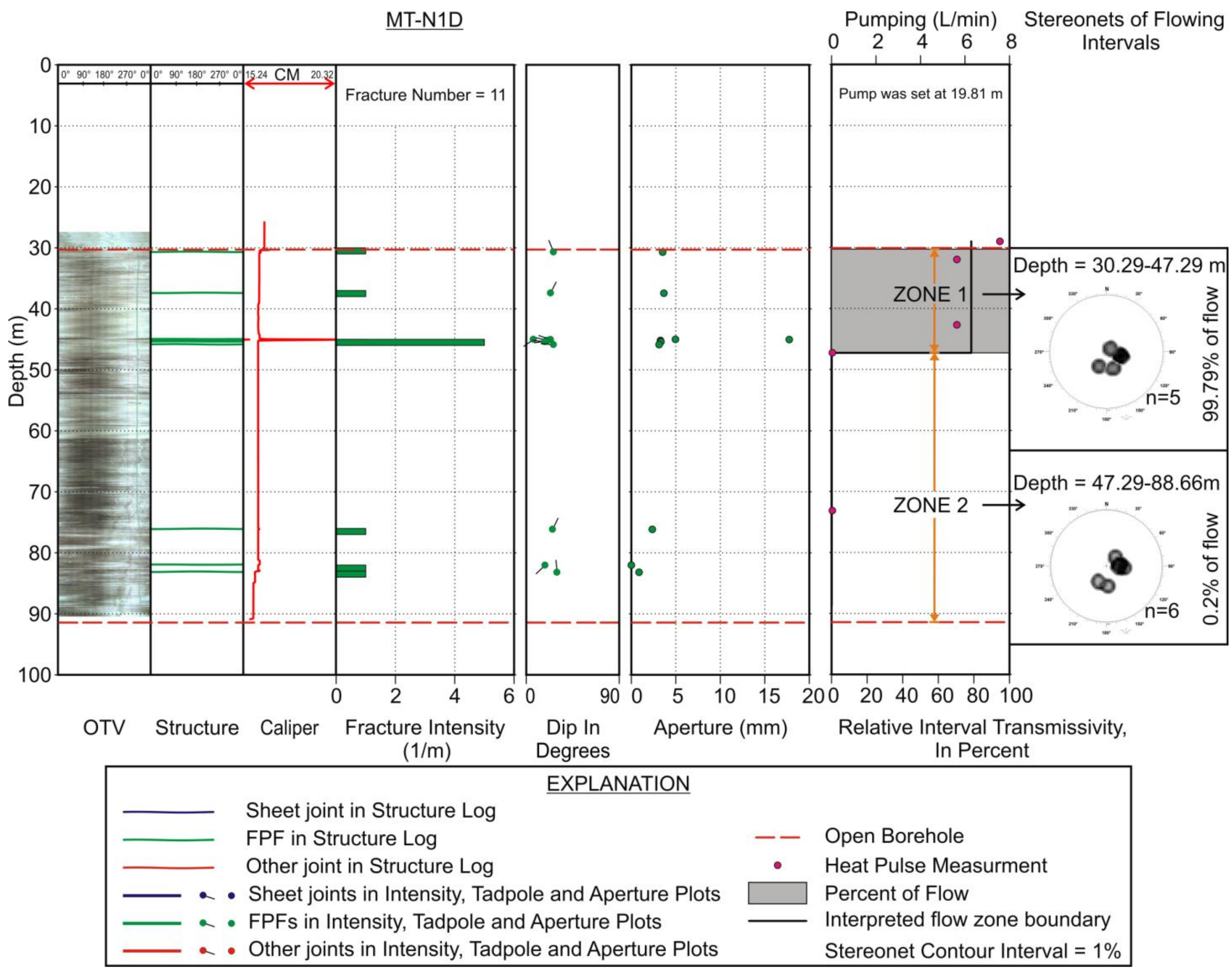
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	30.72	3.52	248.46	26.5	p
2	37.45	3.66	296.93	23.73	P
3	45.03	4.96	144.99	7.11	P
4	45.06	17.75	198.85	23.73	P
5	45.21	3.28	194.03	20.34	P
6	45.31	3.29	173.06	19.84	P
7	45.43	3.33	186.09	17.99	P
8	45.89	3.13	184.96	26.5	P
9	76.17	2.36	296.08	25.59	P
10	82.04	0.01	136.77	18.16	p
11	83.21	0.87	265.18	29.86	p

Appendix C-59. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: MT-N1D	#	%
Total Fractures:	11	100.00
Total above 90 m:	11	100.00
Total above 60 m:	8	72.73
Total above 30 m:	0	0.00
FPFs:	11	100.00
Sheet:	0	0.00
Other:	0	0.00

Appendix C-60. Interpreted features for MT-N1D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-61. Location, physical characteristics, borehole logs and interpreted structures for MT-N2D.

MT-N2D is located on Wentworth Street, Reidsville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Milton Terrane, a unit consisting of felsic and mafic gneiss. The well was drilled to 91.44 meters and cased 18.28 meters below the land surface. The well is 204.79 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. MT-N2D intersects bedrock composed of mafic gneiss.

A total of 19 fractures were measured. Of the total number of fractures, 3 are sheet joints and 16 are foliation parallel fractures.

Appendix C-62. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from MT-N2D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	MT-N2D
Location:	Upper Piedmont Research Station Site, Rockingham County, NC
Elevation:	204.79 m
Rock Type:	Mafic Gneiss
Depth of casing:	18.28 m
Depth of well:	91.44 m

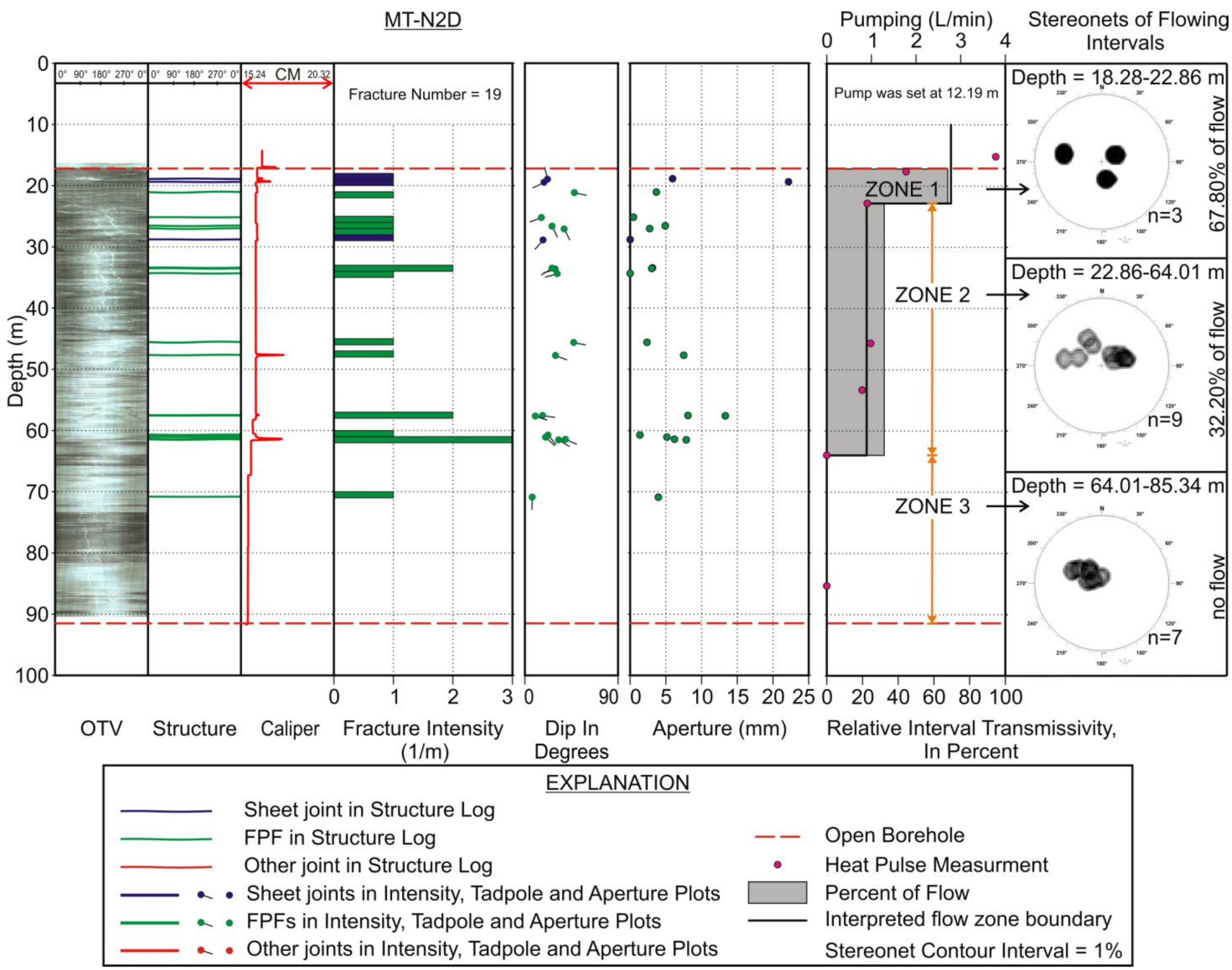
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	18.89	5.95	255.12	22.14	s
2	19.4	22.18	155.2	18.84	s
3	21.08	3.68	10.98	48.04	p
4	25.18	0.48	161.22	16.28	p
5	26.59	4.92	64.84	26.5	p
6	27.04	2.75	62.36	38.1	p
7	28.82	0	132.52	17.82	s
8	33.45	3.13	149.88	26.5	p
9	33.56	3.04	163.7	29.58	p
10	34.35	0	165.12	31.53	p
11	45.61	2.37	9.92	47.45	p
12	47.72	7.51	19.84	30	p
13	57.55	8.11	7.44	17.31	p
14	57.62	13.34	17.72	10.41	p
15	60.76	1.38	49.96	22.62	p
16	61.09	5.16	41.46	20.18	p
17	61.44	6.22	23.39	39.58	p
18	61.54	7.86	31.18	32.74	p
19	70.9	3.97	88.94	7.29	p

Appendix C-63. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: MT-N2D	#	%
Total Fractures:	19	100.00
Total above 90 m:	19	100.00
Total above 60 m:	14	73.68
Total above 30 m:	7	36.84
FPFs:	16	84.21
Sheet:	3	15.79
Other:	0	0.00

Appendix C-64. Interpreted features for MT-N2D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-65. Location, physical characteristics, borehole logs and interpreted structures for MT-N3D.

MT-N3D is located on Wentworth Street, Reidsville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Milton Terrane, a unit consisting of felsic and mafic gneiss. The well was drilled to 79.24 meters and cased 12.19 meters below the land surface. The well is 234.77 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. MT-N3D intersects bedrock composed of felsic gneiss above 48 m and mafic gneiss below 51 m with an interval of Mylonite from approximately 48 to 51 meters depth.

A total of 19 fractures were measured. Of the total number of fractures, 16 are foliation parallel fractures, and 3 are classified as other fractures.

Appendix C-66. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from MT-N3D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	MT-N3D
Location:	Upper Piedmont Research Station Site, Rockingham County, NC
Elevation:	234.77 m
Rock Type:	Gneiss and Mylonite
Depth of casing:	12.19 m
Depth of well:	79.24 m

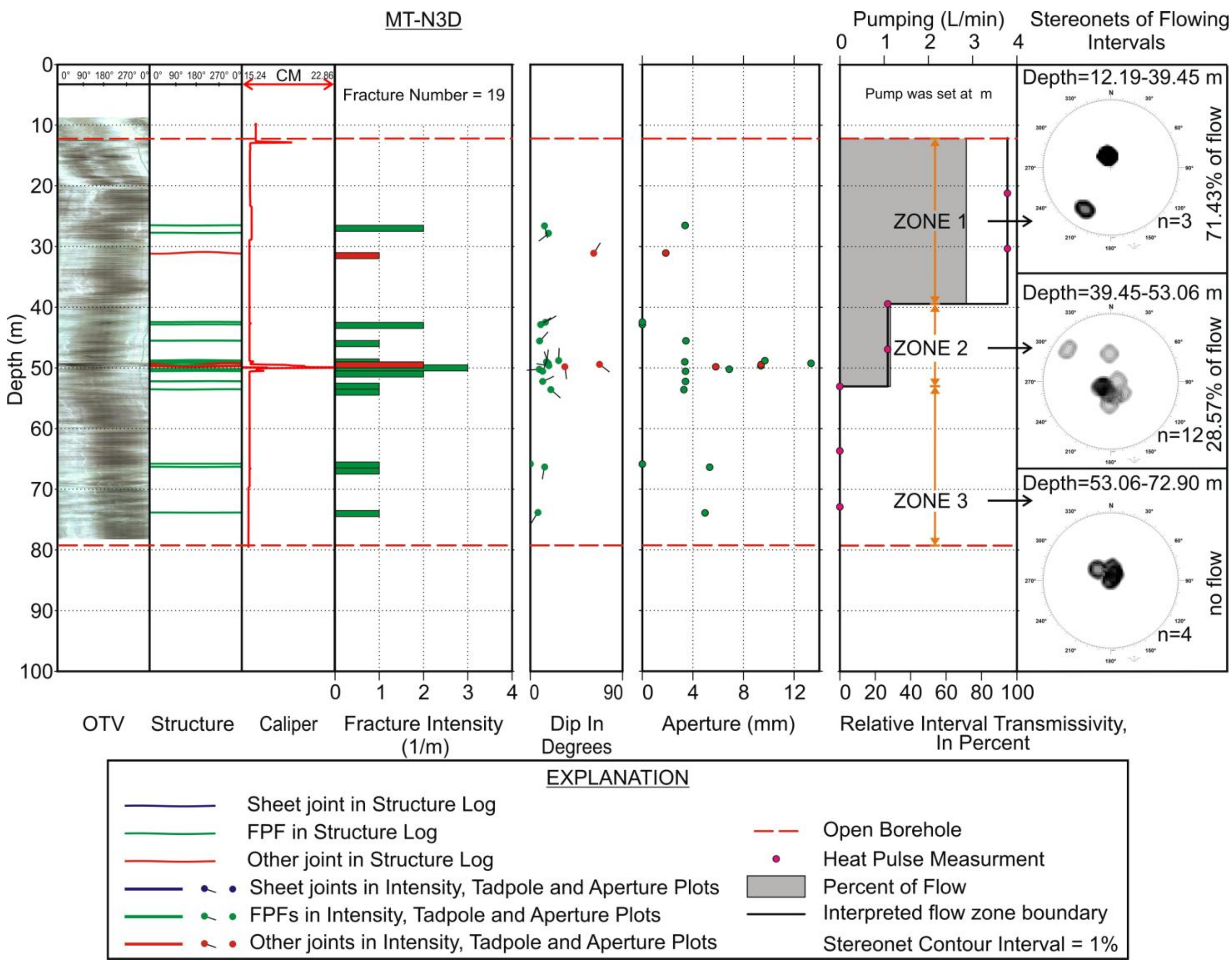
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	26.54	3.39	76.18	14.18	p
2	27.77	6.66	76.2	14.2	P
3	31.07	1.87	301.2	62.2	t
4	42.48	0	329.17	15.06	p
5	42.88	0	324.92	10.41	p
6	45.56	3.45	311.1	9.32	p
7	48.8	9.71	272.48	27.99	p
8	49.02	3.36	277.44	16.11	p
9	49.27	13.35	251.57	17.48	p
10	49.46	9.4	36.5	67.91	t
11	49.68	9.38	225.35	20.18	p
12	49.83	5.82	87.52	33.79	t
13	50.24	6.88	175.75	8.95	p
14	50.57	3.42	288.78	12.4	p
15	52.26	3.42	333.78	12.4	p
16	53.6	3.29	40.04	20.18	p
17	65.87	0	270	0	p
18	66.39	5.33	98.15	14.35	p
19	73.93	4.96	120.12	7.85	p

Appendix C-67. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: MT-N3D	#	%
Total Fractures:	19	100.00
Total above 90 m:	19	100.00
Total above 60 m:	16	84.21
Total above 30 m:	2	10.53
FPFs:	16	84.21
Sheet:	0	0.00
Other:	3	15.79

Appendix C-68. Interpreted features for MT-N3D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-69. Location, physical characteristics, borehole logs and interpreted structures for MT-N4D.

MT-N4D is located on Wentworth Street, Reidsville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Milton Terrane, a unit consisting of felsic and mafic gneiss. The well was drilled to 91.44 meters and cased 24.38 meters below the land surface. The well is 256.09 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. The USGS report suggests that MT-N4D intersects bedrock composed of felsic gneiss with an interval of Mylonite from approximately 85 - 92 meters depth (Huffman et al., 2006). However, visual inspection of the image log provides little evidence of mylonite near the bottom of the well. Further inspection using a video log or other down-hole tools may be necessary to confirm the presence of mylonite.

A total of 20 fractures were measured. All 20 are foliation parallel fractures.

Appendix C-70. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from MT-N4D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

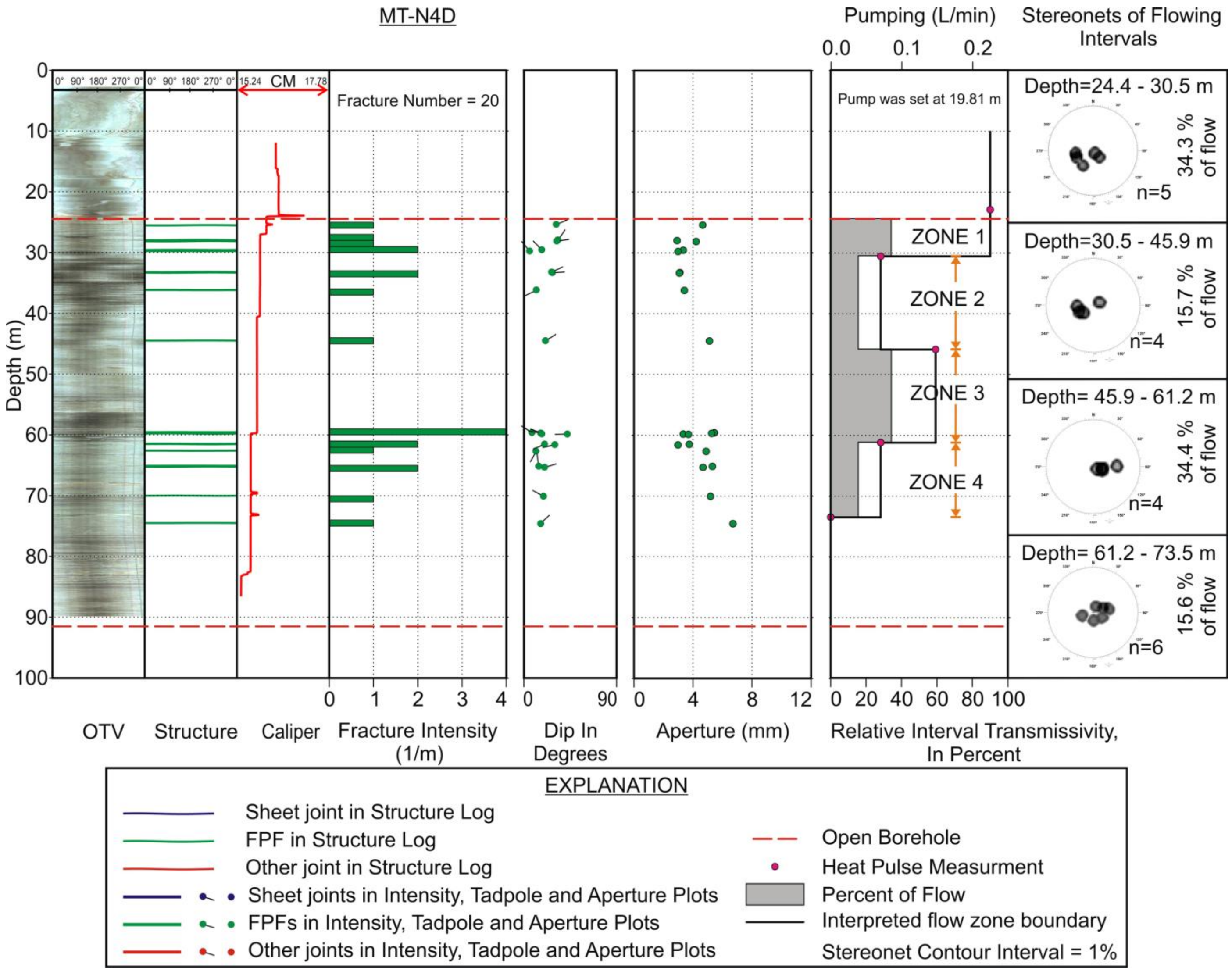
Well ID:	MT-N4D
Location:	Upper Piedmont Research Station Site, Rockingham County, NC
Elevation:	256.09 m
Rock Type:	Gneiss and Mylonite
Depth of casing:	24.38 m
Depth of well:	91.44 m

Fracture Characteristics					
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	25.42	4.67	336.61	31.8	p
2	27.97	2.93	303.66	33.22	p
3	28.14	4.23	351.5	32.21	p
4	29.58	3.34	226.06	17.48	p
5	29.79	2.99	231.38	5.71	p
6	33.24	3.12	335.2	27.02	p
7	33.33	3.09	356.1	27.92	p
8	36.19	3.42	154.84	12.41	p
9	44.51	5.12	323.5	21.3	p
10	59.61	5.45	212.6	7.97	p
11	59.7	5.27	188.86	16.7	p
12	59.82	3.34	201.26	17.48	p
13	59.85	3.7	178.94	42.3	p
14	61.5	3.75	157.68	20.31	p
15	61.59	2.99	167.6	30.11	p
16	62.67	4.89	119.76	12.13	p
17	65.14	5.32	262.91	14.57	p
18	65.3	4.69	342.64	20.3	p
19	70.08	5.19	207.28	19.29	p
20	74.57	6.71	310.04	16.7	p

Appendix C-71. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: MT-N4D	#	%
Total Fractures:	20	100.00
Total above 90 m:	20	100.00
Total above 60 m:	13	65.00
Total above 30 m:	5	25.00
FPFs:	20	100.00
Sheet:	0	0.00
Other:	0	0.00

Appendix C-72. Interpreted features for MT-N4D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-73. Location, physical characteristics, borehole logs and interpreted structures for MT-S3D.

MT-S3D is located on Wentworth Street, Reidsville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Milton Terrane, a unit consisting of felsic and mafic gneiss. The well was drilled to 133.50 meters and cased 26.67 meters below the land surface. The well is 215.03 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. MT-S3D intersects bedrock composed of Felsic gneiss.

A total of 30 fractures were measured. All 30 are foliation parallel fractures.

Appendix C-74. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from MT-S3D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	MT-S3D
Location:	Upper Piedmont Research Station Site, Rockingham County, NC
Elevation:	215.03 m
Rock Type:	Felsic Gneiss
Depth of casing:	26.67 m
Depth of well:	133.50 m

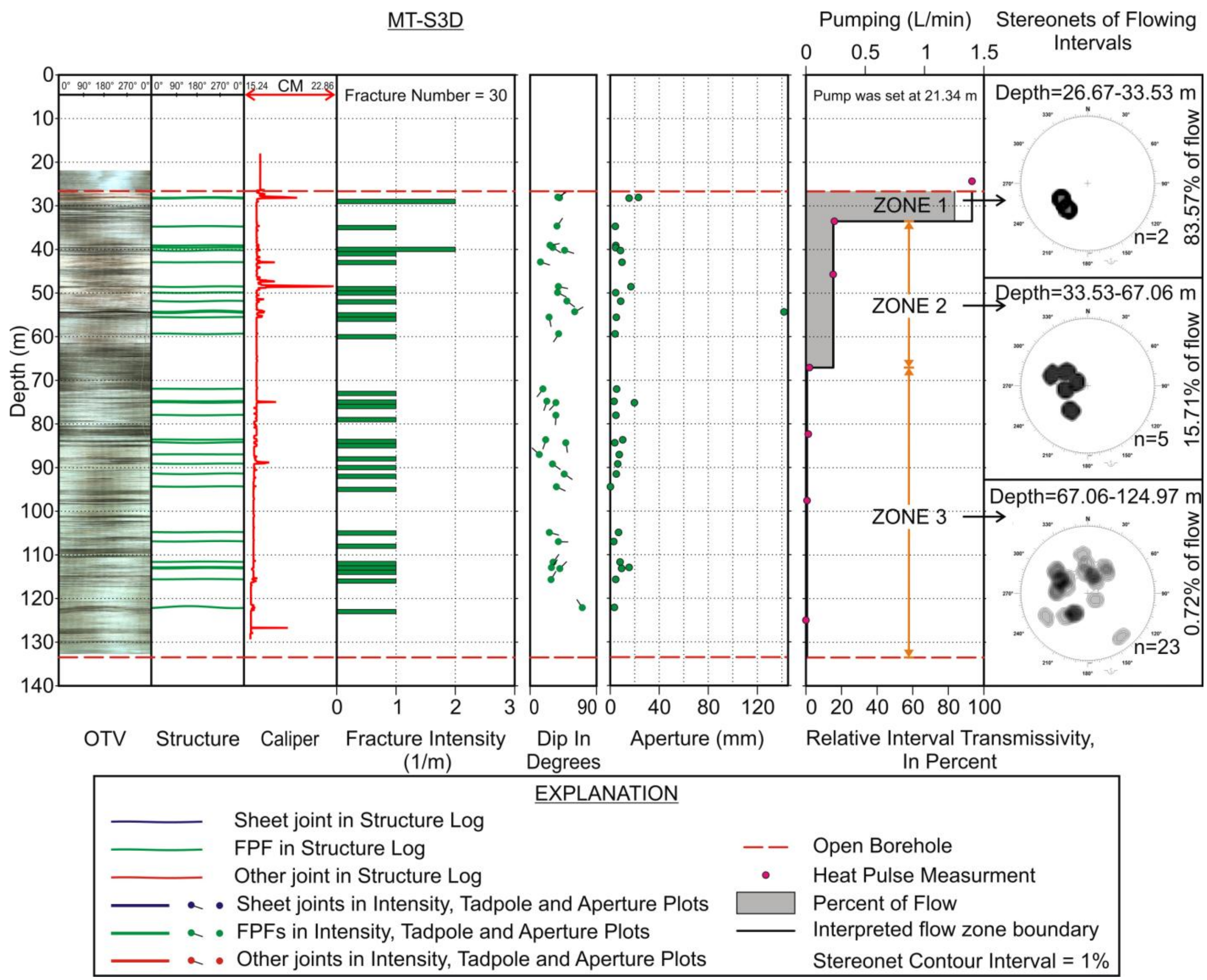
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	28.11	22.9	328.11	37.85	p
2	28.26	15.3	308.98	40.28	p
3	34.73	4.01	303.66	36.76	p
4	39.12	4.44	350.08	27.36	p
5	39.62	4.29	32.6	30.78	p
6	40.28	8.28	17.01	46.94	p
7	42.96	9.69	17.36	14.27	p
8	48.57	16.81	6.38	38.55	p
9	49.95	4.37	26.57	37.44	p
10	51.91	8.37	36.14	49.92	p
11	54.35	141.52	329.88	60.55	p
12	55.59	4.81	80.08	25.98	p
13	59.4	3.89	123.66	39.02	p
14	72.04	5.25	127.56	17.51	p
15	74.87	3.22	111.26	22.97	p
16	75.17	19.63	133.58	35	p
17	78.06	4.5	88.58	35.12	p
18	83.68	10.24	104.88	21.47	p
19	84.35	3.62	82.2	48.78	p
20	87.06	7.4	220.04	12.63	p
21	89.21	6.02	35.08	30.68	p
22	91.52	4.81	34.02	46.53	p
23	94.44	0	24.8	36.02	p
24	104.91	6.71	14.88	26.34	p
25	107.02	2.74	0.35	38.4	p
26	111.71	7.93	304.02	31.45	p
27	112.94	15.26	305.08	29.32	p
28	113.18	9.14	313.94	40.42	p
29	115.7	4.39	299.76	28.5	p
30	122.12	3.28	232.44	70.87	p

Appendix C-75. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: MT-S3D	#	%
Total Fractures:	30	100.00
Total above 90 m:	21	70.00
Total above 60 m:	13	43.33
Total above 30 m:	2	6.67
FPFs:	30	100.00
Sheet:	0	0.00
Other:	0	0.00

Appendix C-76. Interpreted features for MT-S3D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-77. Location, physical characteristics, borehole logs and interpreted structures for MT-S4D.

MT-S4D is located on Wentworth Street, Reidsville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Milton Terrane, a unit consisting of felsic and mafic gneiss. The well was drilled to 115.82 meters and cased 23.46 meters below the land surface. The well is 201.03 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. MT-S4D intersects bedrock composed of felsic gneiss with an interval of amphibolite from approximately 23 to 60 meters depth.

A total of 16 fractures were measured. Of the total number of fractures, 5 are classified as other fractures and 11 are foliation parallel fractures.

Appendix C-78. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from MT-S4D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	MT-S4D
Location:	Upper Piedmont Research Station Site, Rockingham County, NC
Elevation:	201.03 m
Rock Type:	Gneiss and Amphibolite
Depth of casing:	23.46 m
Depth of well:	115.82 m

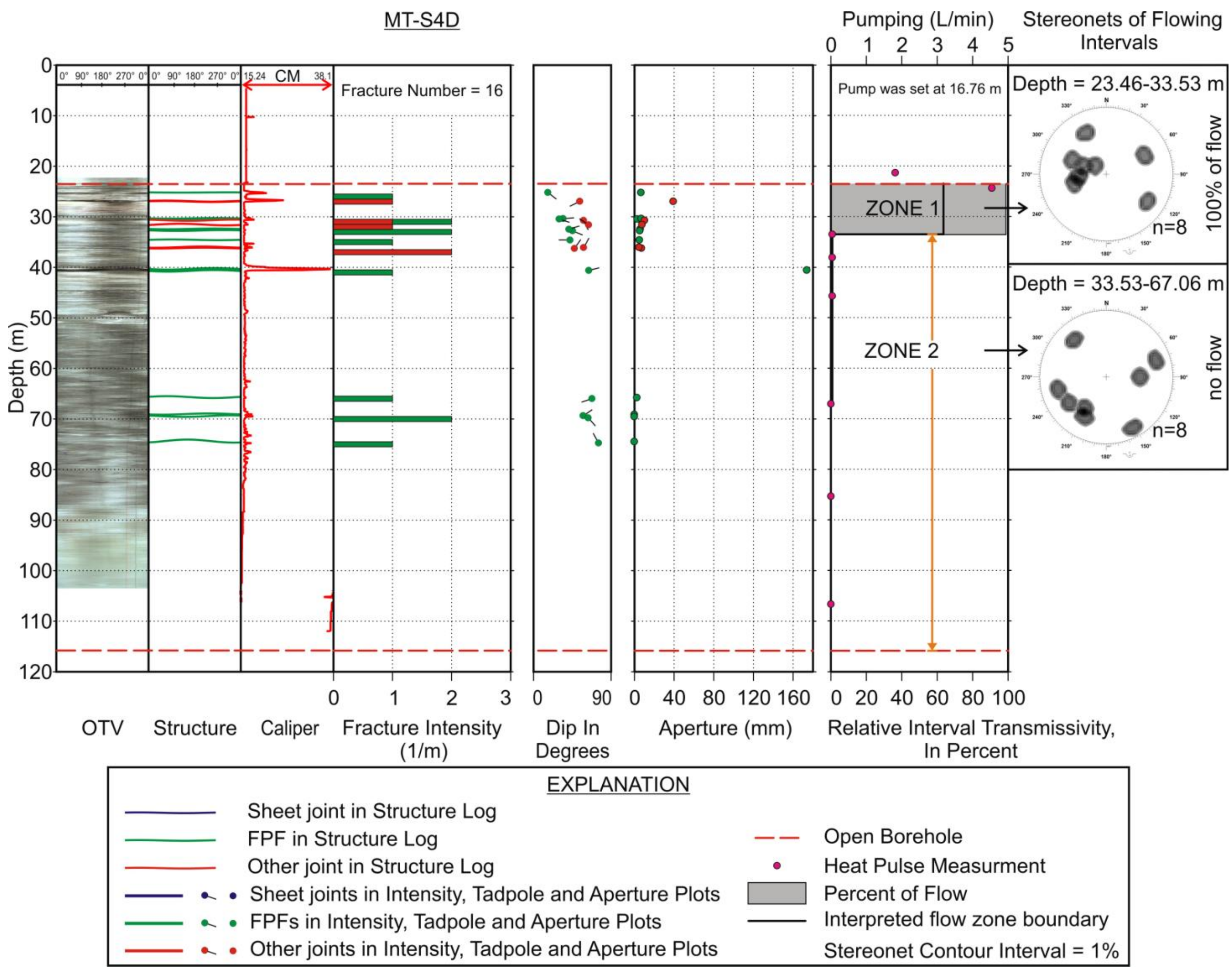
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	25.19	6.7	37.91	16.8	p
2	26.94	38.24	154.49	53.77	t
3	30.33	7.02	355.04	34.31	p
4	30.42	3.03	17.36	30	p
5	30.7	9.2	63.43	58.27	t
6	31.55	6.65	213.66	63.97	t
7	32.42	6.01	344.06	41.32	p
8	32.73	5.61	22.32	45.48	p
9	34.57	5.15	180	42.57	p
10	36.02	3.68	298.7	58.33	t
11	36.2	6.09	305.08	47.45	t
12	40.52	174	345.83	64.11	p
13	65.74	2.64	161.57	67.83	p
14	69.09	0	325.28	57.8	p
15	69.51	0	48.54	63.52	p
16	74.45	0	242.36	75.66	p

Appendix C-79. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: MT-S4D	#	%
Total Fractures:	16	100.00
Total above 90 m:	16	100.00
Total above 60 m:	12	75.00
Total above 30 m:	2	12.50
FPFs:	11	68.75
Sheet:	0	0.00
Other:	5	31.25

Appendix C-80. Interpreted features for MT-S4D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-81. Location, physical characteristics, borehole logs and interpreted structures for TT-1D.

TT-1D is located at the Bent Creek research station in Asheville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Tugaloo Terrane, a unit consisting of interlayered, migmatitic schist and(or) metagraywacke. The well was drilled to 67.113 meters and cased 16.86 meters below the land surface. The well is 671.10 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. TT-1D intersects bedrock composed of Migmatitic schist and metagraywacke.

A total of 10 fractures were measured. Of the total number of fractures, 6 are classified as other fractures, and 4 are foliation parallel fractures.

Appendix C-82. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from TT-1D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	TT-1D
Location:	Bent Creek Research Station, Buncombe County, NC
Elevation:	671.10 m
Rock Type:	Migmatitic schist and metagraywacke
Depth of casing:	16.86 m
Depth of well:	67.113 m

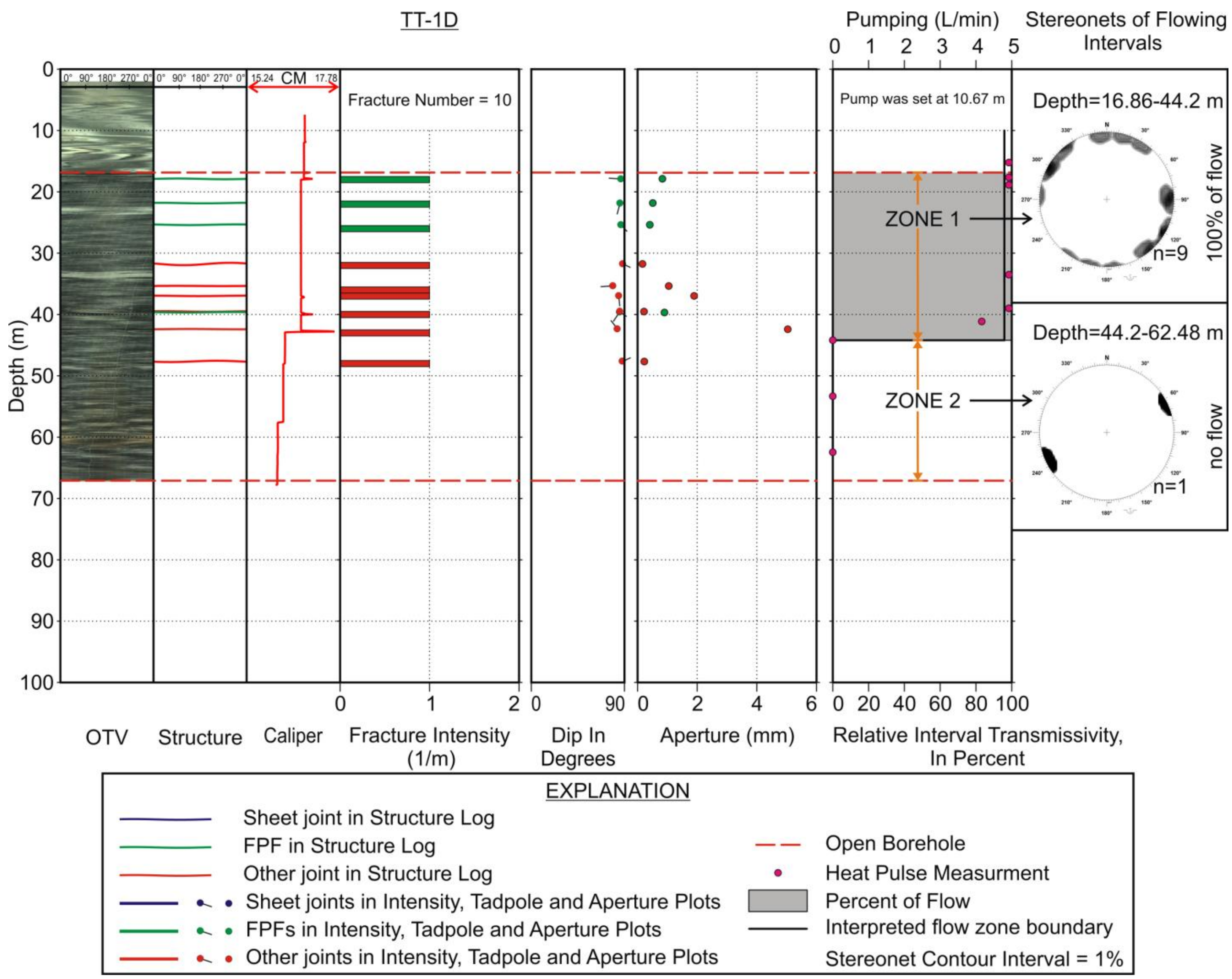
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	17.88	0.83	183.2	86.62	p
2	21.83	0.51	104.65	85.82	p
3	25.37	0.41	47.31	86.67	p
4	31.78	0.17	25.45	89.02	t
5	35.37	1.05	177.1	79.04	t
6	36.99	1.9	84.97	84.7	t
7	39.54	0.22	123.03	85.72	t
8	39.67	0.9	31.85	85.62	p
9	42.42	5.04	232.98	83.29	t
10	47.69	0.23	334.55	88.27	t

Appendix C-83. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: TT-1D	#	%
Total Fractures:	10	100.00
Total above 90 m:	10	100.00
Total above 60 m:	10	100.00
Total above 30 m:	3	30.00
FPFs:	4	40.00
Sheet:	0	0.00
Other:	6	60.00

Appendix C-84. Interpreted features for TT-1D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-85. Location, physical characteristics, borehole logs and interpreted structures for TT-2D.

TT-2D is located at the Bent Creek research station in Asheville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Tugaloo Terrane, a unit consisting of interlayered, migmatitic schist and(or) metagraywacke. The well was drilled to 86.92 meters and cased 15.53 meters below the land surface. The well is 667.56 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. TT-2D intersects bedrock composed of Migmatitic schist and metagraywacke.

A total of 23 fractures were measured. Of the total number of fractures, 7 are classified as other fractures and 16 are foliation parallel fractures.

Appendix C-86. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from TT-2D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	TT-2D
Location:	Bent Creek Research Station, Buncombe County, NC
Elevation:	667.56 m
Rock Type:	Migmatitic schist and metagraywacke
Depth to water:	
Depth of casing:	15.54 m
Depth of well:	86.92 m

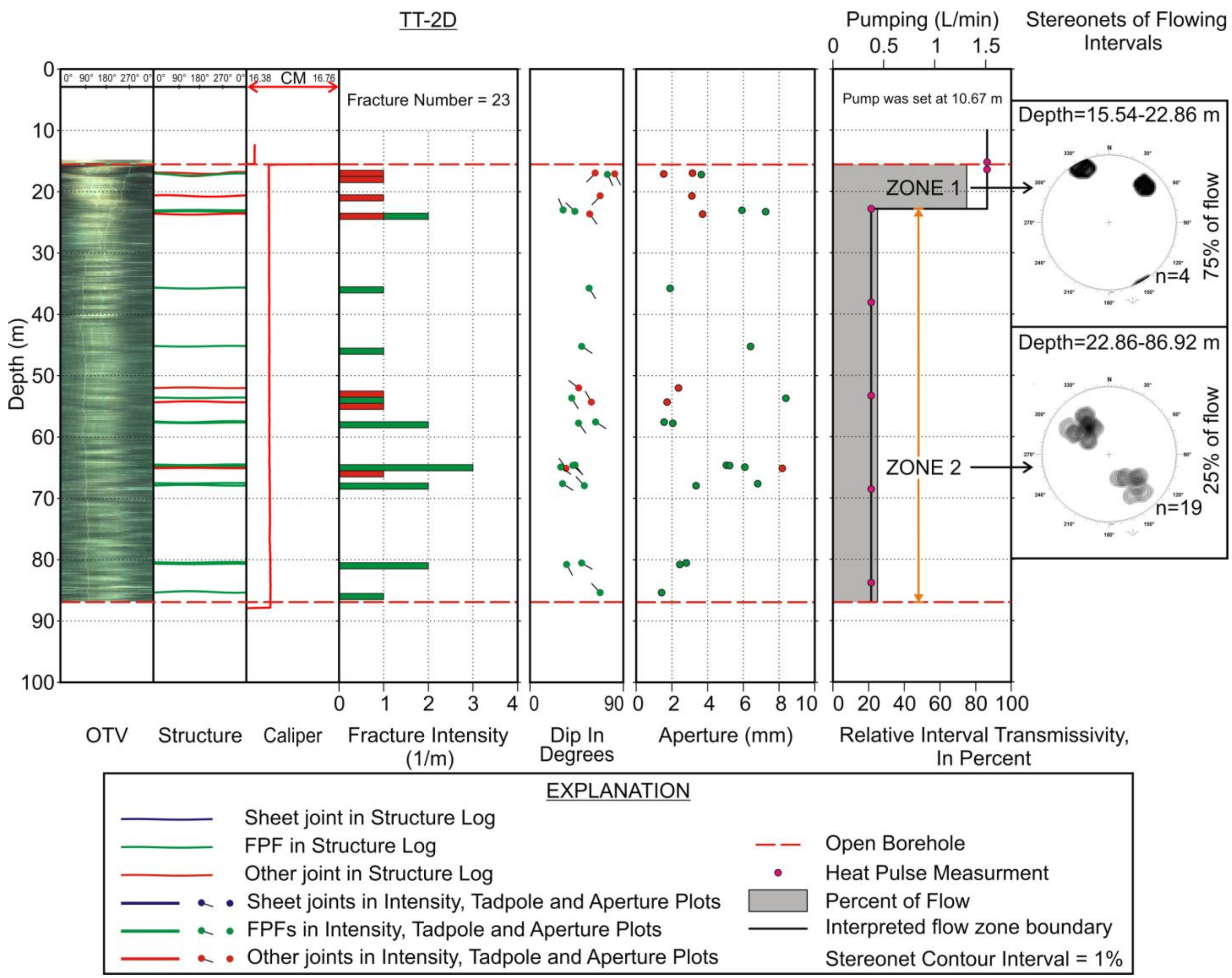
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	16.99	3.16	134.88	63.2	t
2	17.13	1.55	61.65	81.89	t
3	17.21	3.65	64.96	74.88	p
4	20.7	3.13	134.37	68.12	t
5	23.02	5.92	248.27	32.21	p
6	23.25	7.25	223.7	43.53	p
7	23.67	3.73	55.04	57.83	t
8	35.75	1.9	58.43	57.17	p
9	45.24	6.4	33.22	50.19	p
10	52.03	2.38	217.43	47.2	t
11	53.67	8.38	58.26	40.37	p
12	54.32	1.74	240.88	59.53	t
13	57.57	1.56	31.89	63.55	p
14	57.75	2.05	54.57	46.94	p
15	64.6	5.05	51.56	43.83	p
16	64.66	5.23	42.03	41.67	p
17	64.91	6.08	35.2	29.68	p
18	65.13	8.19	235.04	34.99	t
19	67.61	6.8	31.42	31.8	p
20	67.94	3.35	228.25	52.54	p
21	80.54	2.81	29.7	50.19	p
22	80.79	2.44	60.84	35.37	p
23	85.37	1.42	228	67.8	p

Appendix C-87. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: TT-2D	#	%
Total Fractures:	23	100.00
Total above 90 m:	23	100.00
Total above 60 m:	14	60.87
Total above 30 m:	7	30.43
FPFs:	16	69.57
Sheet:	0	0.00
Other:	7	30.43

Appendix C-88. Interpreted features for TT-2D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-89. Location, physical characteristics, borehole logs and interpreted structures for TT-3D.

TT-3D is located at the Bent Creek research station in Asheville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Tugaloo Terrane, a unit consisting of interlayered, migmatitic schist and(or) metagraywacke. The well was drilled to 91.144 meters and cased 16.45 meters below the land surface. The well is 673.32 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. TT-3D intersects bedrock composed of Migmatitic schist and metagraywacke.

A total of 26 fractures were measured. Of the total number of fractures, 5 are sheet joints and 21 are foliation parallel fractures.

Appendix C-90. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from TT-3D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

Well ID:	TT-3D
Location:	Bent Creek Research Station, Buncombe County, NC
Elevation:	673.32 m
Rock Type:	Migmatitic schist and metagraywacke
Depth to water:	
Depth of casing:	16.45 m
Depth of well:	91.144 m

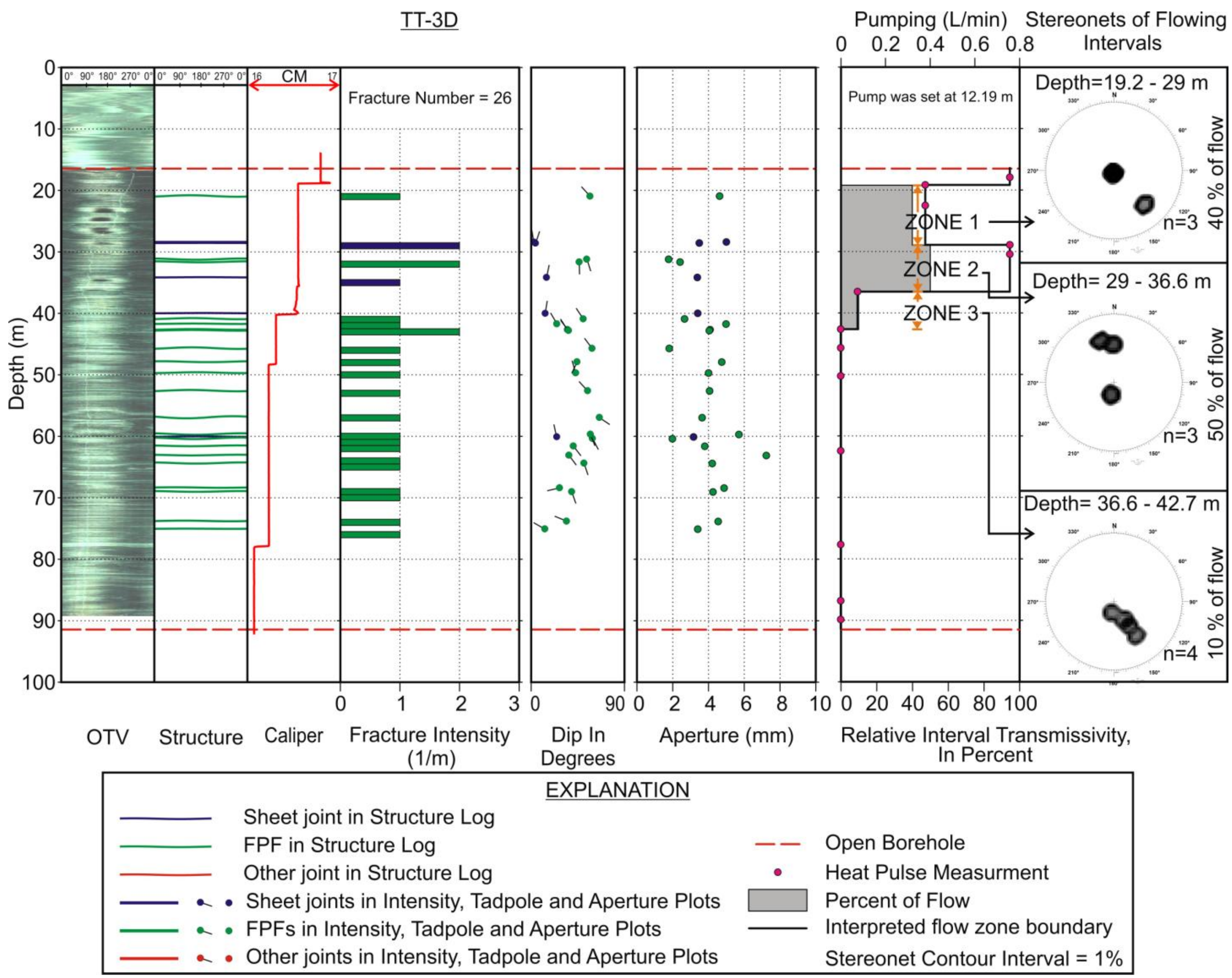
Fracture Characteristics

Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	20.93	4.62	227.75	57.04	p
2	28.41	5	261.24	2.63	s
3	28.58	3.49	289.07	4.5	s
4	31.21	1.77	72.38	53.77	p
5	31.65	2.41	89.32	46.39	p
6	34.17	3.38	282.05	15.06	s
7	40.01	3.4	278.86	13.65	s
8	40.91	2.66	236.65	50.37	p
9	41.74	4.98	240.05	25.07	p
10	42.66	4.09	237.64	34.99	p
11	42.81	4.04	233.73	36.19	p
12	45.71	1.8	233.15	59.04	p
13	47.92	4.74	115.92	44.55	p
14	49.71	4	254.05	43.28	p
15	52.63	4.06	228.52	54.54	p
16	56.97	3.64	33.7	66.14	p
17	59.7	5.7	68.31	57.15	p
18	60.12	3.17	257.63	24.96	s
19	60.4	1.98	62.09	59.33	p
20	61.62	3.79	51.36	40.68	p
21	63.13	7.23	52.69	36.56	p
22	64.42	4.21	71.48	50.97	p
23	68.42	4.87	168	27.7	p
24	69.05	4.25	70.32	39.36	p
25	73.86	4.54	202.48	34.31	p
26	75.13	3.4	210.11	13.29	p

Appendix C-91. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: TT-3D	#	%
Total Fractures:	26	100.00
Total above 90 m:	26	100.00
Total above 60 m:	17	65.38
Total above 30 m:	3	11.54
FPFs:	21	80.77
Sheet:	5	19.23
Other:	0	0.00

Appendix C-92. Interpreted features for TT-3D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-93. Location, physical characteristics, borehole logs and interpreted structures for TT-4D.

TT-4D is located at the Bent Creek research station in Asheville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Tugaloo Terrane, a unit consisting of interlayered, migmatitic schist and(or) metagraywacke. The well was drilled to 152.71 meters and cased 18.59 meters below the land surface. The well is 688.4 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. TT-4D intersects bedrock composed of Migmatitic schist and metagraywacke.

A total of 14 fractures were measured. Of the total number of fractures, 4 are classified as other fractures, and 10 are foliation parallel fractures.

Appendix C-94. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from TT-4D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

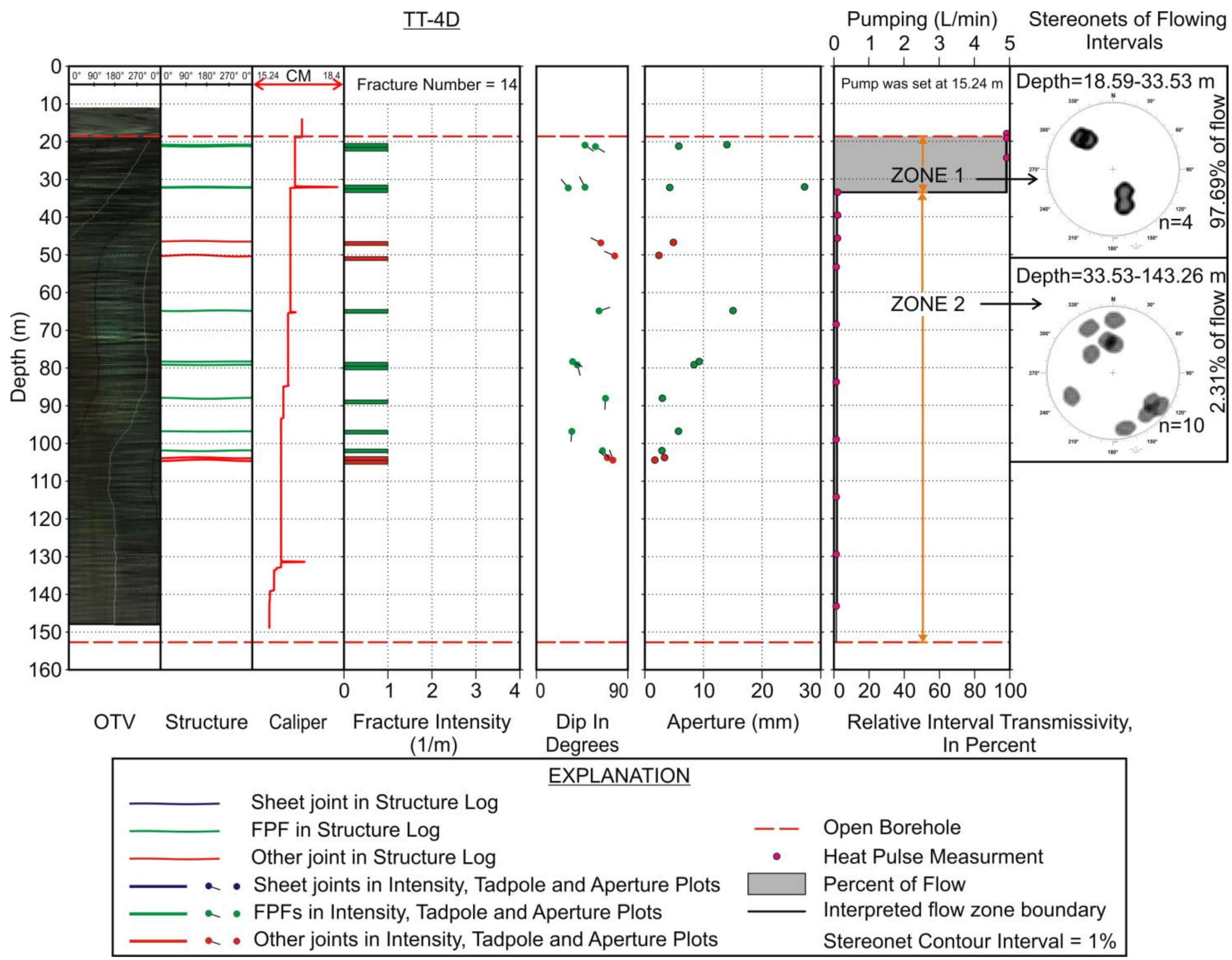
Well ID:	TT-4D
Location:	Bent Creek Research Station, Buncombe County, NC
Elevation:	688.4 m
Rock Type:	Migmatitic schist and metagraywacke
Depth of casing:	18.59 m
Depth of well:	152.71 m

Fracture Characteristics					
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	20.8	13.99	48.72	48.24	p
2	21.19	5.78	43.94	58.31	p
3	31.98	27.23	252.5	48.24	p
4	32.15	4.25	243.81	31.8	p
5	46.73	4.9	218	63.5	t
6	50.18	2.42	215	77.3	t
7	64.79	15.03	330.59	61.99	p
8	78.28	9.27	40.04	35.75	p
9	79.13	8.38	80.79	40.37	p
10	88.01	2.97	91.42	68.2	p
11	96.77	5.73	92.3	34.99	p
12	101.9	2.91	61.48	65.46	p
13	103.78	3.39	229.43	70.22	t
14	104.43	1.74	257.42	75.65	t

Appendix C-95. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: TT-4D	#	%
Total Fractures:	14	100.00
Total above 90 m:	8	57.14
Total above 60 m:	6	42.86
Total above 30 m:	2	14.29
FPFs:	10	71.43
Sheet:	0	0.00
Other:	4	28.57

Appendix C-96. Interpreted features for TT-4D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-97. Location, physical characteristics, borehole logs and interpreted structures for TT-5D.

TT-5D is located at the Bent Creek research station in Asheville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Tugaloo Terrane, a unit consisting of interlayered, migmatitic schist and(or) metagraywacke. The well was drilled to 86.87 meters and cased 18.89 meters below the land surface. The well is 702.52 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. TT-5D intersects bedrock composed of Migmatitic schist and metagraywacke.

A total of 15 fractures were measured. Of the total number of fractures, 12 are classified as other fractures, and 3 are foliation parallel fractures.

Appendix C-98. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from TT-5D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

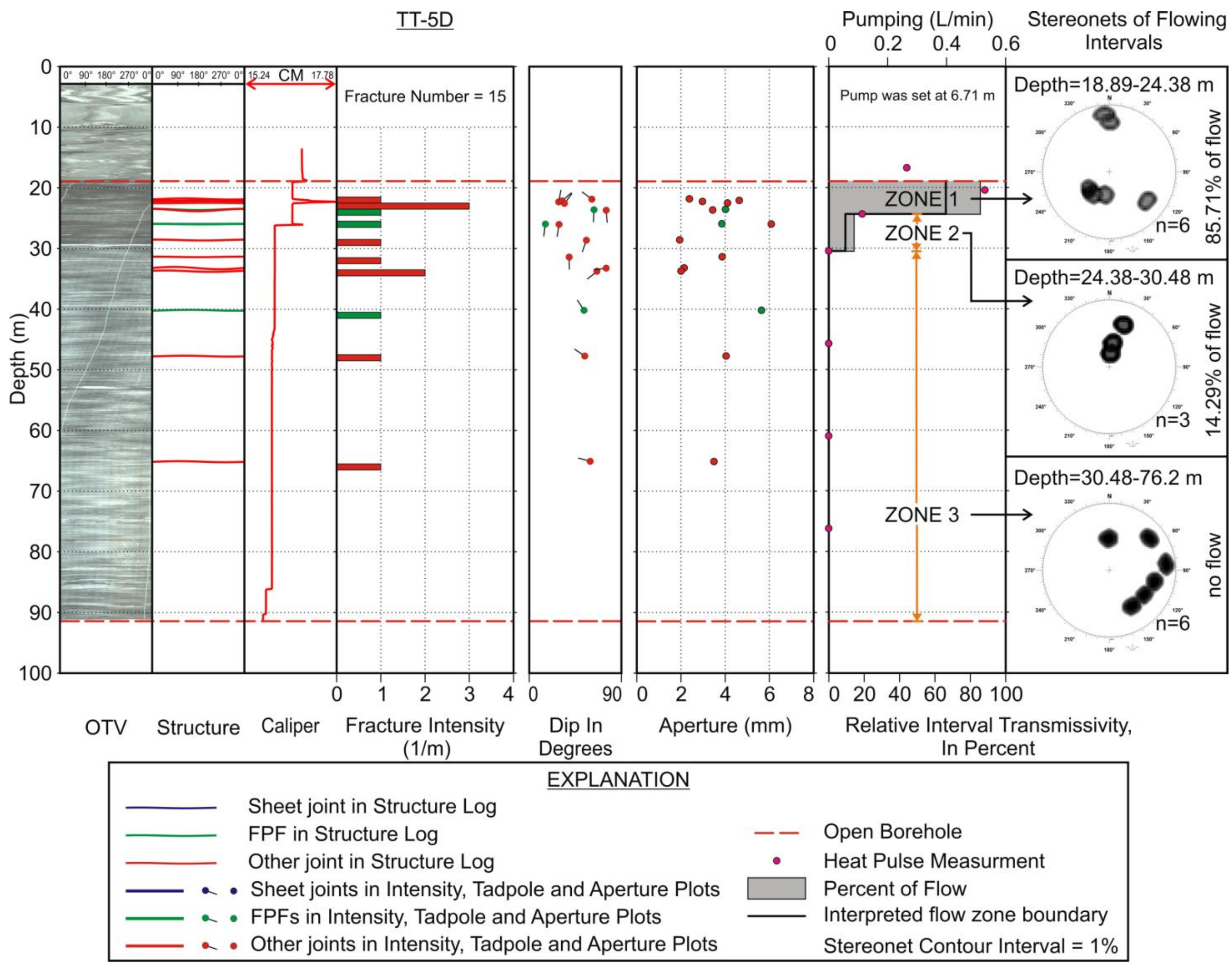
Well ID:	TT-5D
Location:	Bent Creek Research Station, Buncombe County, NC
Elevation:	702.52 m
Rock Type:	Migmatitic schist and metagraywacke
Depth of casing:	18.89 m
Depth of well:	86.87 m

Fracture Characteristics					
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	21.82	2.39	217.17	61.41	t
2	22.08	4.64	318.96	32.42	t
3	22.25	2.98	280.05	28.81	t
4	22.5	4.11	306.59	34.61	t
5	23.54	4.01	91.16	63.55	p
6	23.65	3.44	84.97	75.55	t
7	25.92	3.85	96.31	15.91	p
8	25.98	6.09	99.15	29.47	t
9	28.59	1.95	109.2	56.13	t
10	31.37	3.87	89.1	39.35	t
11	33.21	2.15	174.4	75.37	t
12	33.72	2.01	141.93	66.27	t
13	40.17	5.64	237.01	53.87	p
14	47.73	4.05	214.34	54.66	t
15	65.13	3.5	194.75	59.97	t

Appendix C-99. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: TT-5D	#	%
Total Fractures:	15	100.00
Total above 90 m:	15	100.00
Total above 60 m:	14	93.33
Total above 30 m:	9	60.00
FPFs:	3	20.00
Sheet:	0	0.00
Other:	12	80.00

Appendix C-100. Interpreted features for TT-5D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



Appendix C-101. Location, physical characteristics, borehole logs and interpreted structures for TT-7D.

TT-7D is located at the Bent Creek research station in Asheville, North Carolina. The PMREP constructed the well in 2002 to investigate ambient groundwater flow and quality in the Tugaloo Terrane, a unit consisting of interlayered, migmatitic schist and(or) metagraywacke. The well was drilled to 86.87 meters and cased 18.89 meters below the land surface. The well is 722.34 meters above sea level.

The bedrock is overlain by weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium. TT-7D intersects bedrock composed of Migmatitic schist and metagraywacke.

A total of 25 fractures were measured. Of the total number of fractures, 5 are sheet joints, 9 are classified as other fractures, and 11 are foliation parallel fractures.

Appendix C-102. Depth, Aperture, Strike, Dip and fracture type of features identified in optical televiewer log from TT-7D (t = other fractures, s = sheet joints, p = foliation parallel fractures).

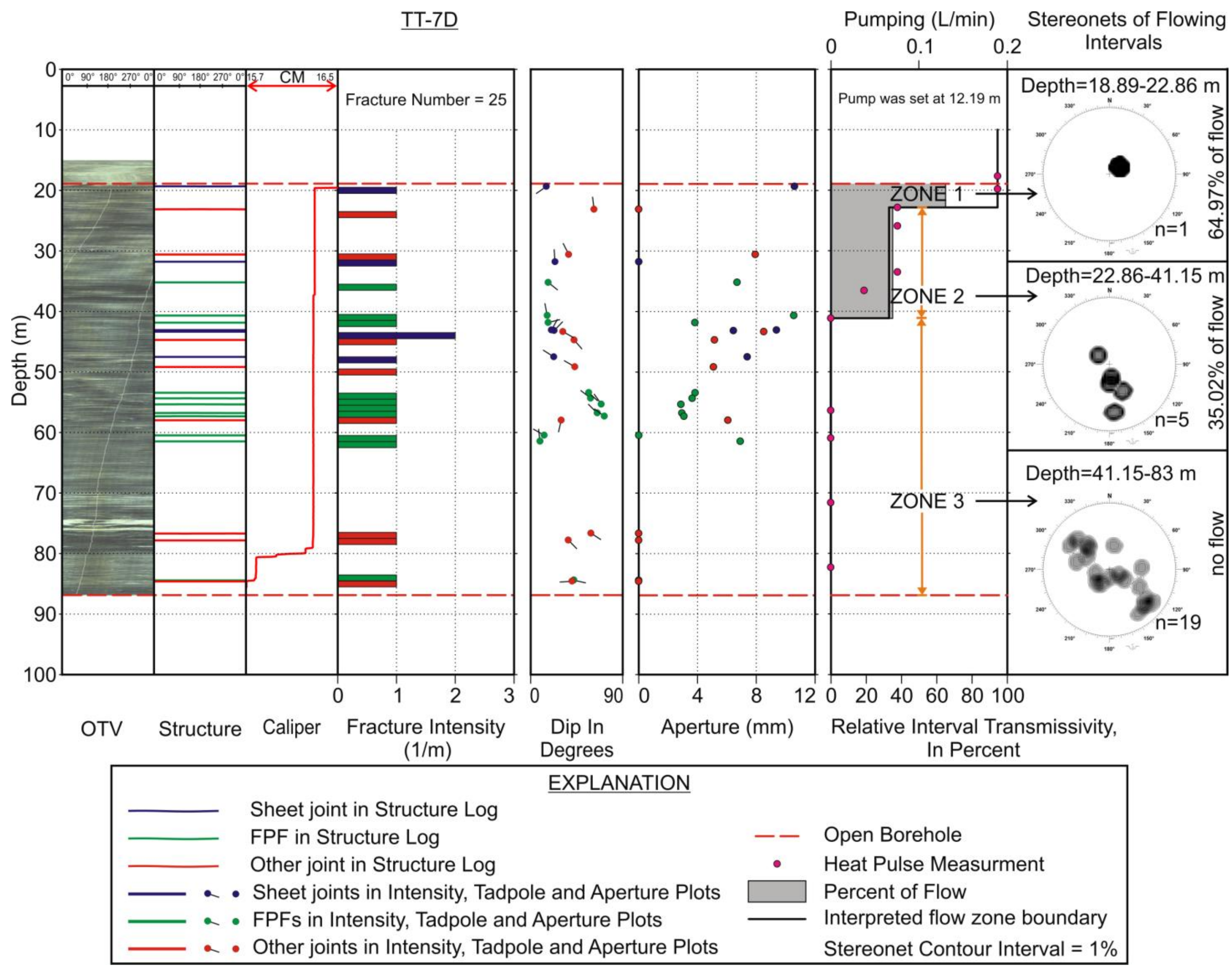
Well ID:	TT-7D
Location:	Bent Creek Research Station, Buncombe County, NC
Elevation:	722.34 m
Rock Type:	Migmatitic schist and metagraywacke
Depth of casing:	18.89 m
Depth of well:	86.87 m

Fracture Characteristics					
Number	Depth (m)	Aperture (mm)	Strike	Dip	Type
1	19.32	10.6	145.28	15.41	s
2	23.11	0	263.82	62.2	t
3	30.58	7.94	243.01	37.45	t
4	31.77	0	267.42	24.1	s
5	35.18	6.69	38	17.1	p
6	40.66	10.55	259.93	16.45	p
7	41.83	3.82	345.54	17.14	p
8	43.06	9.37	298.32	20.51	s
9	43.15	6.44	313.5	23.1	s
10	43.32	8.51	28.96	31.67	t
11	44.69	5.16	48.28	42.54	t
12	47.49	7.38	212.16	22.78	s
13	49.15	5.09	209.85	43.38	t
14	53.41	3.83	42.71	56.81	p
15	54.33	3.63	218.2	58.74	p
16	55.32	2.86	234.84	69.05	p
17	56.75	2.93	225.39	65.21	p
18	57.29	3.07	217.41	72.14	p
19	57.95	6.07	101.79	30	t
20	60.45	0	209.74	13.29	p
21	61.44	6.91	265.2	9.37	p
22	76.66	0	31.89	59.04	t
23	77.79	0	45.61	37.04	t
24	84.4	0	12.56	42.57	p
25	84.57	0	177.23	40.68	t

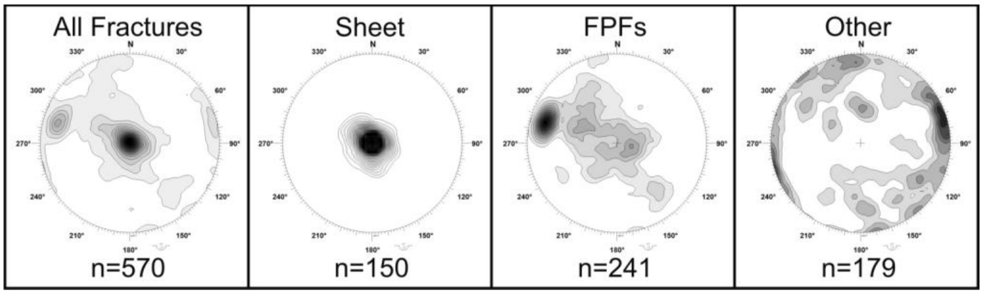
Appendix C-103. Total number of fractures and their occurrences above 90, 60 and 30 m. Also listed is the number of Sheet, Foliation Parallel Fractures (FPFs) and Other fractures.

Stats: TT-7D	#	%
Total Fractures:	25	100.00
Total above 90 m:	25	100.00
Total above 60 m:	19	76.00
Total above 30 m:	2	8.00
FPFs:	11	44.00
Sheet:	5	20.00
Other:	9	36.00

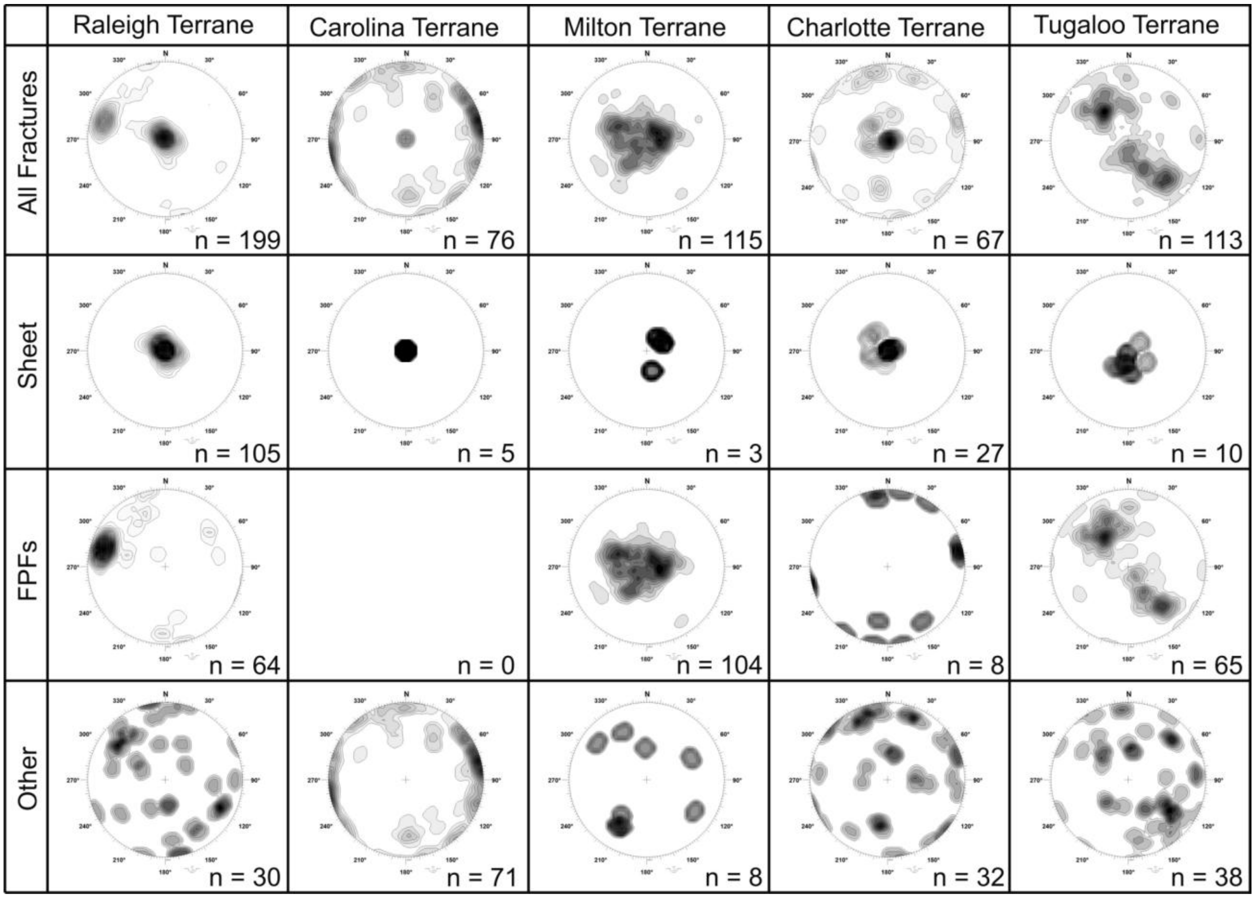
Appendix C-104. Interpreted features for TT-7D. Optical televiewer (OTV), structure, caliper, fracture intensity plot, tadpole plot, fracture aperture plot, pumping flow log, interpreted flow zones and Lower-hemisphere equal-area stereonet projection of fracture poles intersecting the borehole within flowing intervals. Right hand rule convention was used to plot stereonets.



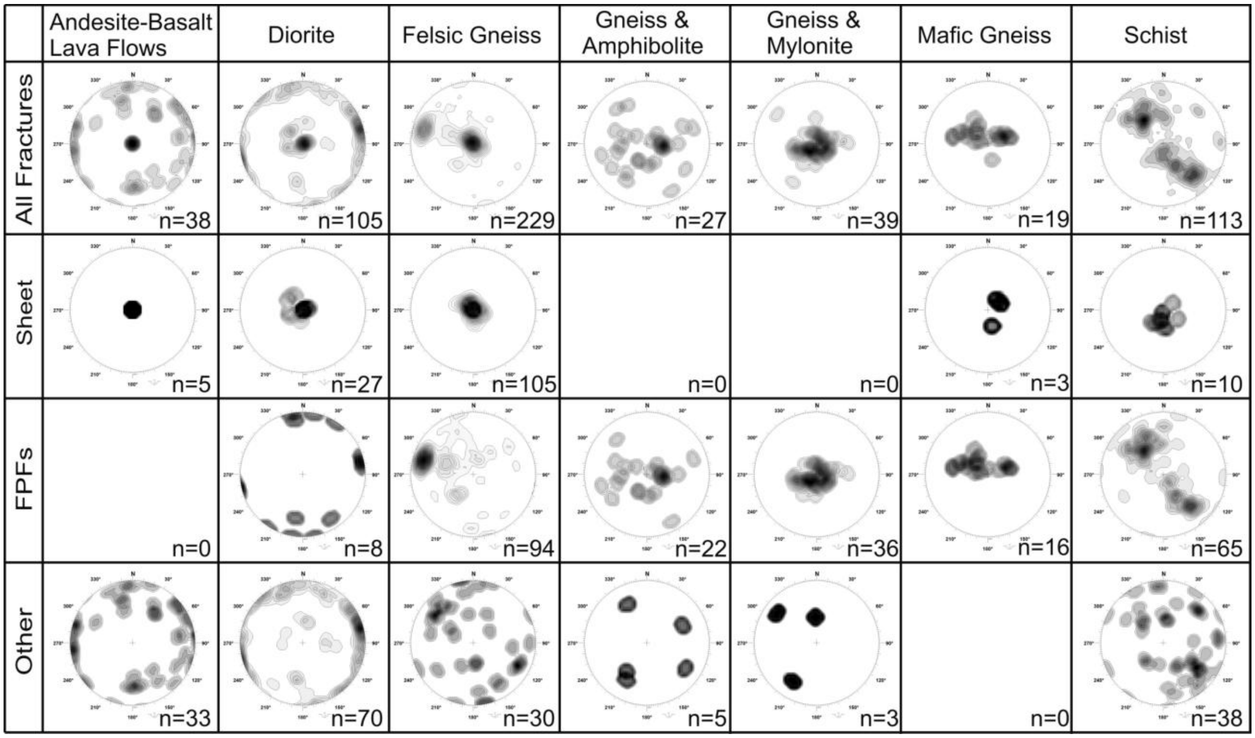
Appendix C-105. Lower-hemisphere equal-area stereonet plots of all fractures, all sheet joints, all foliation parallel fractures (FPFs) and all Other fractures measured in the 26 bedrock wells drilled in the crystalline rocks of North Carolina. Stereonet contour interval is 1%.



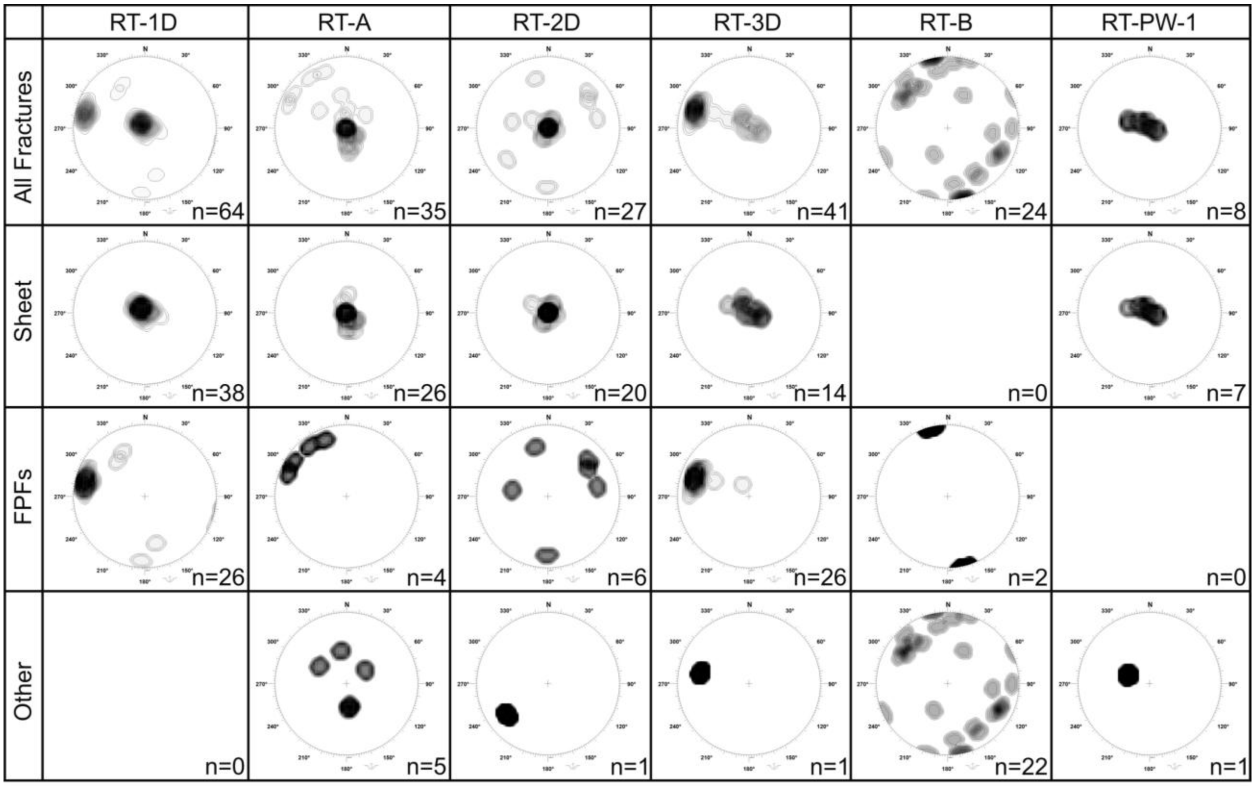
Appendix C-106. Lower-hemisphere equal-area stereonet plots of all fractures, sheet joints, foliation parallel fractures (FPFs) and Other fractures separated by geologic terrane the wells were within. Stereonet contour interval is 1%.



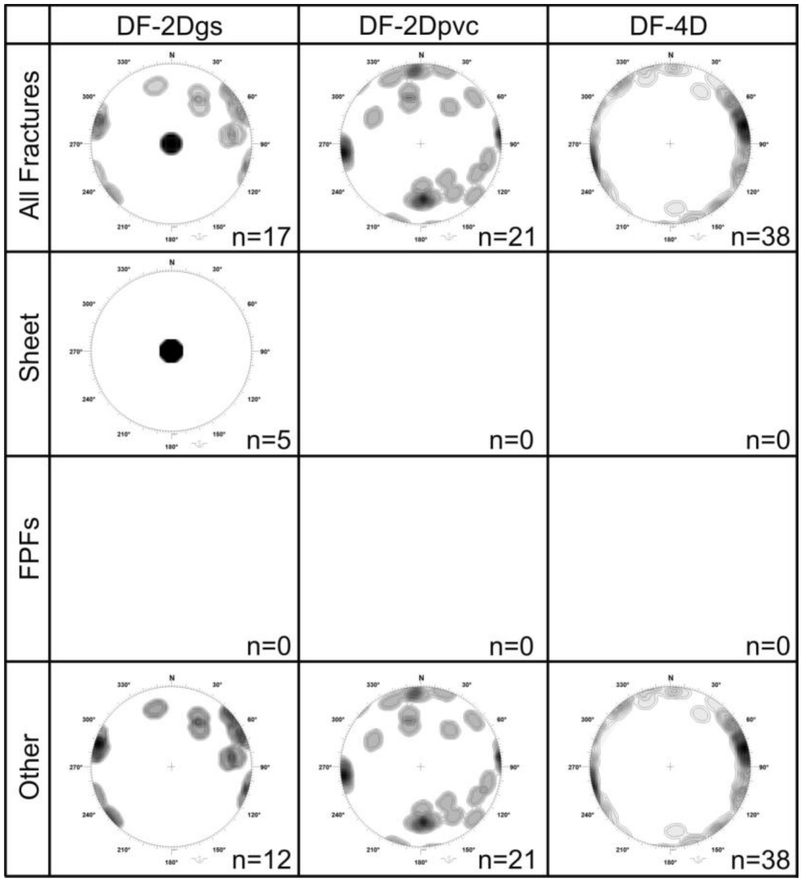
Appendix C-106. Lower-hemisphere equal-area stereonet plots of all fractures, sheet joints, foliation parallel fractures (FPFs) and Other fractures separated by the rock type in which the well was drilled. Stereonet contour interval is 1%.



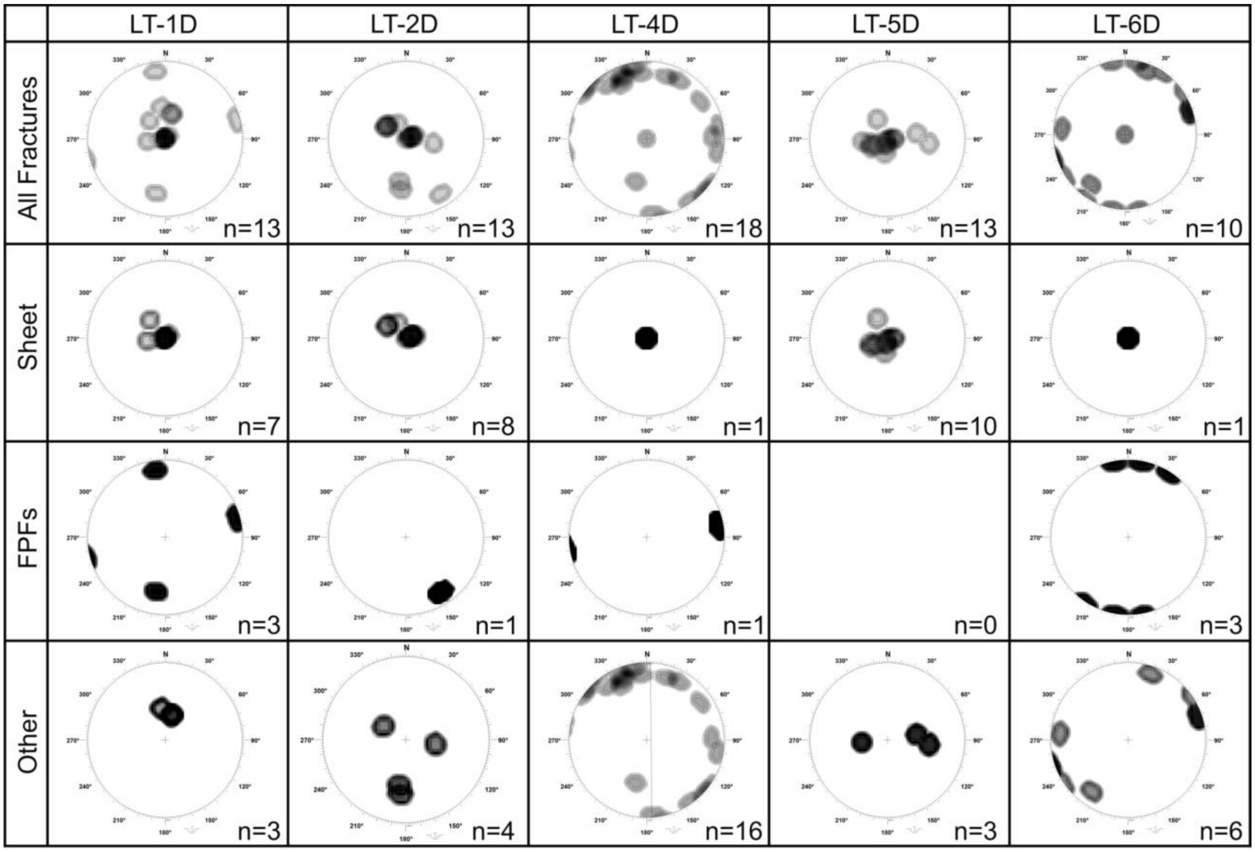
Appendix C-107. Lower-hemisphere equal-area stereonet plots of all fractures, sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Raleigh Terrane at the Lake Wheeler site, Raleigh NC. Stereonet contour interval is 1%.



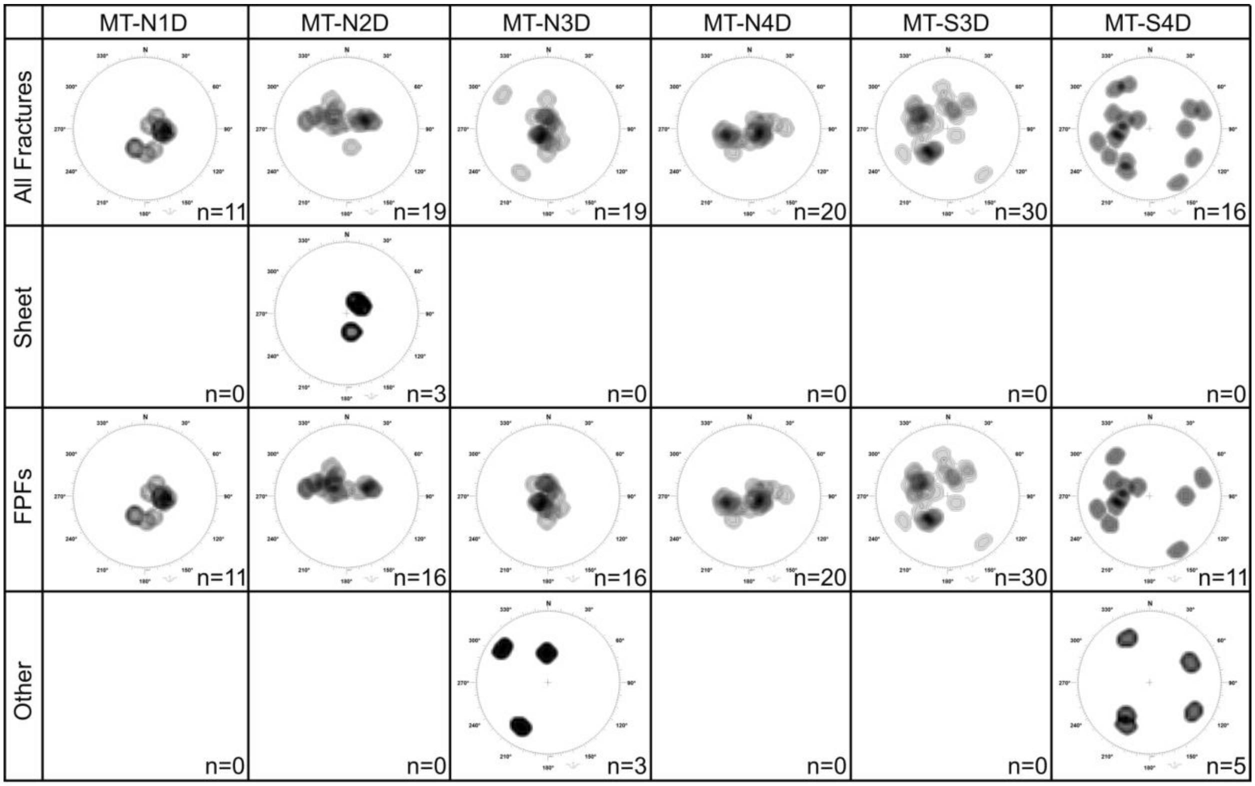
Appendix C-108. Lower-hemisphere equal-area stereonet plots of all fractures, sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Carolina Terrane at the Duke Forest site, Durham, NC. Stereonet contour interval is 1%.



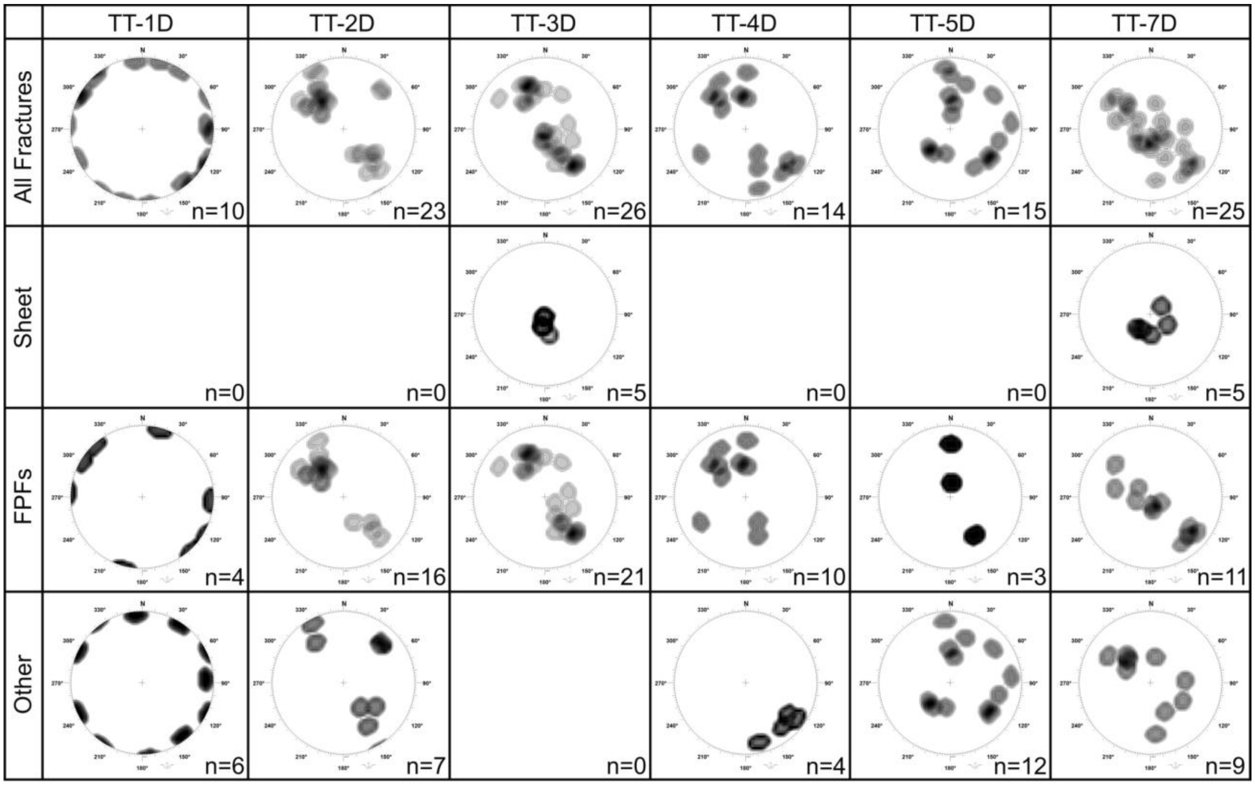
Appendix C-109. Lower-hemisphere equal-area stereonet plots of all fractures, all sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Charlotte Terrane at the Langtree Peninsula site, Cornelius, NC. Stereonet contour interval is 1%.



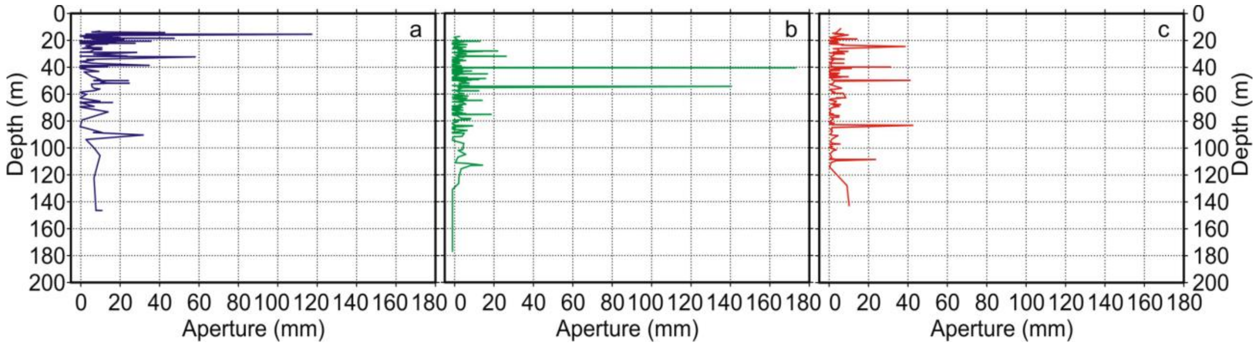
Appendix C-110. Lower-hemisphere equal-area stereonet plots of all fractures, sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Milton Terrane at the Upper Piedmont site, Reidsville, NC. Stereonet contour interval is 1%.



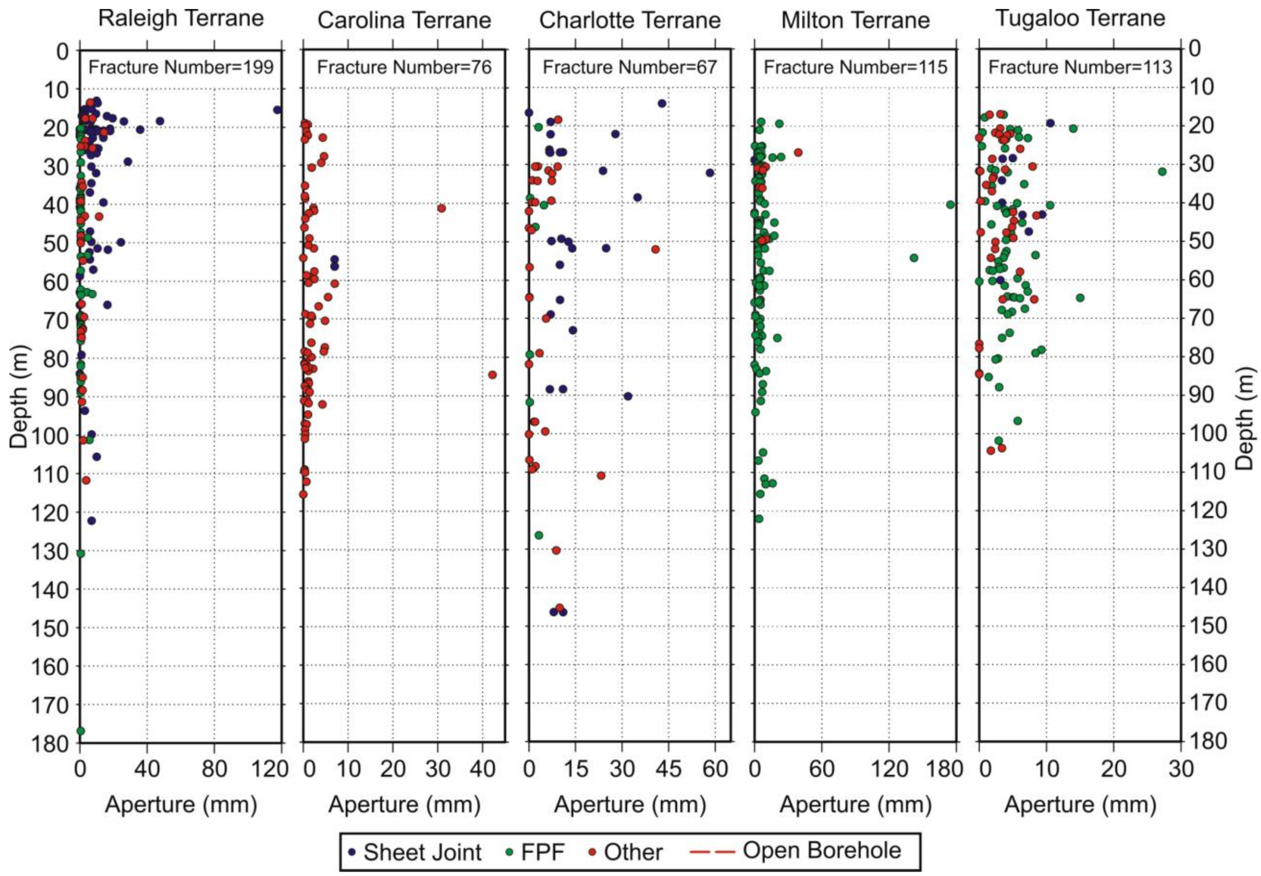
Appendix C-111. Lower-hemisphere equal-area stereonet plots of all fractures, sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Tugaloo Terrane at the Bent Creek site, Asheville, NC. Stereonet contour interval is 1%.



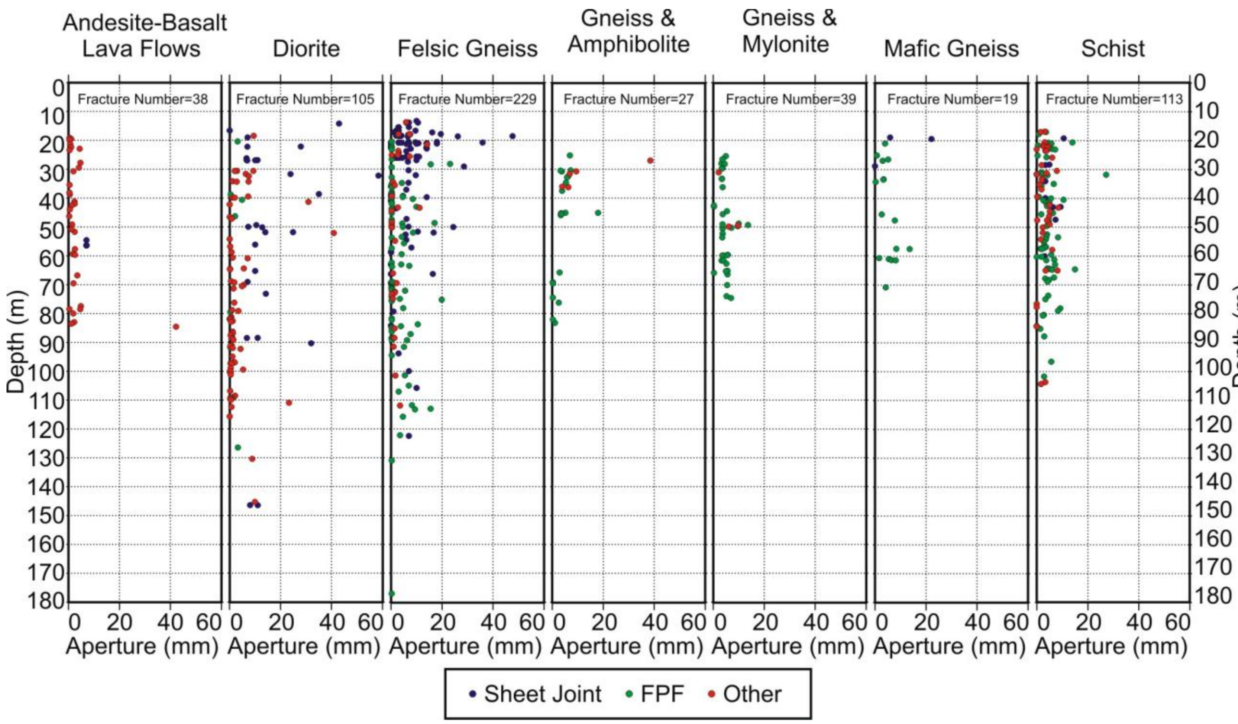
Appendix C-112. Fracture aperture distributions with depth of (a) sheet joints, (b) FPFs, and (c) other fractures.



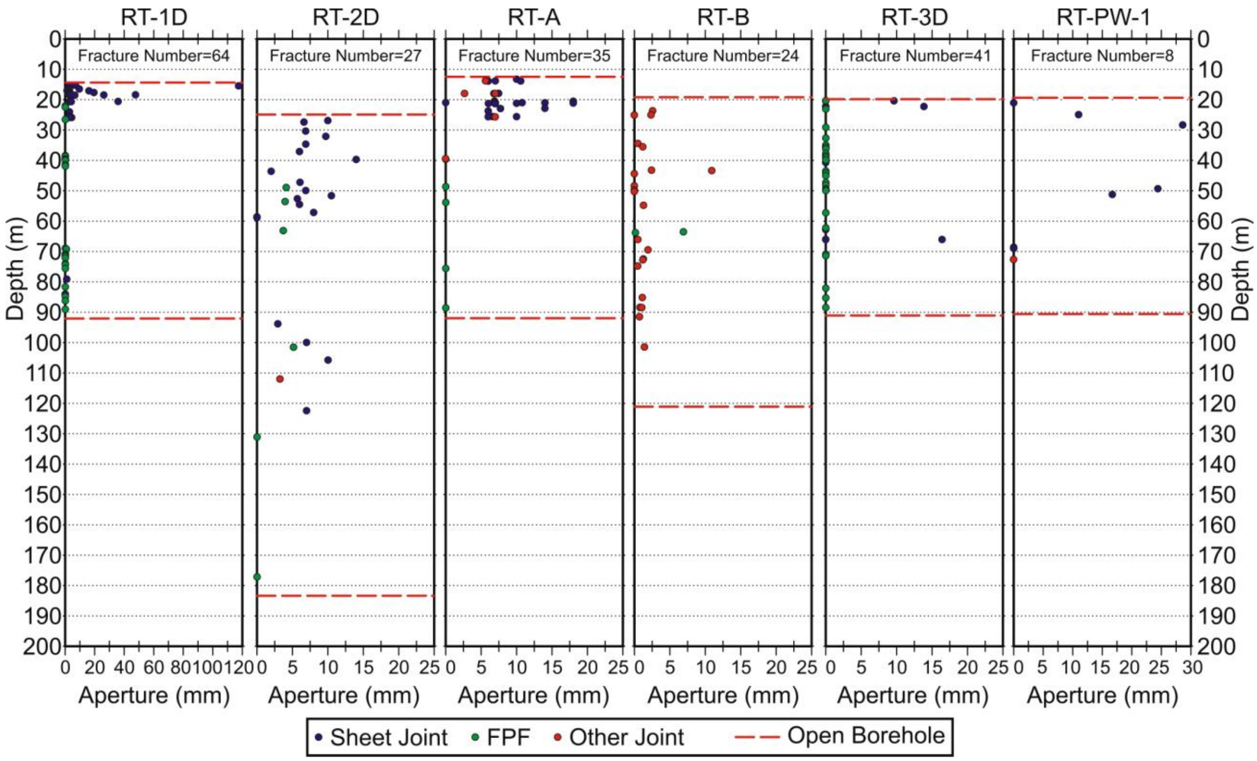
Appendix C-113. Depth distribution of fracture apertures by geologic terrane.



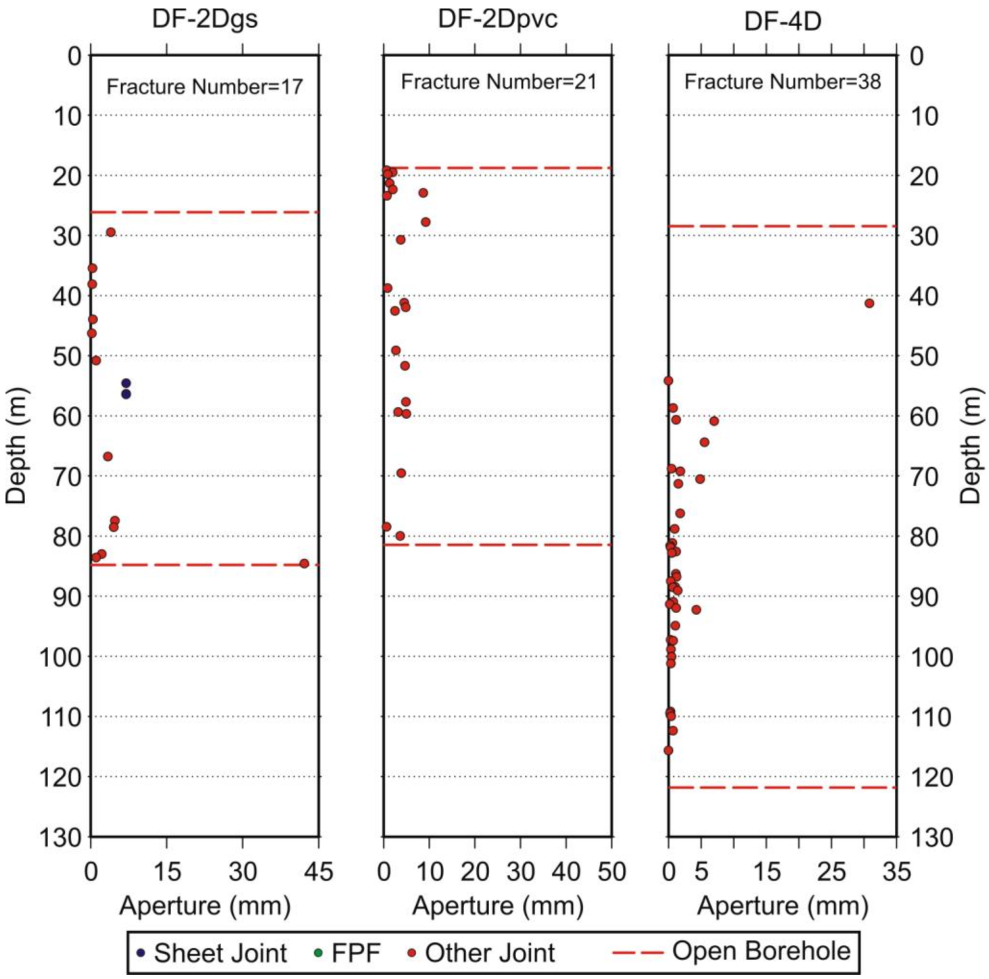
Appendix C-114. Depth distribution of fracture apertures by rock type.



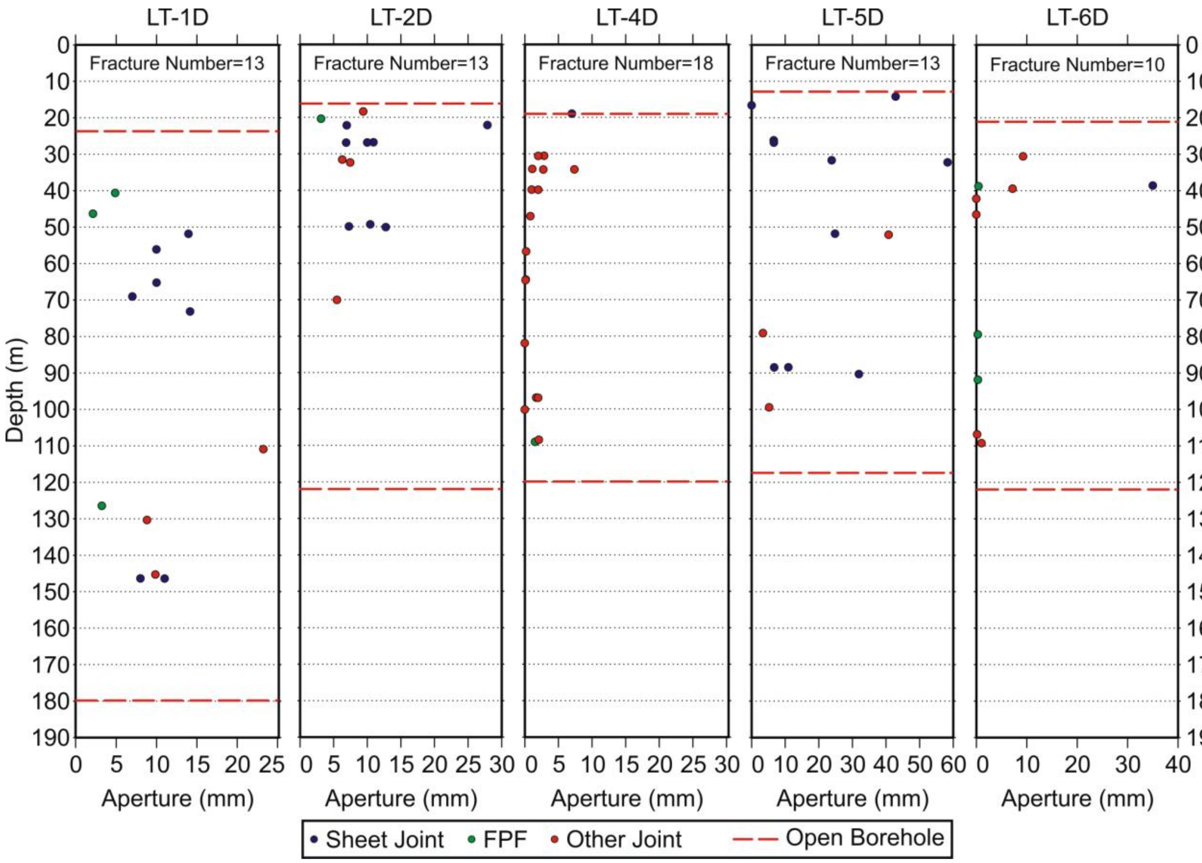
Appendix C-115. Fracture aperture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Raleigh Terrane at the Lake Wheeler site, Raleigh NC.



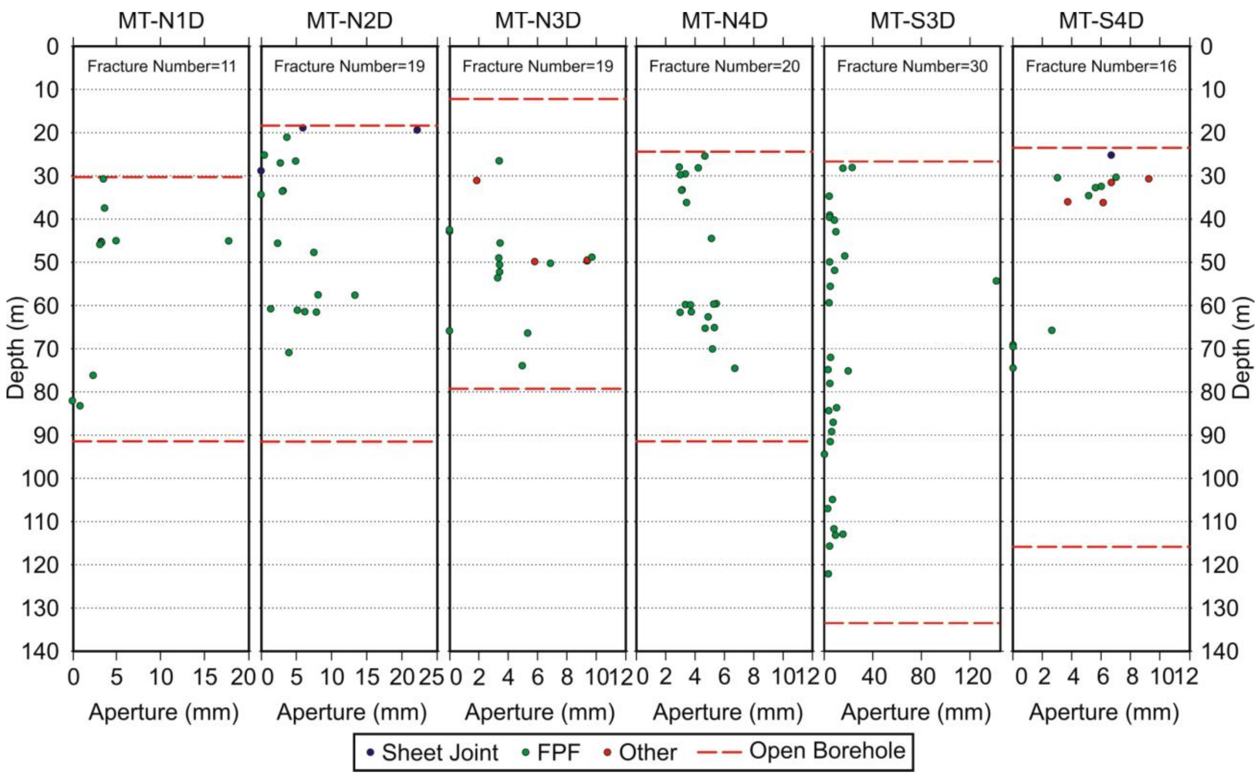
Appendix C-116. Fracture aperture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Carolina Terrane at the Duke Forest site, Durham, NC.



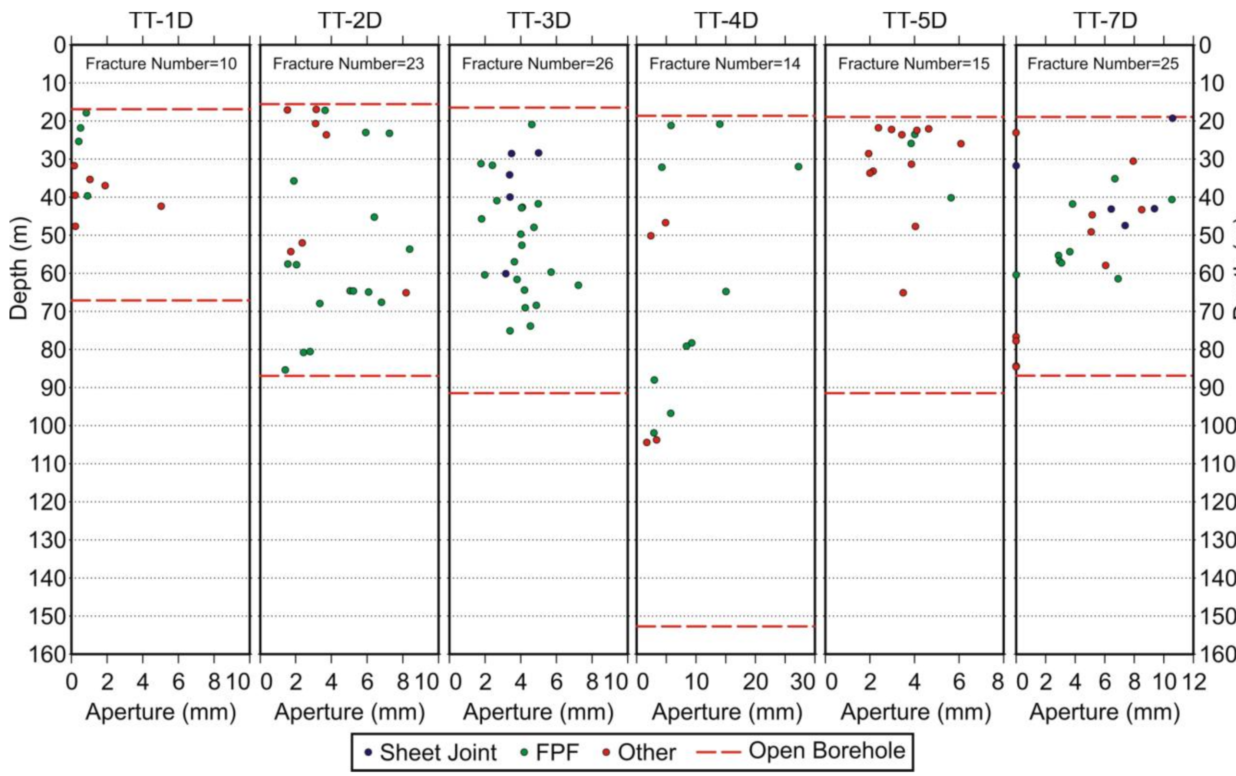
Appendix C-117. Fracture aperture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Charlotte Terrane at the Langtree Peninsula site, Cornelius, NC.



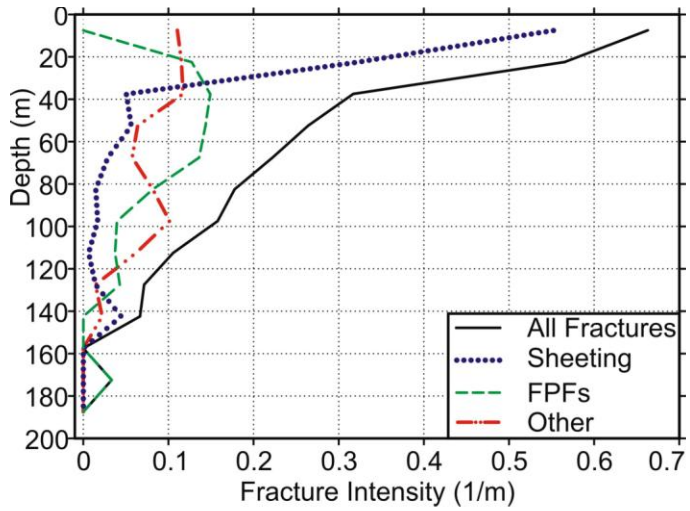
Appendix C-118. Fracture aperture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Milton Terrane at the Upper Piedmont site, Reidsville, NC.



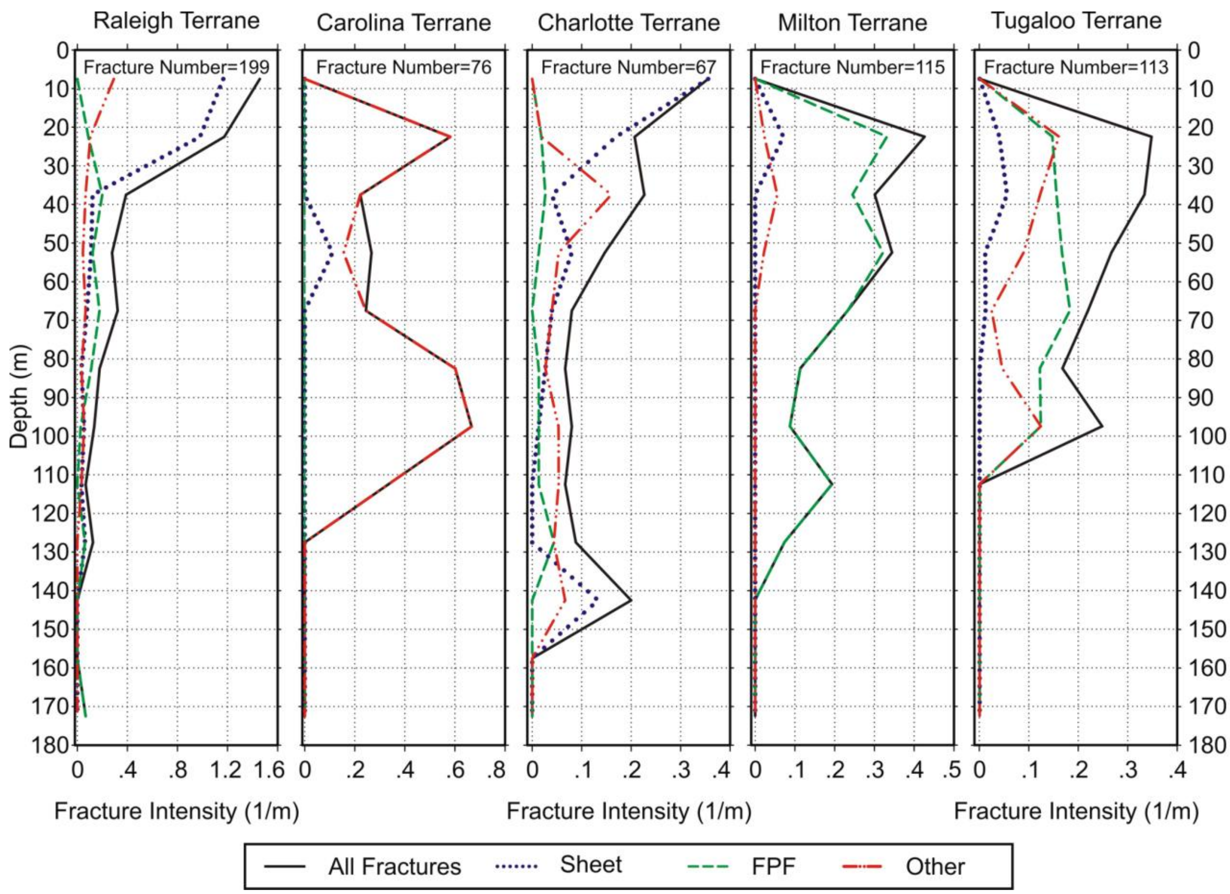
Appendix C-119. Fracture aperture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Tugaloo Terrane at the Bent Creek site, Asheville, NC.



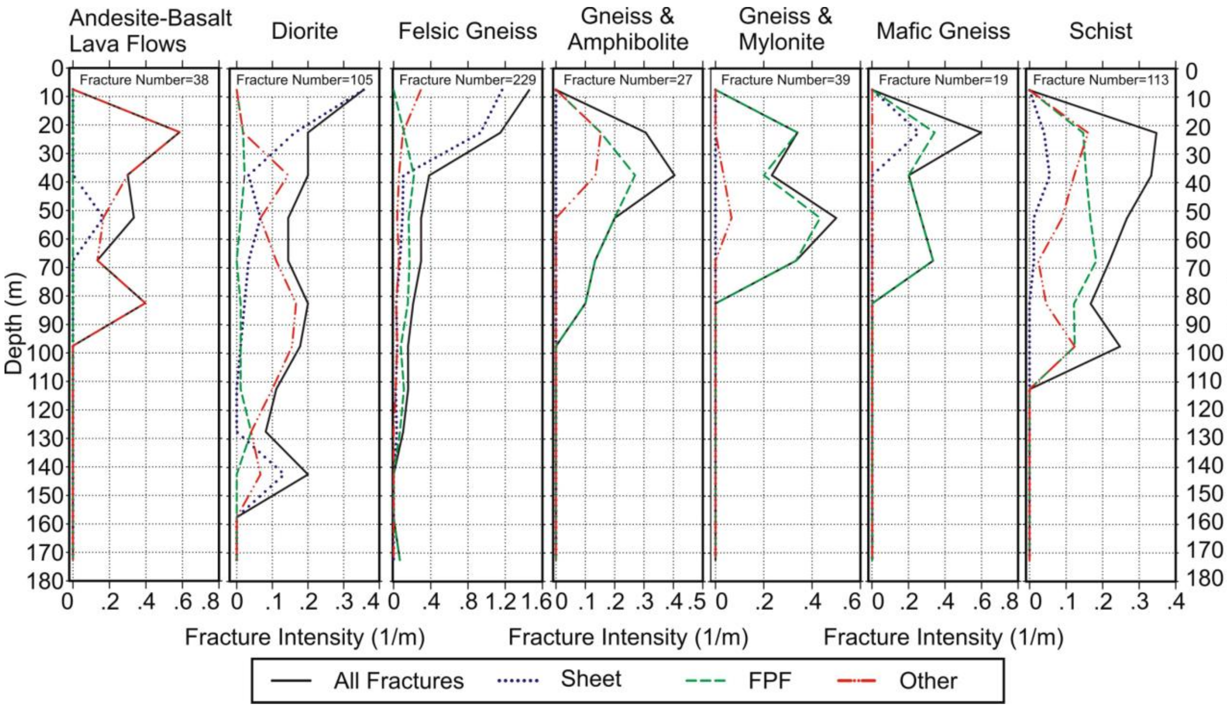
Appendix C-120. Composite plot of normalized fracture intensity for the different fracture types identified in the study area. In general, the normalized intensity for all fracture types decreases with depth.



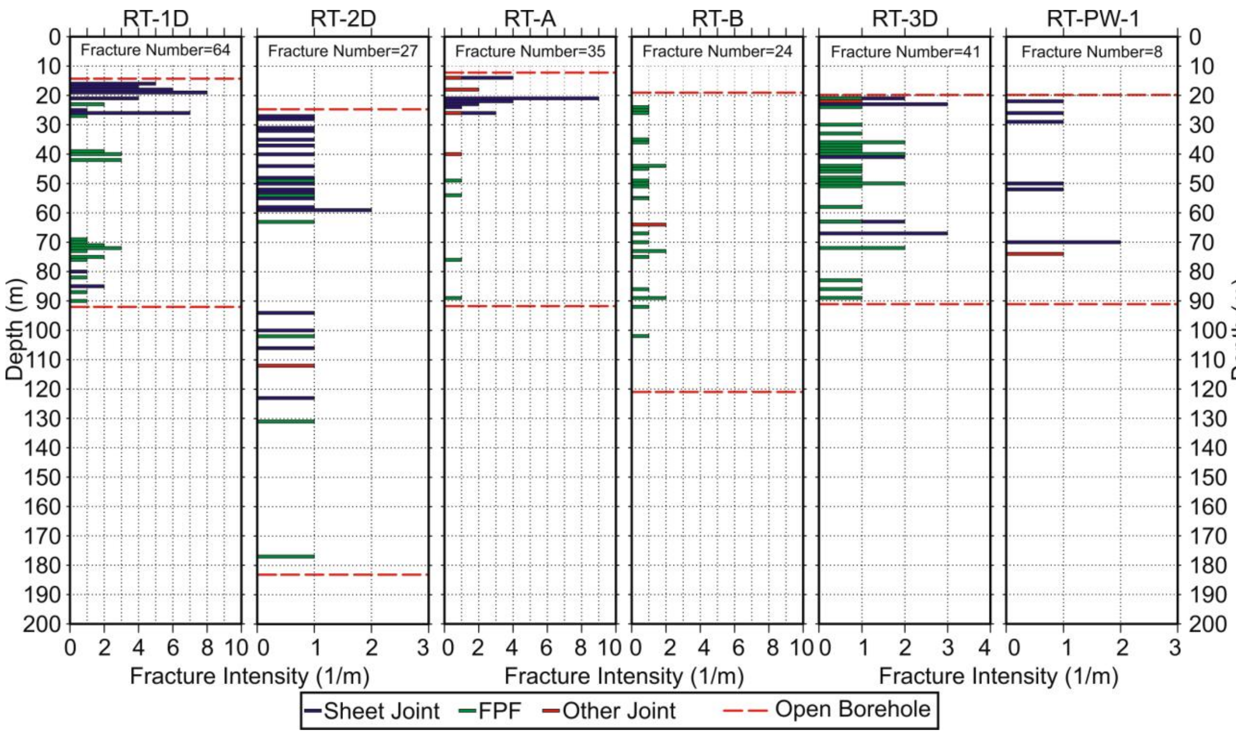
Appendix C-121. Depth distribution of fractures by geologic terrane.



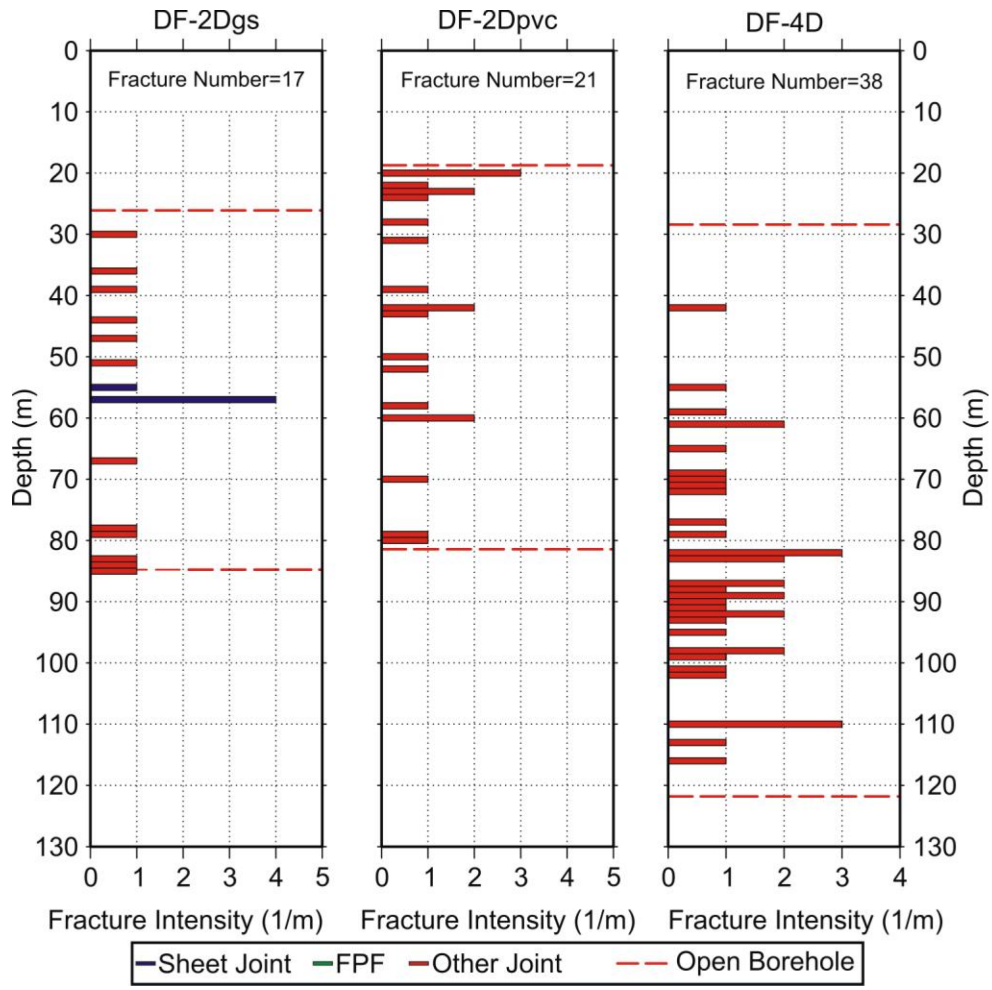
Appendix C-122. Depth distribution of fractures by rock type.



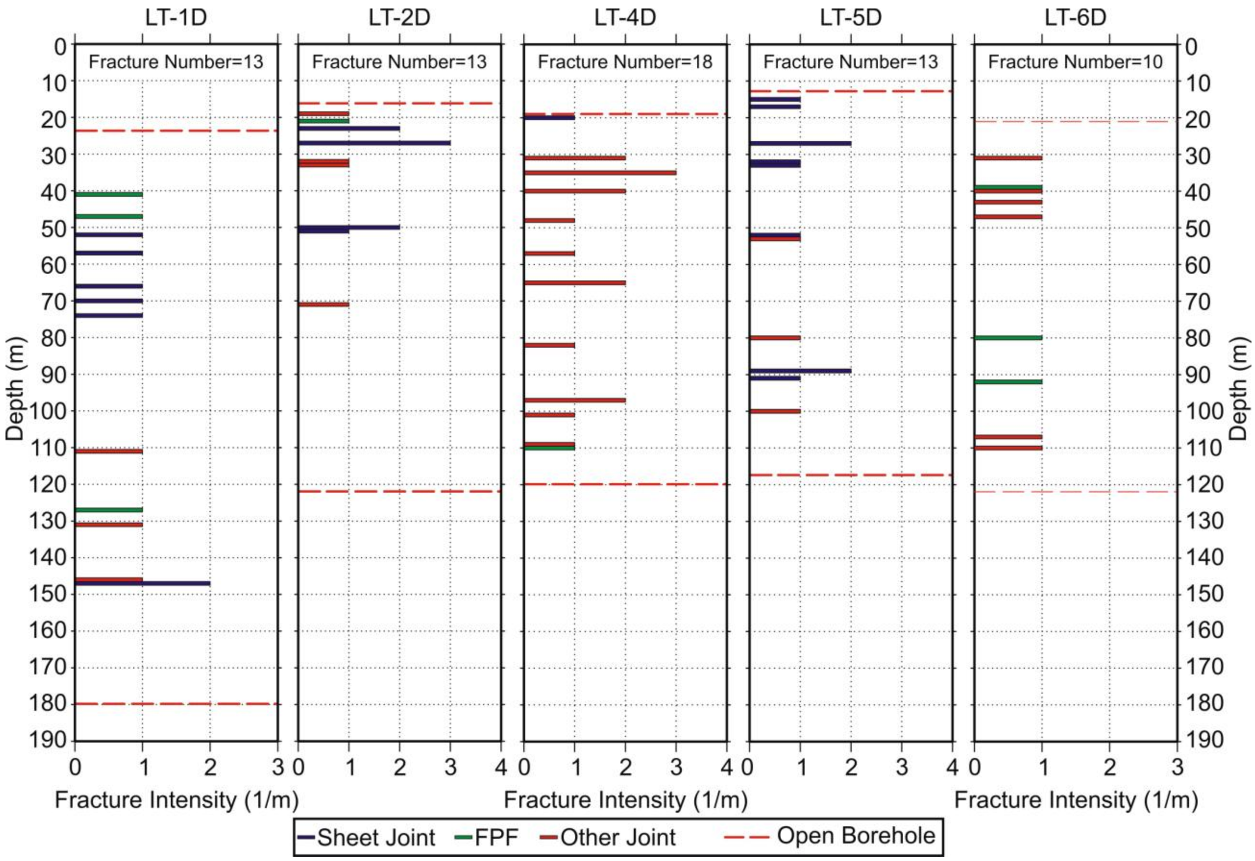
Appendix C-123. Fracture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Raleigh Terrane at the Lake Wheeler site, Raleigh NC.



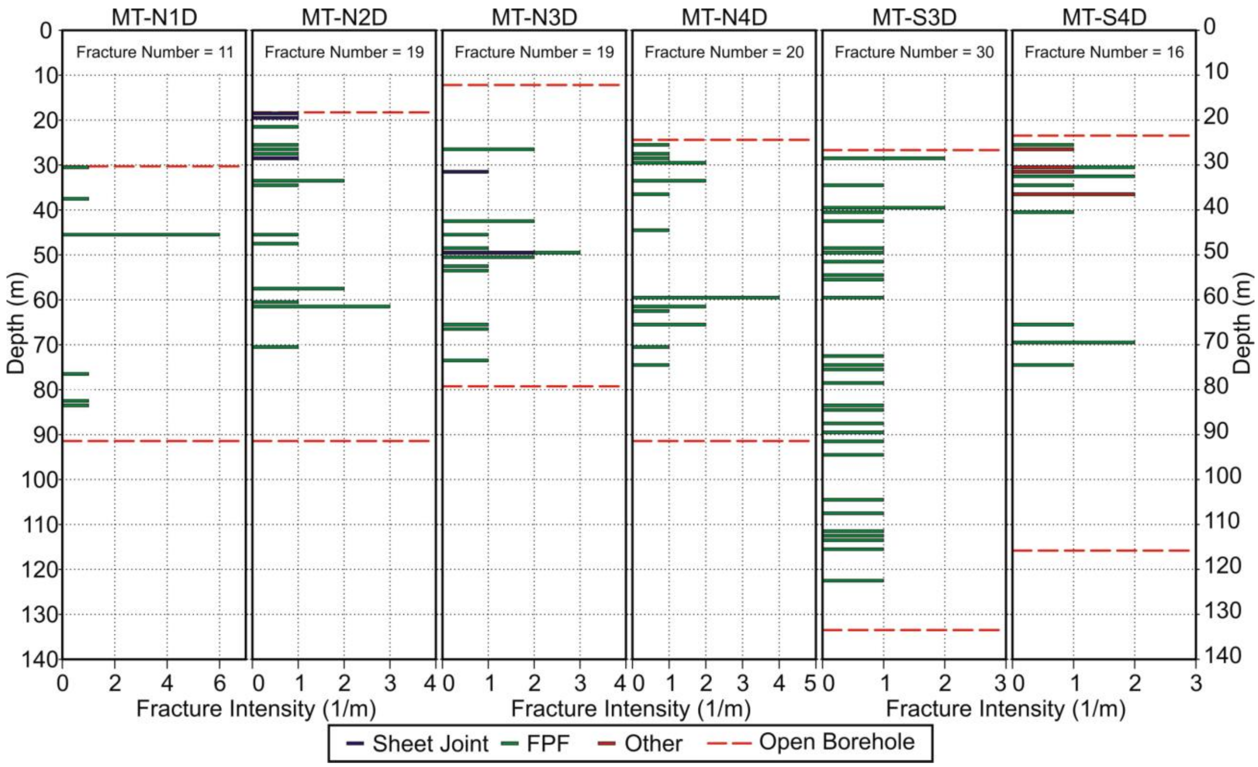
Appendix C-124. Fracture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Carolina Terrane at the Duke Forest site, Durham, NC.



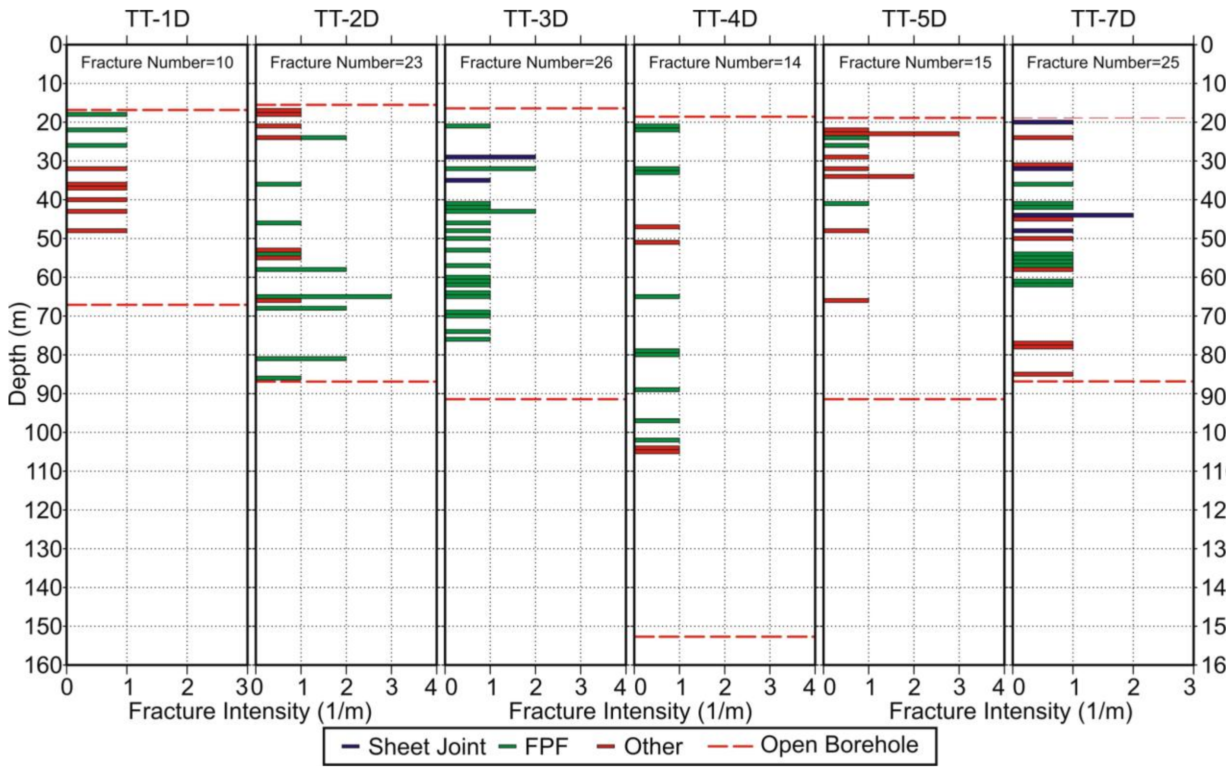
Appendix C-125. Fracture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Charlotte Terrane at the Langtree Peninsula site, Cornelius, NC.



Appendix C-126. Fracture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Milton Terrane at the Upper Piedmont site, Reidsville, NC.



Appendix C-127. Fracture depth distribution of sheet joints, foliation parallel fractures (FPFs) and Other fractures for each well in the Tugaloo Terrane at the Bent Creek site, Asheville, NC.



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