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I am submitting herewith a thesis written by Matthew Patrick Gatewood entitled "Structure and tectonics of the northeastern Inner Piedmont, northwestern NC, from detailed geologic mapping, petrologic, geochemical, and geochronologic studies, with structural analyses of ductile fault zones." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

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**Tectonics of the Northeastern Inner Piedmont, northwestern NC,
from Detailed Geologic Mapping, Geochronologic, Geochemical, and
Petrologic Studies with Structural Analyses of Ductile Fault Zones**

A Thesis
Presented for the
Master of Science Degree
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Matthew Patrick Gatewood
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DEDICATION

This thesis is dedicated to my parents, Malcum and Linda Gatewood,
whose endless patience, love, support, and encouragement
made its completion possible. Thank you!!!

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ABSTRACT

New field and laboratory data collected for the northeastern Inner Piedmont (IP) reveal the structure and composition of a portion of the southern Appalachian crystalline core, delimited the timing of orogenesis, and provide new insight into the nature of deep crustal processes during orogenesis. Previously recognized lithologies are continuous throughout the study area and comprise two distinct crystalline thrust sheets: the Marion and Brindle Creek thrust sheets, or eastern Tugaloo and western Cat Square terranes, respectively. Western IP Precambrian-Cambrian(?) metasedimentary lithologies and Ordovician metaigneous lithologies make up the Marion thrust sheet northwest of a Neoacadian suture, the Brindle Creek fault zone (BCFZ). To the southeast, the Brindle Creek thrust sheet contains Siluro-Devonian metasedimentary lithologies, which were intruded by Devonian anatectic metaigneous units.

Rocks in the study area preserve a polyphase thermal, metamorphic, and deformational history. Textural evidence suggests that two high-temperature events, followed by a retrograde event affected these lithologies. Peak metamorphic conditions of 745°C and 7.1 kbar are estimated for eastern IP assemblages using garnet core compositional data. Garnet rim compositional data indicate a clockwise P-T path for eastern IP lithologies. This is supported by textural observations of sillimanite replacing kyanite, further suggesting prograde conditions during metamorphism.

Northeastern IP lithologies retain evidence of six deformation events. The Mill Spring fault zone is recognized as a late dextral strike-slip fault that splayed from the Alleghanian Brevard fault zone. Map and outcrop-scale truncations of structures and lithologies of known ages provide relative and absolute timing constraints for IP orogenic pulses. Western IP D₁ structures were produced by a pre-Neoacadian event, likely related to the 480-460 Ma Taconic orogeny. Eastern IP D₁ structures are the product of initial subduction of Cat Square terrane lithologies beneath the Carolina terrane before BCFZ emplacement. D₂ and D₃ are responsible for regional structural trends, developed during the Neoacadian orogeny. SW-vergent D₄ dextral shear fabrics are related to dextral movement along the Alleghanian Brevard fault zone. Subsequent deformation features are brittle and result from Alleghanian uplift, and Mesozoic and Cenozoic extensional and rifting events.

The presence of two ductile fault zones in the study area, the Tumblebug

Creek fault zone (TCFZ) and the BCFZ, provides a unique opportunity to study the development of two crustal-scale structures in an orogenic core. Here, the relationships between mineral reactions, deformation mechanisms, fluid flow, volume loss, and mylonitization are investigated for two granitic mylonites. Fluid flow paths are interpreted from SW-trending regional linear fabrics. Shear zone formation is characterized by the breakdown of quartz and feldspar, coeval with the formation of myrmekite and biotite. Crystal-plastic mechanisms operating at temperatures $>400^{\circ}\text{C}$ were responsible for the deformation during shear-zone development. Silica and alkalis were lost during deformation, while immobile major and trace element concentrations remained constant. Volume losses of 41 and 48% occurred for the TCFZ and BCFZ, respectively.

Zircon geochronologic data for northeastern IP lithologies provide new limits on the timing of orogenesis in the IP, and have produced a new developmental model for the Paleozoic development of the southern Appalachian crystalline core. Western IP Ordovician granitoids record the development of a volcanic arc system off of the Laurentian margin ~ 490 Ma. Taconic (480-460 Ma) arc accretion affected western IP lithologies, causing deformation, metamorphism, and magmatism. Eastern IP detrital zircon data indicate that the Cat Square terrane was being deposited after 430 Ma. Initial subduction of Cat Square sediments by the Carolina superterrane began by ~ 415 Ma. The Cat Square and Carolina terranes were accreted to the Laurentian margin together during the 360-340 Ma Neocadian orogeny, causing the first shared thermal events between eastern and western IP terranes. Penetrative structures and dominant IP fabrics were developed during this event. Subsequent deformation occurred during dextral strike-slip motion along the Alleghanian Brevard fault zone.

TABLE OF CONTENTS

<u>CHAPTER</u>	<u>PAGE</u>
PART I: Overview	1
PART II: Geology of Part of the Northeastern Brushy Mountains, North Carolina Inner Piedmont: Lithologic and Metamorphic Relationships from the Moravian Falls and Part of the Taylorsville 7.5-minute Quadrangles, North Carolina	5
ABSTRACT	6
INTRODUCTION	6
GEOLOGIC SETTING	10
Regional Inner Piedmont Structure and Metamorphism	10
Lithostratigraphy	11
<i>Marion thrust sheet</i>	12
<i>Brindle Creek thrust sheet</i>	14
LOCATION OF STUDY AREA	15
METHODS	15
NORTHEASTERN INNER PIEDMONT LITHOLOGIES	18
Marion Thrust Sheet (western IP)	20
<i>Tallulah Falls/Ashe Formation</i>	20
<i>Henderson Gneiss</i>	22
<i>Lenoir Quarry migmatite</i>	31
<i>Brooks Crossroads Granite</i>	34
<i>Hibriten mylonite (BCFZ)</i>	35
Brindle Creek Thrust Sheet (eastern IP)	37
<i>Walker Top Granite</i>	37
<i>Toluca Granite</i>	43
<i>Sillimanite Schist</i>	46
<i>Metagraywacke</i>	49
<i>Calc-Silicate</i>	49
METAMORPHIC RELATIONSHIPS FROM THE NORTHEASTERN BRUSHY MOUNTAINS	51
Inner Piedmont Metamorphism	51
Methodology	51
Sample Descriptions	55
Mineralogy	59
<i>Garnet</i>	59
<i>Biotite</i>	59
<i>Plagioclase</i>	63
<i>K-feldspar</i>	63
<i>Sillimanite</i>	63
<i>Accessory Phases</i>	64

Northeastern IP Regional Metamorphism.....	64
Petrogenesis of EMP Samples	64
Thermobarometry	66
P-T Paths.....	68
Timing of Metamorphism	70
CONCLUSIONS.....	72
REFERENCES CITED	73

PART III: Structural Geology of Part of the Northeastern Inner Piedmont:

New Mapping Reveals Important Structural and Timing Relationships.....	81
ABSTRACT	82
INTRODUCTION	83
STRUCTURAL SETTING AND LOCATION OF THE STUDY AREA.....	84
METHODS.....	86
DEFORMATION EVENTS AND TIMING	89
D ₁ Deformation.....	91
D ₂ Deformation.....	91
D ₃ Deformation.....	92
D ₄ Deformation.....	92
D ₅ and D ₆ Deformation	93
MACROSCOPIC STRUCTURES	93
Western Inner Piedmont (Marion thrust sheet).....	93
Eastern Inner Piedmont (Brindle Creek thrust sheet)	96
MESOSCOPIC AND MICROSCOPIC STRUCTURES	99
Foliations.....	99
Lineations	101
Folds	109
WIP <i>F</i> ₁ Folds	109
EIP <i>F</i> ₁ Folds.....	109
<i>F</i> ₂ Folds	113
<i>F</i> ₃ Folds	113
<i>F</i> ₄ Folds	116
<i>F</i> ₅ Folds	116
<i>F</i> ₆ Folds	116
Joints	118
STRUCTURAL TRENDS.....	118
Domain I	120
Domain II.....	124
Domain III	124
TRANSPORT AND FLOW KINEMATICS	125
CROSS SECTION INTERPRETATION.....	130

Section A-A'	130
Section B-B'	131
Section C-C'	131
CONCLUSIONS.....	132
REFERENCES CITED	134

**PART IV: High-Temperature Mylonite Formation and Petrogenesis of
Northeastern Inner Piedmont Orthogneisses: Structural and
Geochemical Analyses of Ductile Shear Zones139**

ABSTRACT	140
INTRODUCTION	140
GEOLOGIC SETTING	141
ANALYTICAL PROCEDURES	143
Structural Analysis	143
Whole-rock Geochemistry.....	144
NORTHEASTERN IP DUCTILE FAULT ZONES	144
Tumblebug Creek Fault Zone	144
Brindle Creek Fault Zone	147
FAULT ZONE STRUCTURE AND KINEMATICS.....	148
MYLONITES.....	150
Petrography	150
Deformation Mechanisms	155
GEOCHEMICAL TRENDS AND VOLUME LOSS	155
Theoretical Considerations	155
Chemical Analyses	156
DISCUSSION.....	165
CONCLUSIONS.....	166
REFERENCES CITED	167

**PART V: Inner Piedmont Orogenic Timing Relationships From Zircon
Geochronology Delimits the Timing of Orogenesis in the Southern
Appalachians.....171**

ABSTRACT	172
INTRODUCTION	172
GEOLOGIC SETTING	174
ANALYTICAL METHODS	181
SAMPLES	182
Igneous and Metagneous Lithologies	182
<i>Walker Top Granite</i>	182
<i>Hibriten Mylonite</i>	185
<i>Granitic Intrusives</i>	188
Metasedimentary Lithologies.....	188

RESULTS	191
Detrital	191
Magmatic	198
<i>Walker Top Granite</i>	<i>198</i>
<i>Hibriten mylonite</i>	<i>202</i>
<i>Granitic Intrusives</i>	<i>202</i>
Metamorphic	203
DISCUSSION.....	203
Depositional Constraints	204
Magmatic Constraints	205
<i>Western IP</i>	<i>205</i>
<i>Eastern IP.....</i>	<i>208</i>
Metamorphic and Deformational Constraints	209
CONCEPTUAL MODEL	213
Neoproterozoic-Early Paleozoic Rifting and Passive	
Margin Evolution	213
Taconic Events.....	219
Acadian Events.....	220
Neoacadian Events.....	221
Alleghanian Events	221
CONCLUSIONS.....	221
REFERENCES CITED	222
 PART VI: Conclusions.....	 233
 APPENDICES	 239
Appendix A: Electron Microprobe Data	240
Appendix B: Structural and Lithologic Data for the Moravian Falls	
and Taylorsville quadrangles	245
VITA.....	265

LIST OF TABLES

PART II

Table 2-1.	Modal mineralogy of the Tallulah Falls/Ashe Formation in the study area	24
Table 2-2.	Modal mineralogy for Henderson Gneiss lithologies	28
Table 2-3.	Modal mineralogy for western Inner Piedmont metagneous lithologies in the study area	32
Table 2-4.	Modal mineralogy of Walker Top Granite samples	40
Table 1-5.	Modal mineralogy for Toluca Granite lithologies.....	44
Table 2-6.	Modal mineralogy for eastern Inner Piedmont metasedimentary units in the study area	48

PART III

Table 3-1.	Deformation hierarchy and relative timing of deformation events in the northeastern IP, North Carolina*	90
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PART IV

Table 4-1.	Modal mineralogy data (%) for mylonitic gneisses.....	153
Table 4-2.	Whole-rock chemical analyses of mylonitic Henderson Gneiss.....	157
Table 4-3.	Whole-rock chemical analyses of mylonitic Walker Top Granite	159

PART V

Table 5-1.	Deformation hierarchy and relative timing of deformation events in the northeastern IP, North Carolina*	180
Table 5-2.	Sample location and formation association	184
Table 5-3.	U-Pb SHRIMP zircon data.....	192
Table 5-4.	Pooled $^{206}\text{Pb}/^{238}\text{U}$ and concordia ages for magmatic samples	196

LIST OF FIGURES

PART II

Figure 2-1.	Generalized tectonic map of the southern Appalachians	8
Figure 2-2.	Index map of the study area (in red) showing counties, Interstate 40, and the Inner Piedmont in southern North Carolina and northern South Carolina.....	9
Figure 2-3.	Index map showing the location of the study area.....	16
Figure 2-4.	Simplified geologic map of the Moravian Falls and Taylorsville quadrangles, Wilkes and Alexander Counties, North Carolina.....	17
Figure 2-5.	Inner Piedmont lithostratigraphy and generalized lithologic column for the study area.....	19
Figure 2-6.	Typical outcrops of the Tallulah Falls Formation metagraywacke	21
Figure 2-7.	Petrographic characteristics of the Tallulah Falls Formation.....	23
Figure 2-8.	Quartz-feldspar-mica ternary diagram comparing the modal composition of the upper Tallulah Falls Formation (open circles) and lower Tallulah Falls Formation (filled circles).....	25
Figure 2-9.	Outcrop and hand sample photographs of typical Henderson Gneiss samples from the study area.....	26
Figure 2-10.	Petrographic characteristics of representative Henderson Gneiss samples from the study area.....	27
Figure 2-11.	IUGS modal classification (Streckeisen, 1976) for Henderson Gneiss lithologies from the study area.....	29
Figure 2-12.	IUGS modal classification (Streckeisen, 1976) for western IP igneous and metaigneous lithologies from the study area	33
Figure 2-13.	Field and petrographic characteristics of the Hibriten mylonite.....	36
Figure 2-14.	Field and hand samples of textural variations of the Walker Top Granite	38
Figure 2-15.	Petrographic characteristics of the Walker Top Granite from the study area	39
Figure 2-16.	IUGS modal classification (Streckeisen, 1976) of the Walker Top Granite	42
Figure 2-17.	IUGS modal classification (Streckeisen, 1976) of the Toluca Granite.....	45
Figure 2-18.	Petrographic characteristics of aluminous schist lithologies from the study area	47
Figure 2-19.	Quartz-feldspar-mica ternary diagram comparing the modal composition of eastern IP metagraywacke lithologies.....	50
Figure 2-20.	Metamorphic isograd map of the southern Appalachian crystalline core.....	52
Figure 2-21.	Metamorphic P-T estimates plotted for recent IP studies	53
Figure 2-22.	Metamorphic isograd map of the northeastern IP.....	54
Figure 2-23.	Representative lithologies from the Vulcan Materials 115 quarry sample locality	56
Figure 2-24.	Petrographic characteristics of EMP samples.....	58

Figure 2-25.	X-ray maps showing zonation of Fe, Mg, Mn, and Ca for sample GL-1 garnet C	60
Figure 2-26.	Chemical zoning profile from sample GL-1-WT.....	61
Figure 2-27.	Chemical zoning profile from sample GL-2-WT.....	62
Figure 2-28.	Simplified petrogenetic grid for the KFMASH system (after Spear, 1993)	65
Figure 2-29.	Temperature and pressure estimates for sample GL-2-WT	67
Figure 2-30.	Temperature and pressure estimates for sample GL-2-WT	69
Figure 2-31.	P-T path for eastern IP lithologies from the study area	71
 PART III		
Figure 3-1.	Generalized tectonic map of the southern Appalachians	85
Figure 3-2.	Simplified geologic map of the Moravian Falls and Taylorsville quadrangles, Wilkes and Alexander Counties, North Carolina.....	87
Figure 3-3.	S ₂ foliations in the study area.....	100
Figure 3-4.	Scatter plots and fabric diagrams for all S ₂ , F ₂ , and F ₃ axial surface measurements obtained in the study area	102
Figure 3-5.	Microscopic S-C fabrics from the study area	103
Figure 3-6.	Hand sample and photomicrograph of L ₂ fabrics in the study area ...	104
Figure 3-7.	Mineral lineations for the northern part of the Inner Piedmont	106
Figure 3-8.	D ₂ linear fabric map of the study area.....	107
Figure 3-9.	Scatter plots and fabric diagrams for all L ₂ lineation with F ₂ and F ₃ fold-axis measurements obtained in the study area.....	108
Figure 3-10.	D ₄ linear fabric map of the study area.....	110
Figure 3-11.	Scatter plots and fabric diagrams for S-C intersection lineations and F ₄ crenulation axes and fold hinges in the study area	111
Figure 3-12.	F ₁ and F ₂ folds in the study area.....	112
Figure 3-13.	Mesoscopic F ₁ sheath folds in the study area	114
Figure 3-14.	Field photographs showing F ₃ refolds of F ₂ folds.....	115
Figure 3-15.	SW-vergent mesoscopic F ₄ folds in the study area	117
Figure 3-16.	Distribution of systematic joint orientations in the study area	119
Figure 3-17.	S ₂ foliation form line and domain map of the Moravian Falls and Taylorsville quadrangles	121
Figure 3-18.	Contoured, lower-hemisphere equal-area projections of poles to foliation.....	122
Figure 3-19.	Contoured, lower-hemisphere equal-area projections of mineral lineation and fold axis orientations	123
Figure 3-20.	Microstructural kinematic indicators from the study area	127
 PART IV		
Figure 4-1.	Southern Appalachian index maps.....	142
Figure 4-2.	Simplified geologic map of the Brushy Mountains	145
Figure 4-3.	Distribution of mylonitic rocks within the study area	146
Figure 4-4.	Mineral lineations for the northern part of the Inner Piedmont	149

Figure 4-5.	Microstructural textural variation of northeastern IP mylonites	151
Figure 4-6.	Element variation in northeastern IP mylonite suites relative to protomylonites	161
Figure 4-7.	Chondrite-normalized rare earth element concentrations for northeastern IP mylonite variations	163
Figure 4-8.	Isocon diagrams for northeastern IP mylonites.....	164
 PART V		
Figure 5-1.	Southern Appalachian tectonostratigraphic terranes.....	176
Figure 5-2.	Tectonic map of a portion of the southern Appalachians with sample locations.....	177
Figure 5-3.	Metamorphic isograd map of the southern Appalachian crystalline core.....	178
Figure 5-4.	Simplified geologic map of the Brushy Mountains	183
Figure 5-5.	Representative images of zircon grains from geochronology samples.....	186
Figure 5-6.	Outcrop photograph of geochronology sample MV-29-ggn.....	189
Figure 5-7.	Outcrop photograph of geochronology sample GL-30-ggn.....	190
Figure 5-8.	Concordia and summed probability plots for eastern IP detrital zircon samples.....	197
Figure 5-9.	Summed probability of individual analyses of magmatic and metamorphic samples.....	199
Figure 5-10.	Concordia plots of ²⁰⁴ Pb-corrected SHRIMP data for magmatic and metamorphic samples.....	200
Figure 5-11.	Projected P-T-t path for the Brindle Creek thrust sheet (arrows)	211
Figure 5-12.	Tectonothermal history of the eastern Inner Piedmont	212
Figure 5-13.	Tectonic model for the Paleozoic development of the southern Appalachian crystalline core.....	214

LIST OF PLATES

- Plate 1** Detailed Geologic Map of the Moravian Falls and a portion of the Taylorsville, 7.5 minute quadrangles, Wilkes and Alexander Counties, North Carolina*In Pocket*
- Plate 2** Station Map of the Moravian Falls and Taylorsville, 7.5 minute quadrangles, Wilkes and Alexander Counties, North Carolina*In Pocket*
- Plate 3** Detailed Geologic Map of the Northeastern Inner Piedmont, Brushy Mountains, NC*In Pocket*

PART I

Overview

This thesis presents a study conducted over three years of work in the eastern and western North Carolina Inner Piedmont. An integrated approach, incorporating detailed geologic mapping with metamorphic petrology techniques, geochemical methods, and state-of-the-art geochronologic analyses, was utilized in order to resolve the tectonic development of the northeastern Inner Piedmont. Detailed geologic mapping performed during this study is complemented by recent detailed mapping in the adjoining areas by Jay Kalbas (Kings Creek quadrangle), Arthur Merschat (Ellendale and Boomer quadrangles), and Crystal Wilson (Gilreath quadrangle). Initially, this project was intended to trace the Brindle Creek fault zone northeastward across the Moravian Falls quadrangle, an area located in the northeastern Brushy Mountains. Field work from this study yielded 1,721 structural and lithologic data stations collected over two field seasons. In addition to producing 1:24,000-scale detailed geologic maps of the Moravian Falls and Taylorsville quadrangles a 1:36,000-scale detailed geologic map of the northeastern Inner Piedmont (Brushy Mountains) was compiled.

For purposes of tectonic reconstructions, detailed geologic mapping is greatly complemented by geochemical and geochronologic data. During this study, high-resolution geochronologic data were collected for several northeastern Inner Piedmont lithologies. Detrital, magmatic, and metamorphic ages were determined for important lithologies to provide absolute timing constraints for Inner Piedmont orogenesis. These ages refine the timing of Inner Piedmont development when combined with relative ages determined from field observations and crosscutting relationships. Additionally, the Moravian Falls quadrangle provided access to two map-scale ductile fault zones in close proximity to one another. This unique opportunity allowed for a study of the interaction between large ductile fault zones in an exhumed orogenic core. Geochemical analyses of mylonite suites in the fault zones provide estimates of volume loss and models of fluid flow during the development of the fault zones. Data from this study provide greater insight into the structural make-up, composition, and tectonic history of the Inner Piedmont, along with enhancing our understanding of metasomatic processes during coupled metamorphism and deformation.

This thesis contains four chapters. Each chapter is intended to be a free-standing, potentially publishable work, and therefore each contains individual abstracts, introductions, geologic settings, discussions, conclusions, and references. This produced duplication of certain introductory and reference notations, but each is centered on the unique theme, perspective, or interpretations of the individual chapter. Part II describes the lithologic make-up of the study area and addresses metamorphic relationships that

pertain to the timing and nature of metamorphism in the northeastern Inner Piedmont. Part II is largely descriptive, containing mineralogical and petrographic descriptions of lithologic units in the study area. However, the latter parts of Part II do contain interpretive sections centering around the metamorphic history of the northeastern Inner Piedmont.

Part III addresses the structural and kinematic history of the study area. Structural analyses collected during fieldwork are presented here. Structural relationships documented at micro-, meso-, and macroscales are representative of macroscopic structural trends throughout the northeastern Inner Piedmont. The nature, magnitude, and timing of successive deformation events are discussed in light of new absolute age constraints provided by geochronologic data from the study area.

Part IV presents a study of two map-scale ductile fault zones from the northeastern Inner Piedmont. The structure and composition of these fault zones are studied in detail and kinematic interpretations are given. Deformation mechanisms, interpreted from textural evidence, provide a qualitative estimate of deformation conditions. Estimates of volume loss and dilatational strain are calculated from isocon analyses using geochemical data. Elements enriched in the mylonites are interpreted as immobile, while depleted elements in the mylonites are taken to be enriched in a metasomatic fluid during deformation. These interpretations are combined with structural data to suggest a possible fluid flux path and are compared with modal analyses to determine if the phases present in the mylonites agree with enrichment of certain elements. Finally, volume loss estimates are compared with those of other studies.

Part V presents the results of ion microprobe U-Pb analyses of zircons from selected samples from the northeastern Inner Piedmont. Magmatic and metamorphic samples analyzed for age determination were selected based on map- and outcrop-scale crosscutting relationships. Eastern Inner Piedmont detrital zircon data are also presented here and is compared with eastern Inner Piedmont detrital zircon ages from previous studies. Metamorphic zircon ages are combined with P-T estimate data to produce a P-T-t path for the Inner Piedmont. Finally, a conceptual model is devised for the Paleozoic development of the southern Appalachian crystalline core utilizing new geochronologic data from this study and older data from previous studies.

Accessory data are compiled in the appendices. Appendix A contains electron microprobe data collected for northeastern Inner Piedmont samples. Appendix B is a table of all primary structural data and lithologic descriptions recorded in the Moravian Falls and Taylorsville quadrangles. Data in Appendix B consists of station localities

shown in Plate 2.

PART II

Geology of Part of the Northeastern Brushy Mountains, North Carolina Inner Piedmont: Lithologic and Metamorphic Relationships from the Moravian Falls and Part of the Taylorsville 7.5-minute Quadrangles, North Carolina

ABSTRACT

New detailed geologic mapping in the northeastern Brushy Mountains reveals the geometry of the northeastern Brindle Creek fault zone (BCFZ), the boundary between the eastern and western Inner Piedmont (IP). Two distinct crystalline thrust sheets are present: the Marion and Brindle Creek thrust sheets, or eastern Tugaloo and Cat Square terranes, respectively. The Marion sheet lies between the Neoacadian (BFZ) and the BCFZ. Western Inner Piedmont lithologies in the study area consist of Lower Ordovician Henderson Gneiss bodies thrust over the three-part stratigraphy of the Tallulah Falls Formation, and migmatitic bimodal volcanic equivalents of the Middle Ordovician Poor Mountain Formation. The Brindle Creek thrust sheet is bounded to the northwest by the BCFZ and is continuous southeastward throughout the study area. It is composed of repeated metagraywacke and aluminous schist lithologies, intruded by Devonian sill-like bodies of Walker Top Granite and Toluca Granite. The BCFZ is continuous across the study area to the northeast, then folded, exposing the western Inner Piedmont Silurian Brooks Crossroads pluton in a reentrant. The Hibriten mylonite is restricted to the BCFZ, is composed of heterogeneous eastern and western Inner Piedmont lithologies, displays prominent block-in-matrix structure, and represents a lithologic mixing zone.

Lithologies in the study area preserve polyphase thermal, metamorphic, and deformational histories. Metamorphic mineral assemblages, textures, and migmatization suggest a prograde metamorphic path. Textural associations indicate progressive metamorphism from kyanite-grade to sillimanite-grade conditions. Pressure-temperature estimates also indicate a clockwise progression from kyanite stability field into sillimanite stability field. Garnets from the Walker Top Granite, located near the Brindle Creek fault zone, yielded peak conditions of 745°C and 7.1 kbar. Retrograde (greenschist) overprint is restricted to the Neoacadian Brevard fault zone, specifically northwest of the Mill Spring fault zone. Therefore, a clockwise (Barovian) P-T path, reaching peak upper amphibolite conditions is favored for eastern Inner Piedmont lithologies.

INTRODUCTION

Exhumed orogenic cores contain the metamorphic internides, or roots, of mountain belts. Here, existing sedimentary and volcanic rocks are juxtaposed

against rocks of different affinities, and partial melting creates new crust. Tectonic reconstructions of these areas are often difficult because of structural complexities, although detailed studies of these areas can provide insight into deep crustal processes that drive and accompany orogenesis.

In deciphering geologic histories of areas such as these, an analytical approach including four basic reference frames is required to ultimately construct a pressure-temperature-time-deformation (P-T-t-D) path for the area: geothermobarometry techniques (P-T), geochronology (t), and structural analysis (D). Although each method independently conveys some information about an area, tectonic histories are incomplete without an integration of the techniques.

The IP and eastern Blue Ridge comprise most of the Neoacadian orogenic core of the southern Appalachians (Fig. 2-1) (Davis, 1993a; Hatcher, 1993; Hatcher and Mersch, in press). The IP can be generalized as a shallowly dipping, high-grade metamorphic and igneous terrane. Although multiple episodes of intense ductile deformation, transposition of earlier structures, high-grade metamorphism, anatexis, and plutonism have affected IP lithologies, regional primary lithostratigraphic successions can be recognized for substantial distances (Rankin et al., 1972; Goldsmith et al., 1988; Hatcher, 1989). Aside from extending our knowledge of IP geology, a major good of this study is to increase our understanding of the processes of large crystalline thrust sheet emplacement in orogenic cores.

Additional work in the vicinity of the study area consists of large areas of small-scale reconnaissance mapping connected by islands of detailed studies. Rankin et al. (1972), Espenshade et al. (1975), and Goldsmith et al. (1988) made reconnaissance maps of the Winston-Salem, NC 1° x 2° sheet and the Charlotte, NC 1° x 2° sheet that covered large areas of the IP (Fig. 2-2).

Numerous attempts to adequately describe the structural and lithostratigraphic framework and constrain the spatial and temporal evolution of the IP have produced detailed studies of the western North Carolina IP (Overstreet et al., 1963a, 1963b; Lemmon and Dunn, 1973a, 1973b; Davis, 1993a, 1993b; Yanagihara, 1994; Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Mersch, 2003), and earlier in the Sauratown Mountains (Heyn, 1984; McConnell, 1990) and Alto allochthons (Hopson and Hatcher, 1988). Together with mapping by Griffin, Garihan and Ranson, and Hatcher, these studies have built large islands of high-quality structural and petrologic data that have produced major breakthroughs in our tectonic evolution knowledge of the IP.

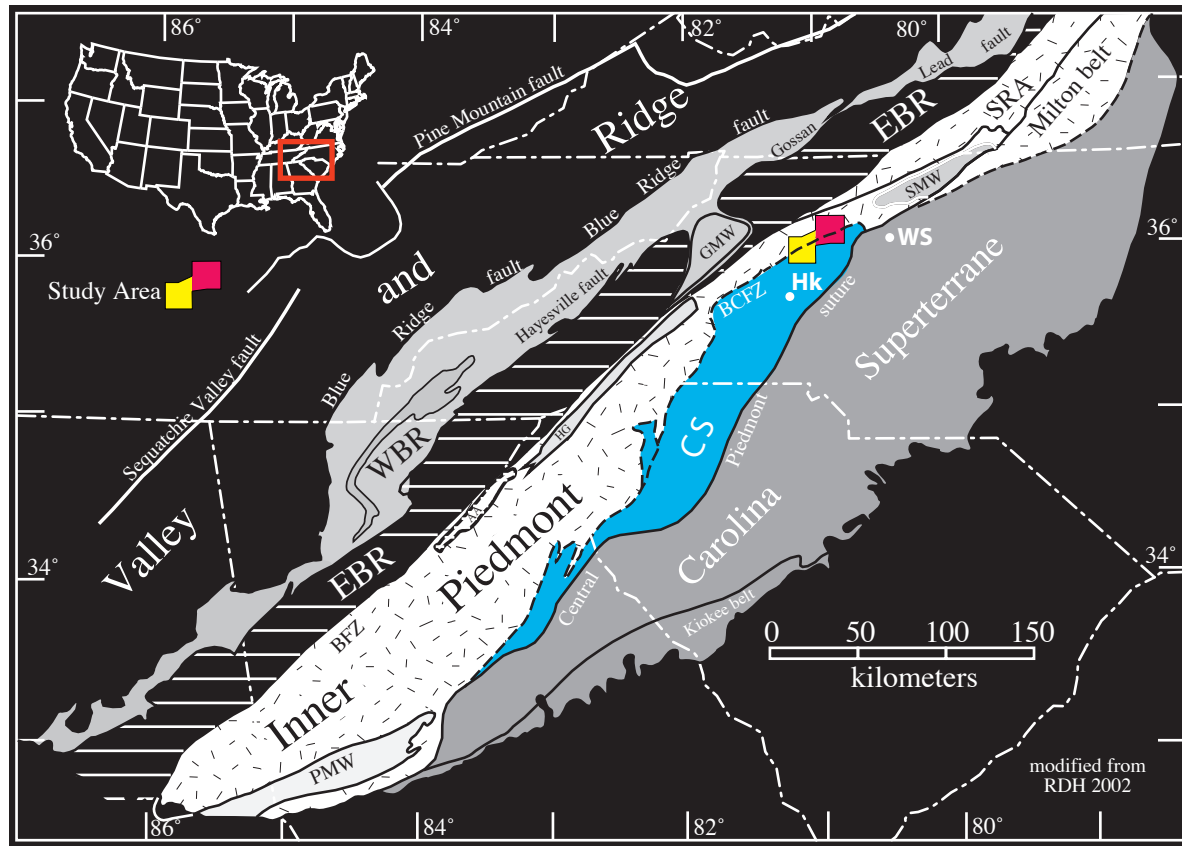


Figure 2-1. Generalized tectonic map of the southern Appalachians. Red box represents the location of present study area. Yellow box represents the location of previous detailed geologic mapping in the Brushy Mountains from Merschat (2003) and Kalbas (2003). Tectonic map of the southern Appalachians (modified from Hatcher, 2002) shows the major lithotectonic units. CS–Cat Square terrane. EBR–Eastern Blue Ridge. WBR–Western Blue Ridge. GMW–Grandfather Mountain window. PMW–Pine Mountain window. SMW–Sauratown Mountains window. BCFZ–Brevard fault zone. BCFZ–Brindle Creek fault zone. AA–Alto allochthon. HG–Henderson Gneiss. SRA–Smith River allochthon. WS–Winston-Salem. Hk–Hickory.

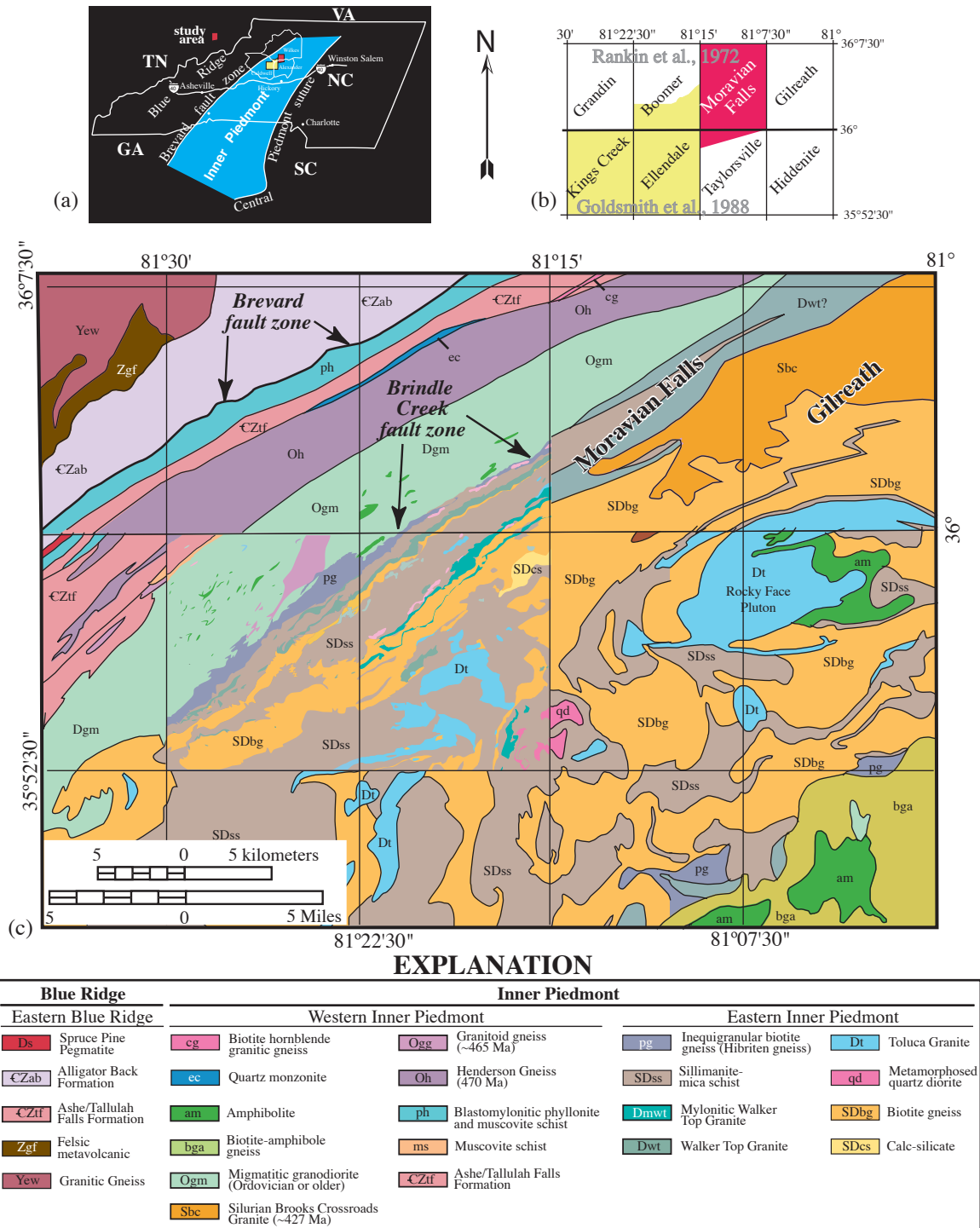


Figure 2-2. (a) Index map of the study area (in red) showing counties, Interstate 40, and the Inner Piedmont in southern North Carolina and northern South Carolina. (b) Quadrangle index showing recently completed Brushy Mountain detailed geologic mapping (yellow) and location of present study (red). (c) Geologic map comparing results of recent detailed mapping (SW Brushy Mountains) with previous regional reconnaissance mapping (from Goldsmith et al., 1988, and Rankin et al., 1972), showing the distribution of major rock units in the study area.

This study contributes to the series of detailed (1:12,000- and 1:24,000-scale) mapping projects completed in the IP in the last 12 years. With moderate relief and good exposure, the Brushy Mountains provide an opportunity to study part of this mid-Paleozoic orogenic core. Kalbas (2003) and Mersch (2003) have established a lithostratigraphic succession and delineated geometries of map-scale structures for the southwestern Brushy Mountains (Fig. 2-2; Plate 3). New detailed mapping in the northeastern Brushy Mountains, introduced in this study and from Wilson (2006), will enhance our knowledge of the spatial and temporal characteristics of the northeastern IP.

In addition to detailed mapping, new petrologic and geochemical data introduced here for the northeastern IP allow for a better understanding of the processes and environmental conditions occurring during IP orogenesis. New IP geochronologic data (Part V, this study) along with data from Bream (2003) provide more precise temporal constraints on relative IP orogenic pulses. Therefore, this study should comprise a complete tectonic synthesis of observed and inferred relationships for a portion of the northeastern IP.

GEOLOGIC SETTING

Regional Inner Piedmont Structure and Metamorphism

The IP comprises the southern Appalachian Neoacadian orogenic core (Davis, 1993a; Hatcher, 1993, 2002), extending approximately 700 km southwestward from the Sauratown Mountains window in North Carolina to the Coastal Plain overlap in Alabama (Fig. 2-1). Large faults bound its eastern and western extents. Its breadth is approximately 100 km from the Central Piedmont suture to the southeast to the Brevard fault zone to the northwest. It can be characterized by a distinct assemblage of para- and orthogneisses, macroscale structures, high-grade metamorphism, migmatization, and plutonism (Osberg et al., 1989; Davis, 1993a; Hatcher, 1993). The Brindle Creek fault zone (BCFZ), originally recognized by Giorgis (1999), separates the western and eastern IP, or eastern Tugaloo and Cat Square terranes, respectively (Bream et al., 2004).

The IP is composed of a stack of westward-verging, crystalline thrust sheets containing predominantly high-grade metamorphic rocks (Griffin, 1969; Hatcher, 1969). Davis (1993a) and Hatcher (1993) described the IP as a polydeformed, high-grade igneous and metamorphic terrane consisting of a series of distal slope-and-rise facies, metasedimentary and igneous rocks of various crustal affinities.

Recognition of the IP as the Neoacadian orogenic core of the southern

Appalachians has stemmed from investigations into the nature and characteristics of deformation in the IP and modern geochronologic techniques. Structurally, the IP closely resembles the orogenic cores of other mountain chains. Hatcher and Hooper (1992) observed that the structure of the IP is dominated by passive or flexural-flow folds, which form low-angle type F thrusts and reclined to recumbent folds. Based on detailed studies from the southern Appalachians, Davis (1993a) concluded that a series of five deformational events affected IP rocks. Of these, D_2 and D_3 were responsible for the major penetrative deformation and overall regional foliation seen in the IP. These deformational events are thought to coincide with peak metamorphic conditions during orogenesis (Davis, 1993a).

New data from the southwestern Brushy Mountains (SW of my study area) have recently been interpreted to indicate the presence of map-scale sheath folds, originating during the emplacement of the Brindle Creek thrust and the Walker Top and Toluca Granites (Merschhat et al., 2005). Sheath fold axes, asymmetric folds, boudins, winged porphyroclasts, mineral lineations, S-C mylonites, and snowball garnets indicate transport directions. Recent studies have concluded that D_2 transport directions in the IP core are EW- and W-directed, but to the NW become strongly constricted and directed SW, most likely related to SW deflection of W-advancing thrust sheets by the primordial Brevard fault zone (Hatcher, 2001; Merschhat and Kalbas, 2002). In these interpretations, D_2 map-scale passive flow folds were generated by W-directed simple shear, then rotated southwestward during initial ductile flow, which rotated these fold hinges into parallelism with the dominant transport direction as sheath folds (Merschhat et al., 2005). Investigations into the extent and nature of map-scale sheath folds to the NE, closer to the Brevard fault zone (BFZ), will be included in this study.

The IP is the largest area of sillimanite-grade metamorphism in the Appalachians. Metamorphism increases from staurolite-kyanite and garnet grade on the flanks to second-sillimanite grade in the core (Butler, 1991). Merschhat (2003) identified small areas of second-sillimanite zone metamorphism in the IP core. Peak metamorphism occurred between 360-340 Ma as indicated by SHRIMP U-Pb analyses of metamorphic rims on zircons from the northeastern IP (Bream, 2003; Part V, this study).

Lithostratigraphy

Detailed mapping studies have supported the general lithologic framework for the IP, first recognized during previous reconnaissance studies (Fig. 2-2). IP paragneisses are commonly considered to have originated from slope and rise-type sediment protoliths,

but some have described alternative and coeval lithotectonic assemblages (Griffin, 1971; Hatcher and Butler, 1979).

The BCFZ separates the northeastern Brushy Mountains into two crystalline thrust sheets, each containing distinct lithostratigraphic packages (Figs. 2-1 and 2-2; Plates 1 and 3). Structurally, the lowest (northwesternmost) sheet, the Marion thrust sheet, contains western IP assemblages and is overlain to the southeast by the Brindle Creek thrust sheet, which contains eastern IP lithologies (Plates 1 and 3). Previous work in the southwestern Brushy Mountains (Kalbas, 2003; Mersch, 2003) indicated the presence of three distinct crystalline thrust packages (Marion, Mill Spring, and Brindle Creek sheets) separated by two fault zones (Mill Spring and Brindle Creek fault zones). Stratigraphic correlation of lithologies across the previously defined Mill Spring fault zone and recognition of only minor dextral strike-slip motion in the area of this study, however, exclude the Mill Spring thrust sheet as a separable lithotectonic package. Therefore, western IP lithologies for this study belong exclusively to the Marion thrust sheet, while eastern IP units correspond to the Brindle Creek thrust sheet.

Marion thrust sheet

The Marion thrust sheet lies immediately southeast of the BFZ and contains Laurentian margin slope-and-rise metasedimentary units of the Tallulah Falls/Ashe Formation, Ordovician metavolcanic/metasedimentary arc sequences of the Poor Mountain Formation, and Ordovician-Silurian metaigneous rocks. Together, these units comprise the lithostratigraphy of the western IP (eastern Tugaloo terrane) for the study area and the Neocadian BFZ (Davis, 1993a; Bream, 1999; Giorgis, 1999).

The Tallulah Falls/Ashe Formation of the Tugaloo terrane consists of a sequence of metagraywacke and pelitic schist with minor amounts of amphibolite. Interpreted as distal slope-and-rise sediments shed from the Laurentian margin, a partially traceable stratigraphy exists as an upper graywacke schist member, a middle aluminous schist member, and a lower graywacke-amphibolite member. The Tallulah Falls stratigraphy, originally subdivided in South Carolina by Hatcher (1971, 1973), has also been identified in the Blue Ridge of southwestern Virginia, North Carolina, and northeastern Georgia (Hatcher, 1993). More recent studies from the North Carolina IP have indicated the presence of the Tallulah Falls southeast of the BFZ (e.g., Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Gatewood, this study). The Tallulah Falls sequence in the western IP is recognized by its three-part stratigraphic succession, and petrologic and geochronologic similarities to Tallulah Falls units from the

adjacent eastern Blue Ridge.

Units petrologically similar to the Tallulah Falls Formation have been recognized southeast of the BCFZ, and were originally correlated with the Tallulah Falls Formation, based on detailed mapping (Giorgis, 1999; Williams, 2000; and Bier, 2001). Detrital zircon work from Bream (2003), however, precludes correlation of units of the eastern IP with the Tallulah Falls Formation. Detrital zircon grains from both eastern and western IP paragneisses contain Grenville-age (1.25-1.10 Ga) detrital zircons. Eastern IP metasedimentary rocks, however, also contain a suite of Devonian-age zircons, which were most likely deposited in a Late Silurian to Early Devonian remnant ocean basin (Bream et al., 2001a, 2001b; Merschat and Hatcher, in press). Western IP paragneisses and schists were most likely deposited along a Neoproterozoic to early Paleozoic rifted continental margin. The absence of this Paleozoic detrital zircon suite in western IP metasedimentary units indicates a different provenance for eastern and western IP assemblages, and prevents correlation of the Tallulah Falls Formation rocks across the BCFZ.

Unconformably overlying the Tallulah Falls Formation, southeast of the BFZ, is the Middle Ordovician Poor Mountain Formation, which consists of a lower amphibolite unit overlain by an upper quartzite-marble/felsic tuff member. Shufflebarger (1961) and Hatcher (1969) first recognized the distinct metavolcanic and metasedimentary succession of the Poor Mountain Formation. Davis (1993b) correlated three equivalent units from the Columbus Promontory of southwestern North Carolina and northwestern South Carolina with Poor Mountain Formation assemblages.

Western IP orthogneiss units have Ordovician-Silurian crystallization ages and are mineralogically dominated by plagioclase (Vinson, 1999; Mapes, 2002; Bream, 2003). These granitoids occur intermittently from northeast of Lenoir, NC to NE Georgia (Reed and Bryant, 1964; Bryant and Reed, 1970; Harper and Fullagar, 1981; Hatcher, 1993; Bream, 2002).

The ~490 Ma Henderson Gneiss (Carrigan et al., 2001) is the most laterally continuous and petrologically distinct western IP orthogneiss. In the Marion, NC area, near the northeastern terminus of its main outcrop belt, the Henderson Gneiss structurally overlies Tallulah Falls Formation units (Hill, 1999). Farther to the SW, however, the Henderson Gneiss structurally overlies Poor Mountain Formation rocks (Hatcher and Acker, 1984; Hatcher, 1993, 2002). Several attempts have been made to explain outcrop patterns and the nature of the contact of the Henderson Gneiss body with its surrounding units (e.g., Davis, 1993a; Hatcher, 2002). The best candidate for a solution to this

problem is that the contact is faulted, as suggested by Davis (1993a). This suggestion is supported by observations of outcrop patterns and mylonitic contact relationships (e.g., Reed, 1964; Davis, 1993a; Bream, 1999; Hill, 1999; Gatewood, this study).

Along with the ~490 Ma Henderson Gneiss, the ~490 Ma Sugarloaf Mountain gneiss (Vinson, 1999), the ~465 Ma Dysartsville tonalite (Bream, 2003), the ~460 Ma Toccoa granitoid (Bream, 2003), the ~427 Ma Brooks Crossroads granite (Harper and Fullagar, 1981), and several unnamed western IP Ordovician and Silurian plutons (e.g., Nelson et al., 1998) comprise the Ordovician-Silurian western IP orthogneiss suite. Vinson (1999) noted that western IP igneous and metaigneous units are most likely the product of syn- or postcollisional crustal thickening, and are not subduction-related continental magmatic arc magmas as they have been typically depicted in tectonic models (e.g., Harper and Fullagar, 1981; Hatcher, 1989; Sinha et al., 1989; Hibbard, 2000). Western IP metaigneous lithologies are compositionally and temporally distinct from eastern IP metaigneous lithologies.

Brindle Creek thrust sheet

Recent detailed geologic mapping, geochemical, and geochronologic data have defined a lithostratigraphy and indicated the presence of a terrane boundary in the IP (Bream and Hatcher, 2002). Based on zircon inheritance, Bream et al. (2001b) concluded the BCFZ is a terrane boundary separating older (Cambrian-Silurian) rocks of the western IP from younger (Silurian-Mississippian) rocks of the eastern IP. Giorgis (1999) first recognized and described the Brindle Creek thrust near Morganton, NC, as a low-angle type F crystalline thrust that juxtaposes migmatitic biotite-amphibolite gneiss of the western IP against pelitic schist and orthogneiss of the eastern IP. Recent detailed mapping northeast of Morganton, NC, has traced the Brindle Creek fault zone along strike from near Lenoir, NC (Mersch and Kalbas, 2002) to just south of Wilkesboro, NC (Plate 3). Large changes in stratigraphic thicknesses of petrologically similar metasedimentary units, first documented by Giorgis (1999) and Bier (2001), occur across the BCFZ (Plate 1; Plate 3). Subdivision of the IP into separate eastern and western IP tectonostratigraphic terranes based on detailed mapping is further supported by detrital and primary igneous zircon data, which indicate that Silurian-Mississippian metasedimentary and metaigneous rocks of the eastern IP were thrust over the older meta-volcanic rocks of the western IP (Bream et al., 2001a).

IP igneous and metaigneous rocks can also be partitioned across the Brindle Creek fault, with primarily Ordovician-Silurian magmatism occurring in the western IP and

Devonian-Mississippian magmatism dominating in the eastern IP (Mapes et al., 2001; Bream, 2002; Mapes, 2002; Part V, this study). The Devonian and Carboniferous Toluca (378 Ma, Mapes, 2002), Walker Top (407 Ma, Part V, this study), and Cherryville (375 Ma, Mapes, 2002) Granites belong to the eastern IP suite (410-366 Ma), and are probably pre- to synmetamorphic. Eastern IP metaigneous units are intraplate, anatectic magmas (Giorgis, 1999; Bier, 2001), are similar in age (Bream, 2002), and occur exclusively in the Cat Square terrane, which contrast with spatial, temporal, and compositional characteristics of western IP metaigneous lithologies.

LOCATION OF STUDY AREA

The study area is located ~65 km NE of Hickory and ~2 km S of Wilkesboro, NC (Fig. 2-3). It comprises the SE quarter of the Boone and the NE quarter of the Hickory 1:100,000-scale sheets. It consists of the Moravian Falls 1:24,000 scale quadrangle and the upper portion of the Taylorsville 1:24,000 scale quadrangle (Fig. 2-3; Plate 1), an area covering ~80 mi² of the northeastern IP. This area, located in the northeastern Brushy Mountains, contains good exposure and moderate relief (~300 m, ~1300 ft). Additionally, the study area offers numerous road access points to locations for good foot traverses along creeks and hunting trails. Many logging and hunting roads are kept clear year round, providing access to otherwise inaccessible property.

The study area is also geologically significant because it is situated along the boundary of the eastern and western IP. The presence of a terrane boundary the BCFZ, and the Neocadian BFZ, along with the Poplar Springs shear zone in the northeastern IP provides a unique opportunity to study the relationships between several northeastern IP ductile fault zones (Figs. 2-2 and 2-4; Plates 1 and 3). The spatial and temporal characteristics of these ductile fault and shear zones provide direct insight into the developmental history of northeastern IP thrust packages.

METHODS

Detailed 1:24,000-scale geologic mapping was completed for all of the Moravian Falls and part of the Taylorsville, NC 7.5-minute topographic quadrangles during the course of two field seasons (January -July, 2003; January-May, 2004). Base maps consisted of standard and enlarged versions of USGS 7.5-minute quadrangles at 1:24,000 and 1:12,000 scales. Field notes, including mineralogical, textural, and lithological descriptions, planar and linear fabric orientations (measured with a BruntonTM pocket transit), field photographs, and scaled field sketches were cataloged by station

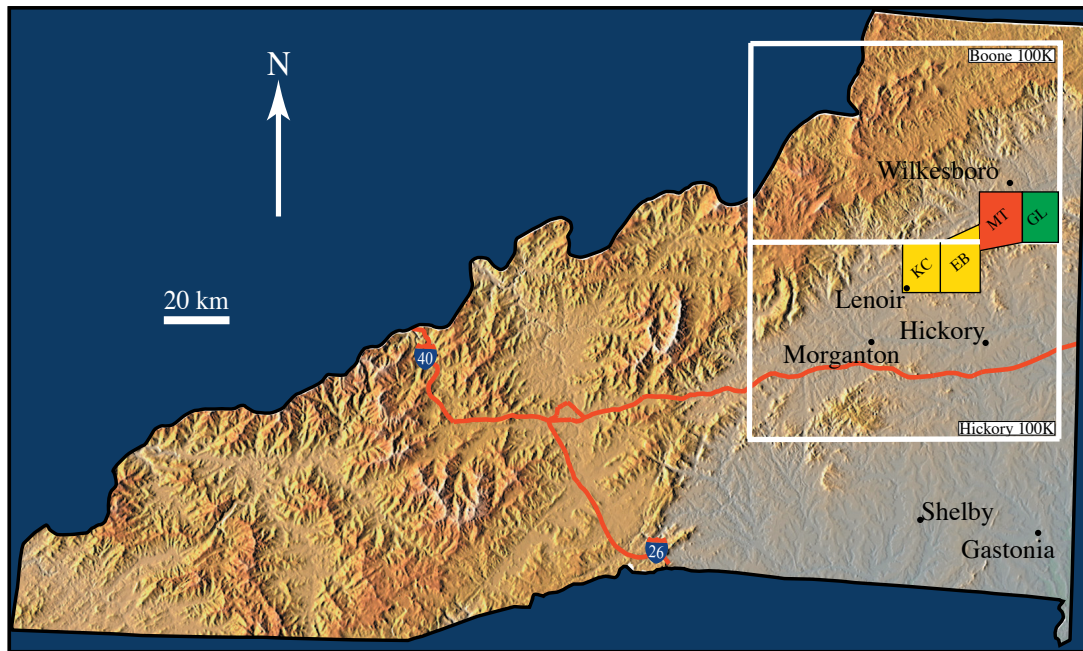
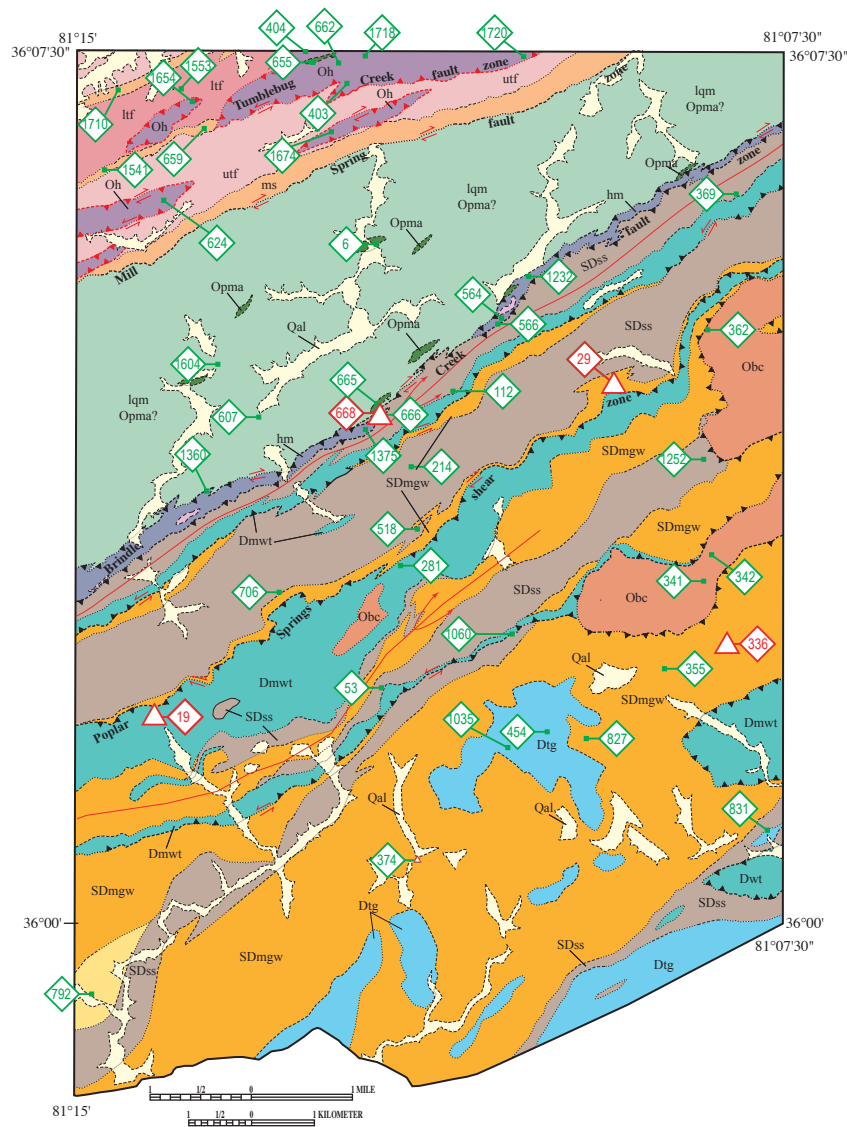


Figure 2-3. Index map showing the location of the study area. Red box shows the location of the present study (Moravian Falls and Taylorsville quadrangles (MT; Gatewood, this study)). Green box corresponds with the location of a detailed study of the Gilreath quadrangle (GL) in progress (Wilson). Yellow boxes correspond to previous detailed mapping in the Ellendale and Boomer quadrangles (EB; Mersch, 2003) and Kings Creek quadrangle (KC; Kalbas, 2003).



LITHOLOGIES

Qal Quaternary alluvium/colluvium

WESTERN INNER PIEDMONT

- Obc Ordovician Brooks Crossroads granitoid
- lqm Lenoir Quarry migmatite/
Ordovician Poor Mtn Amphibolite?
- Opma Poor Mountain amphibolite
- Oh Ordovician Henderson Gneiss
- utf Upper Tallulah Falls/Ashe Formation
(Cambrian?)
- ms garnet-aluminous schist
- ltf Lower Tallulah Falls/Ashe Formation
(Cambrian?)
- hm hibriten mylonite

EASTERN INNER PIEDMONT

- Dwt Devonian Walker Top Granite
- Dmwt Devonian mylonitic Walker Top Granite
- Dtg Devonian Toluca Granite
- SDmgw Silurian-Devonian metagraywacke
- SDss Silurian-Devonian sillimanite schist
- SDcs Silurian-Devonian calc-silicate

MAP SYMBOLS

- Lithologic Contact
- Neoacadian (~366 Ma) thrust fault
(teeth located on hanging wall)
- Early Neoacadian thrust fault (teeth
located on hanging wall)
- Oblique-slip fault (arrows indicate shear
sense)
- Possible sheath fold axis (arrows point in
direction of shear sense)
- 000 Sample collected for SHRIMP geochronologic
analysis
- 000 Sample collected for petrographic analysis

Figure 2-4. Simplified geologic map of the Moravian Falls and a portion of the Taylorsville 7.5-minute quadrangles, Wilkes and Alexander Counties, North Carolina.

number (Plate 2). Structural measurements and lithologic descriptions were recorded at >1,800 stations, and numerous samples were collected for petrographic/chemical/geochronologic analyses. A digital geologic map was compiled using Adobe Illustrator™ and Adobe Photoshop™ software (Plate 1; Fig. 2-4), stations were georeferenced using MAPublisher™, and all data were organized in a Microsoft Excel™ spreadsheet database (Appendix B).

Fifty representative and unique samples were collected from the study area for petrographic analysis (Fig. 2-4). Both oversized (5.08 x 7.62 cm) and standard sized (2.4 x 4.6 cm) thin sections were used to determine modal mineralogy for the selected samples. Stage step distances for modal and petrofabric analyses varied according to grain size and texture. Anorthite components of plagioclase grains were estimated using the Michel-Lévy method (Nesse, 1991).

NORTHEASTERN INNER PIEDMONT LITHOLOGIES

Mapping studies in the northeastern IP have confirmed the existing lithostratigraphies originally established from reconnaissance studies (e.g., Rankin et al., 1972; Goldsmith et. al., 1988). Results from geologic mapping components of this project also indicate that several map-scale structures and lithologies delineated during detailed mapping in the South Mountains and southwestern Brushy Mountains are traceable into the study area.

Although work from this study supports previous reconnaissance studies of the area, it has revealed a much greater complexity at the map and outcrop scales (Figs. 2-2 and 2-4; Plates 1 and 3). Two separable lithotectonic packages, the Marion and Brindle Creek thrust sheets, are composed of 14 distinctive lithologies in the Brushy Mountains area and 11 in the study area (Figs. 2-4 and 2-5; Plates 1 and 3). Lithologies from the Brushy Mountains correlate well with units originally recognized in south-central North Carolina, which collectively correspond to the regionally recognizable lithostratigraphy of the IP. Only lithologic units from the Moravian Falls and Taylorsville 7.5-minute quadrangles will be discussed in detail below. Rock unit descriptions will be grouped into respective lithotectonic packages and description will proceed from northwest to southeast (Figs. 2-4 and 2-5; Plate 1). Modal mineralogical analyses for all rock units are reported in decreasing order of abundance.

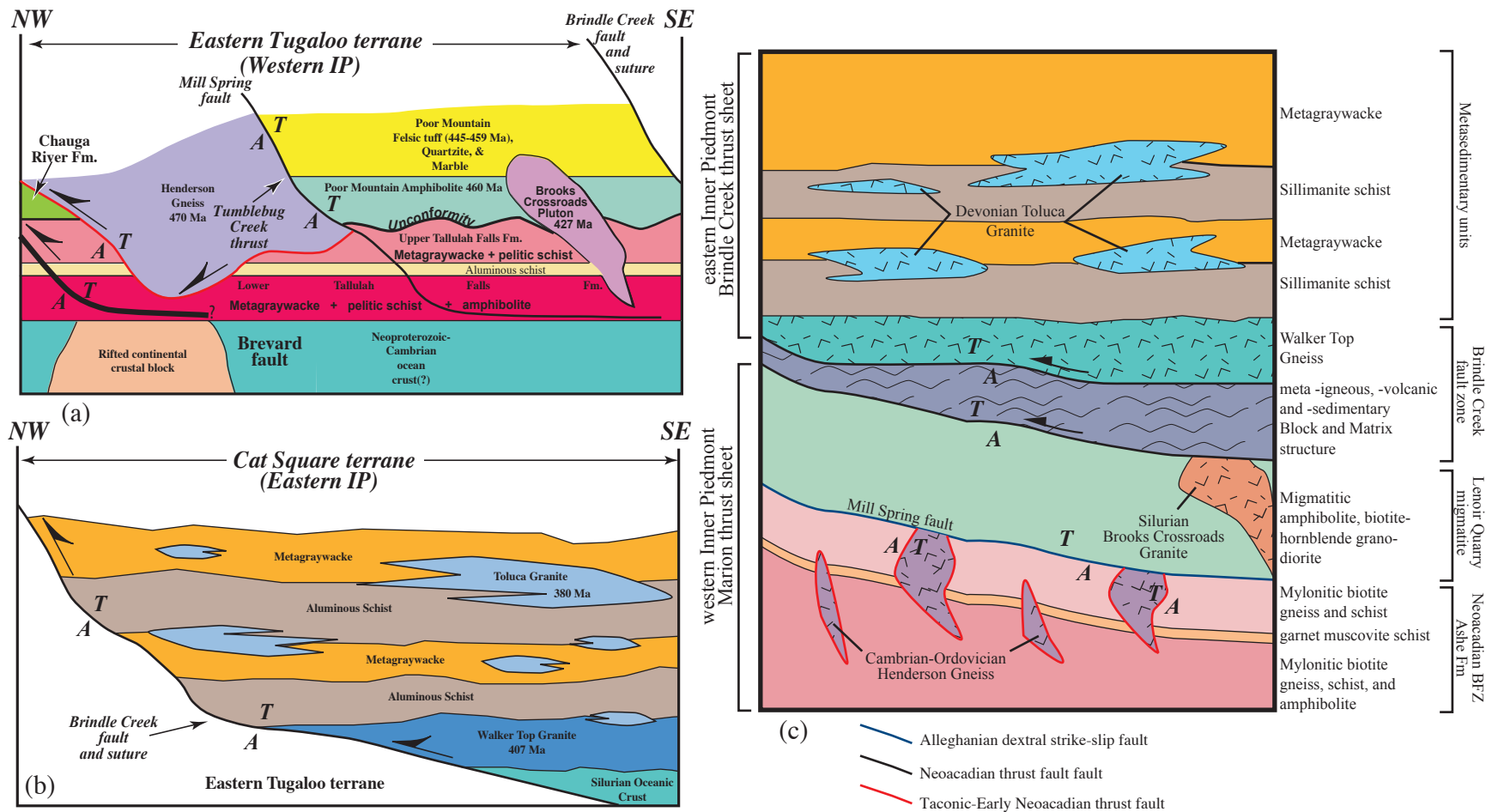


Figure 2-5. Inner Piedmont lithostratigraphy and generalized lithologic column for the study area. Lithostratigraphy by terrane (a and b). (a) Western Inner Piedmont (eastern Tugaloo terrane) generalized lithostratigraphic column showing structural and lithologic relationships (Modified from Hatcher, and Merschat, *in press*). Note: All western Inner Piedmont units not present in the study area. (b) Generalized mechanical stratigraphy for eastern Inner Piedmont Cat Square terrane lithologies (modified from Hatcher and Merschat, *in review*). (c) Generalized lithostratigraphic column for the study area showing stratigraphic positions of map-scale structures and lithologies.

Marion Thrust Sheet (western IP)

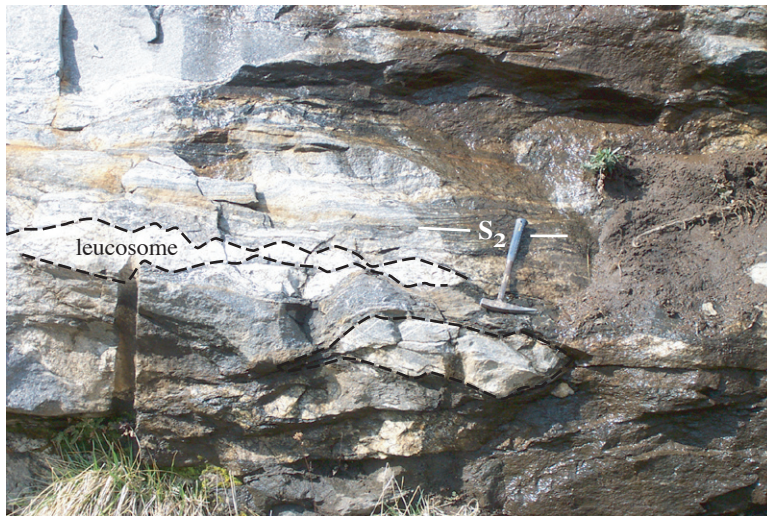
Tallulah Falls/Ashe Formation

The Tallulah Falls/Ashe Formation occupies the northwesternmost portion of the Moravian Falls quadrangle (Fig. 2-4; Plate 1). Original reconnaissance work correlated western IP metasedimentary units with those of the eastern IP. However, petrologic similarities to units described to the southwest and recognition of a distinctive stratigraphy suggest that these northwestern IP metasedimentary units correspond to the well-established stratigraphy of the Tallulah Falls/Ashe Formation (e.g., Lemmon, 1973; Davis, 1993a; Yanagihara, 1994; Bream, 1999; Hill, 1999). Furthermore, significant discrepancies in thickness exist between eastern and western IP metapelitic units and paragneisses (Fig. 2-4; Plates 1 and 3). Detrital zircon work by Bream (2003) ultimately prohibits correlation of these units across the BCFZ, and indicates that this unique stratigraphy is restricted to the western IP.

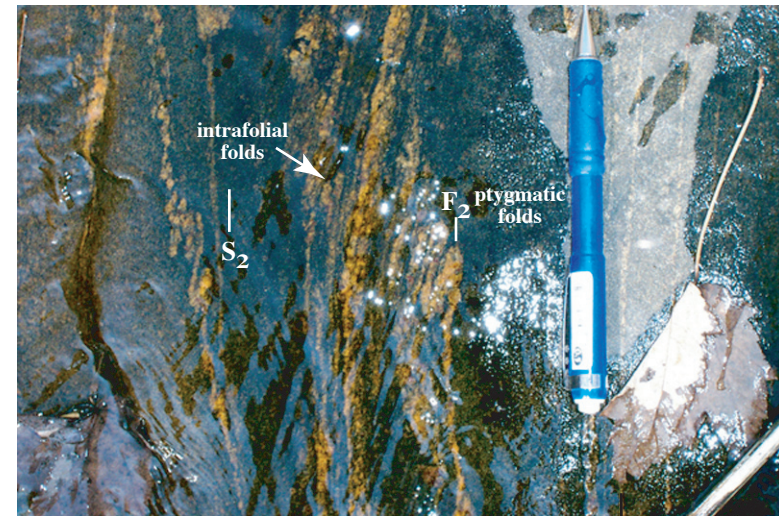
IP metasedimentary rocks of the Tallulah Falls Formation occur exclusively in the lowermost portion of the Marion thrust sheet proximal to the Neoacadian BFZ (Figs. 2-4 and 2-5; Plates 1 and 3). A middle aluminous schist unit separates upper and lower graywacke-amphibolite members (Figs. 2-4 and 2-5; Plate 1). Recognition of Tallulah Falls Formation stratigraphy in the northeastern IP is based on the presence of the aluminous schist marker unit and careful observation of the amphibolite content of the upper and lower metagraywacke-schist units.

Amphibolite bodies occur as layers and discontinuous boudinage pods within the upper and lower metapsammitic-metapelitic units, with a much higher frequency in the lowermost unit. Compositional and migmatitic layering are transposed into parallelism with the dominant foliation (Fig. 2-6). The upper and lower graywacke-schist units can be characterized as fine- to medium-grained, dark gray to green, metagraywacke-biotite gneiss/amphibolite with minor mica schist.

Discontinuous schistose layers within the upper and lowermost units generally consist of muscovite, biotite, and garnet, with minor quartz and opaques. Metapsammitic units are composed of quartz, plagioclase (An_{20-40}), biotite, and muscovite, with minor hornblende, chlorite, microcline, epidote, allanite, sphene, zircon, monazite, and opaques. Foliation planes are defined by parallel alignment of micas and quartzofeldspathic material. Tallulah Falls Formation metagraywacke commonly exhibits a porphyroclastic texture, with sheared porphyroclasts of quartzofeldspathic material in a fine-grained quartz-biotite matrix. Fine-grained quartz aggregates typically display high-angle grain boundaries and evidence for grain boundary migration, indicating that ambient



(a)



(b)

S₂

Figure 2-6. Typical outcrops of the Tallulah Falls Formation metagraywacke. (a) Representative outcrop of migmatitic lower Tallulah Falls Formation near W. Kerr Scott Reservoir (MV-1543). Note the transposed and boudinaged leucocratic migmatite layers. (b) Representative exposure of the upper Tallulah Falls Formation near Whites Creek (MV-1524). Note the ptygmatic and intrafolial folds present in the deformed leucosome layers.

temperatures were high enough after deformation ceased to afford partial to complete recrystallization (Fig. 2-7). Coarse-grained plagioclase displays some primary twinning, while finer-grained plagioclase is often untwinned, indicating partial recrystallization. Chlorite laths commonly overgrow foliation planes and partially replace biotite. Modal mineralogies of Tallulah Falls Formation metagraywacke samples plot within the arkose and graywacke fields on a quartz-feldspar-mica ternary diagram for sandstone classification (Table 2-1; Fig. 2-8).

Along with the determination of amphibolite contents of graywacke-schist members, the most useful method to delineate stratigraphic boundaries in the Tallulah Falls Formation is the recognition of a middle garnet-aluminous schist marker unit, which divides the upper and lower psammite members. Lateral continuity and the occurrence of an aluminum silicate phase (typically pseudomorphs of sillimanite after kyanite) distinguish this unit from schistose layers within the graywacke-schist units. Weathering characteristics and sharp contrasts with surrounding lithologies make this unit easily identifiable. It is recognized in the field as a dark to light red, fine- to medium-grained, muscovite-biotite-garnet-sillimanite-chlorite-quartz-feldspar schist (Fig. 2-7). Pods of leucocratic migmatite occur sporadically. Planar fabrics are defined by the alignment of micas, quartzofeldspathic material, and sillimanite. Texturally, this unit contains rotated porphyroblastic garnets and a Type II S-C mylonitic fabric (Lister and Snoke, 1984), indicating top-to-the-southwest shear sense (Fig. 2-7).

Henderson Gneiss

The Henderson Gneiss comprises the most laterally continuous and the largest granitoid in the North and South Carolina IP. Originally described by Keith (1905, 1907) and later by Reed and Bryant (1964), it can be characterized as an easily recognizable monzogranitic augen orthogneiss, which is laterally continuous from near the Georgia-South Carolina border in South Carolina to the latitude of Marion, North Carolina (Lemmon, 1973; Lemmon and Dunn, 1975; Bream, 1999). It reaches its greatest outcrop width near the type locality in Henderson County, NC (Brown et al., 1985).

The Henderson Gneiss in the study area exists as a coarse- to fine-grained, porphyroclastic augen gneiss (Fig. 2-9), consisting mostly of oligoclase, microcline, quartz, biotite, and muscovite, with accessory chlorite, myrmekite, sericite, epidote, allanite, and sphene (Fig. 2-10; Table 2-2). Modal mineralogy for Henderson Gneiss samples from this study plot in the monzogranite-granodiorite fields using an IUGS (Q-A-P) classification system for felsic igneous rocks (Fig. 2-11). These results correlate

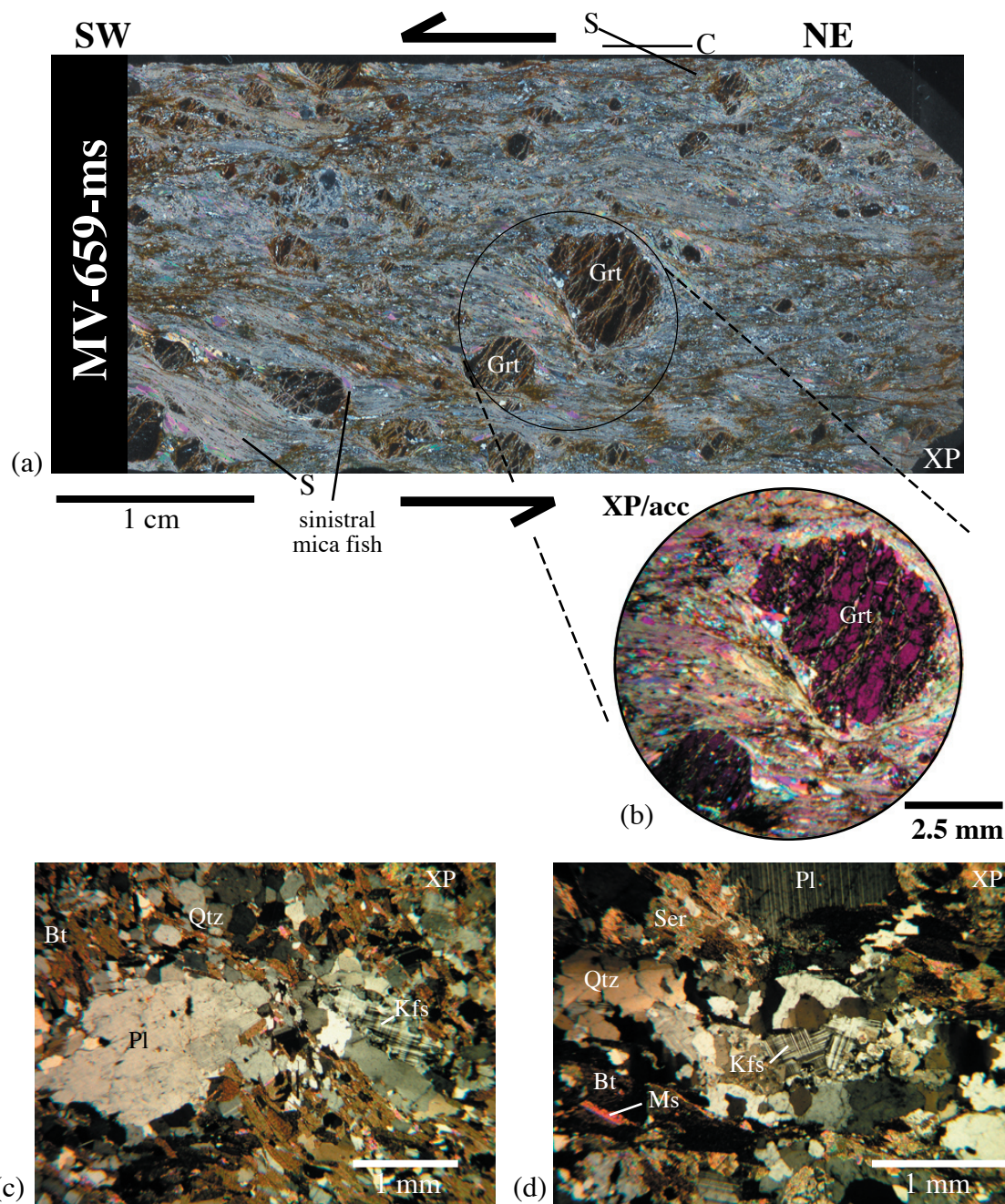


Figure 2-7. Petrographic characteristics of the Tallulah Falls Formation. (a) Scanned thin section of middle Tallulah Falls Fm. garnet-muscovite-sillimanite schist. Field recognition of this unit allows for stratigraphic subdivision. Note the prominent S-C fabric, mica fish, and rotated porphyroblasts indicating top to the SW shear sense. (b) Photomicrograph of a large rotated garnet porphyroblast from (a). (c) Photomicrograph showing typical texture and mineralogy of the upper Tallulah Falls Fm. (d) Photomicrograph showing a representative texture and mineralogy for the lower Tallulah Falls Fm. in the study area. Note the fine grain size and recrystallized textures in (c) and (d). Abbreviations (after Kretz, 1983): Bt=biotite, Qtz=quartz, Pl=plagioclase, Kfs=K-feldspar, Ser=sericite, Ms=muscovite, Grt=garnet, XP=crossed polars, acc=gypsum plate inserted.

Table 2-1. Modal mineralogy of the Tallulah Falls/Ashe Formation in the study area.

	upper Tallulah Falls Fm.			gms	lower Tallulah Falls Fm.		
Sample #	MV-628-utf	MV-1639-utf	MV-1523-utf	MV-659	MV-1539-ltf	MV-1641-ltf	MV-1553-ltf
# points Counted	1018	936	1037	1053	1023	1006	1011
lithology	mgw/bgn	mgw/bgn	mgw/bgn	gms	mgw/bgn	mgw/bgn	mgw/bgn
Quartz	34.8	37.1	32.6	10.6	49.3	34.2	38.6
Plagioclase	55.2 (An ₃₅₋₄₅)	25.4 (An ₁₀₋₂₀)	26.4 (An ₁₀₋₂₀)	3.4 (An ₂₅₋₃₅)	15.6 (An ₂₅₋₃₅)	15.3 (An ₁₅₋₂₅)	42.1 (An ₂₅₋₃₅)
K-feldspar	tr	2.1	3.8	—	—	6.4	—
Hornblende	8.6	—	—	—	—	—	—
Biotite	0.8	24.8	29.1	22.0	25.6	27.8	15.4
Muscovite	tr	6.8	5.7	45.3	9.2	14.1	1.2
Chlorite	tr	tr	tr	tr	—	tr	—
Sericite	—	2.2	0.9	5.4	tr	tr	—
Epidote	—	1.0	—	—	tr	2.2	0.9
Garnet	tr	—	0.1	4.8	—	—	1.8
Sillimanite	—	—	—	6.9	—	—	—
Sphene	tr	—	0.7	—	—	—	tr
Apatite	0.2	—	—	—	—	tr	—
Zircon	tr	0.3	0.4	tr	0.3	tr	tr
Monazite	tr	0.2	0.1	tr	tr	tr	—
Calcite	—	—	—	—	—	—	—
Opakes	0.4	—	0.3	1.4	—	tr	tr
totals	100.0	99.9	100.1	99.8	100.0	100.0	100.0

Trace (tr) minerals comprise less than 0.1% of the thin section. Plagioclase compositions were estimated using the Michel-Lévy method (Nesse, 1991). Point counting stage-step size was 0.1 mm for upper and lower Tallulah Falls Formation metagraywackes and 0.3 mm for the Tallulah Falls gms sample. Abbreviations: MV=Moravian Falls Quadrangle; utf=upper Tallulah Falls Fm; ltf=lower Tallulah Falls Fm; gms=garnet-muscovite schist; mgw=metagraywacke; bgn=biotite gneiss; An=anorthite content; tr = present but not counted. Sections dominantly cut perpendicular to foliation.

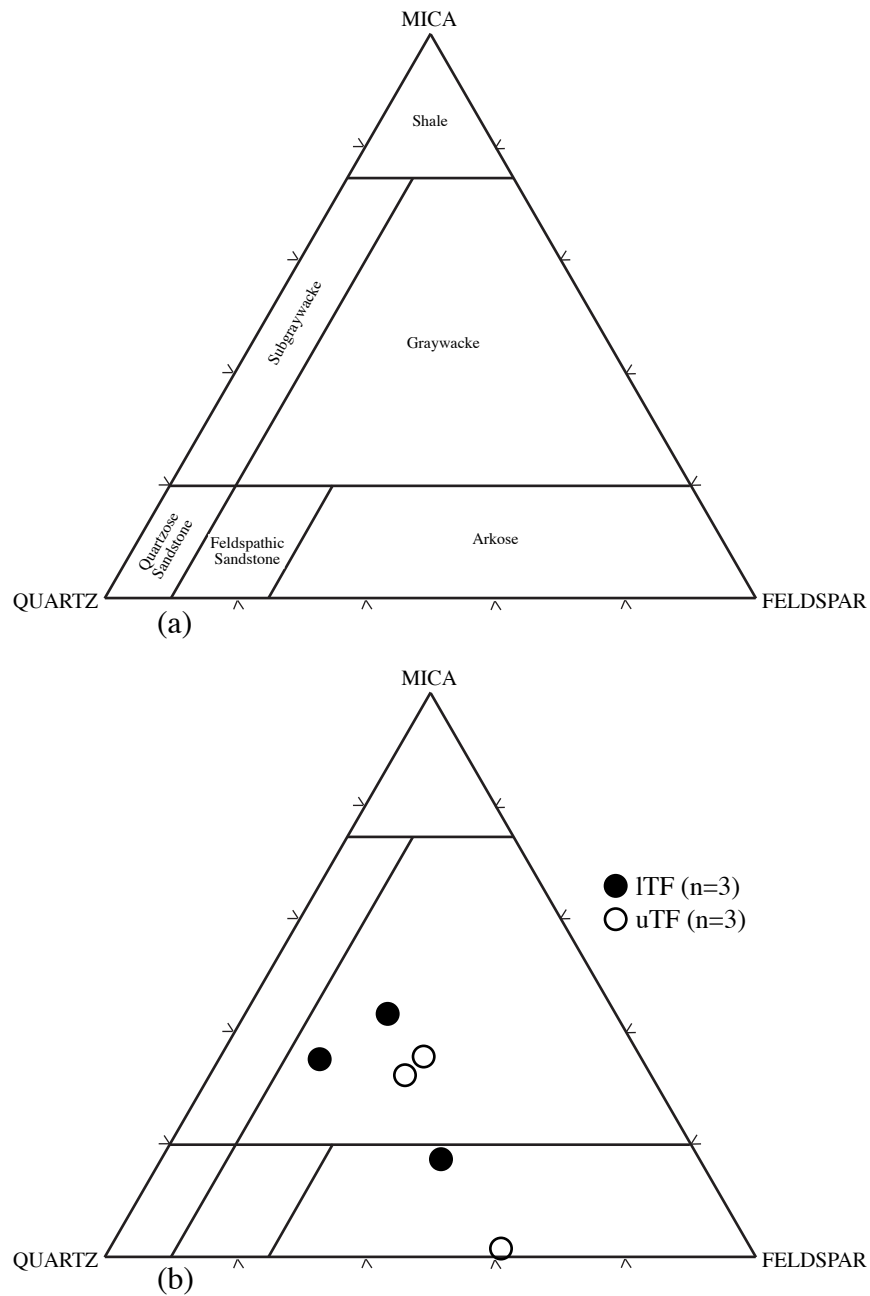


Figure 2-8. Quartz-feldspar-mica ternary diagram comparing the modal composition of the upper Tallulah Falls Formation (open circles) and lower Tallulah Falls Formation (filled circles). (a) Modified sandstone classification from Pettijohn (1949). (b) Q-F-M ternary plot of northeastern IP upper and lower Tallulah Falls Formation.

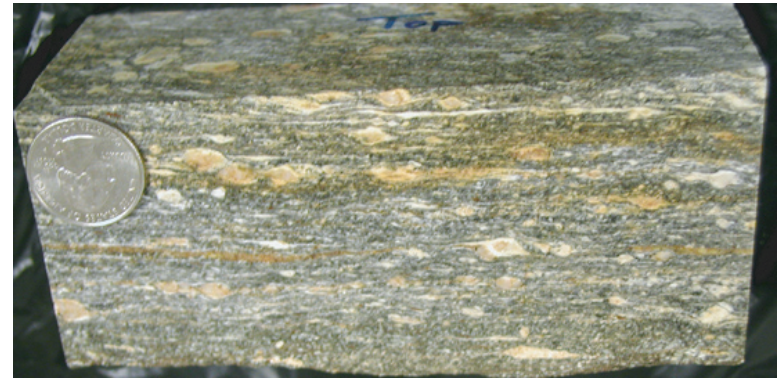


Figure 2-9. Outcrop and hand sample photographs of typical Henderson Gneiss samples from the study area. (a) Outcrop photograph of a NW-vergent fold in mylonitic Henderson Gneiss off Mt. Carmel Church Rd (MV-1673). Note that L_2 is sub-parallel to F_2 . (b) Hand sample photograph of typical mylonitic Henderson augen gneiss off NC Hwy 268. (c) Hand sample photograph of ultramylonitic Henderson Gneiss from the study area near the contact with the Tallulah Falls Fm. Note the textural contrast and grain size reduction between (b) and (c).

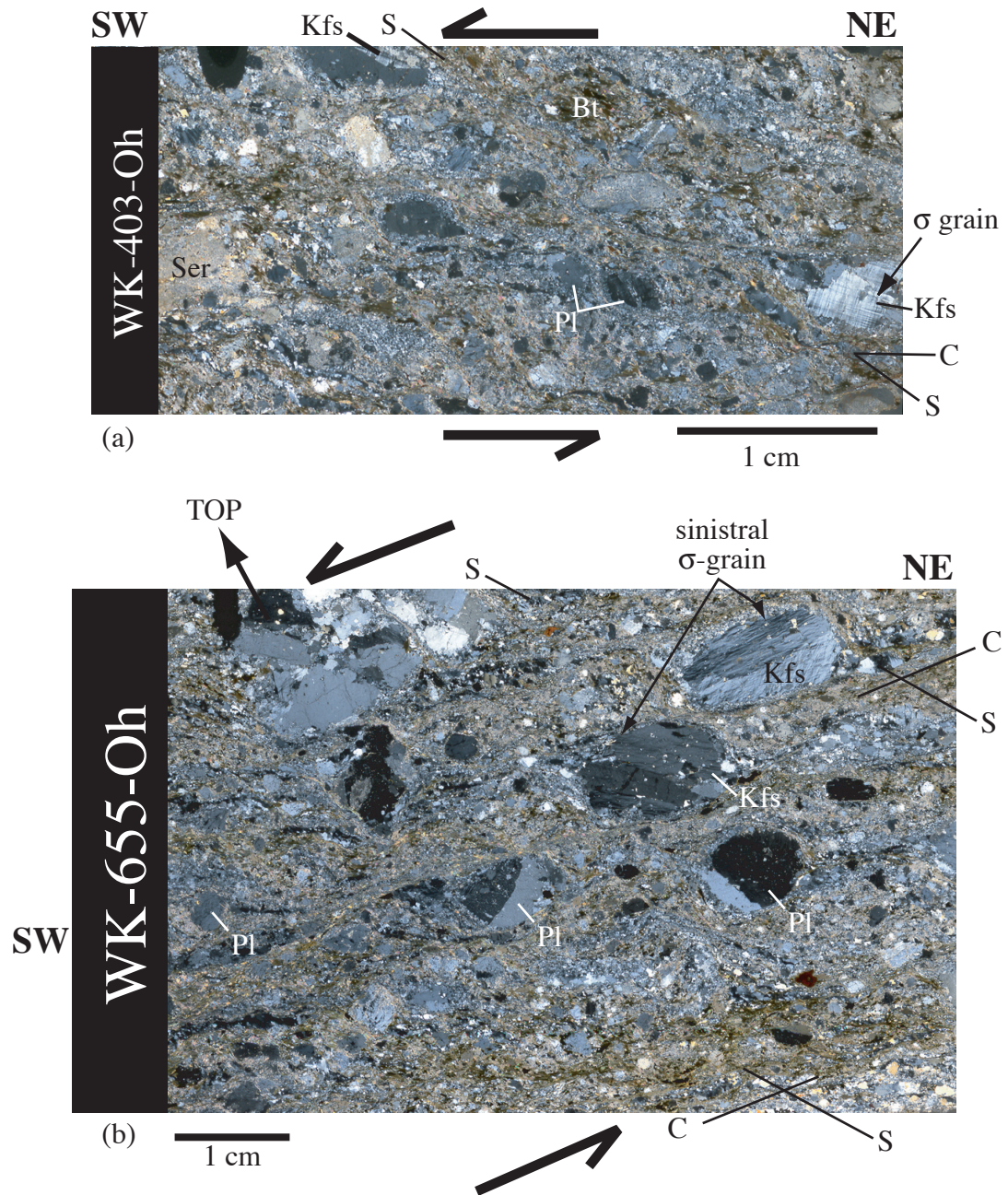


Figure 2-10. Petrographic characteristics of representative Henderson Gneiss samples from the study area. Both scanned thin sections show porphyritic textures and top to the SW shear-sense. (a) Protomylonitic to mylonitic texture, common near fault contacts and in shear zones within the Henderson Gneiss. (b) Augen gneiss displaying a distinct mylonitic S-C fabric, characteristic of Henderson Gneiss textures from the study area (section cut oblique to foliation). Note the Carlsbad twinning displayed by the plagioclase and the tartan twinning by the K-feldspar in both samples. Abbreviations (after Kretz, 1983): Pl=plagioclase, Kfs=K-feldspar, Bt=biotite, Ser=sericite.

Table 2-2. Modal mineralogy for Henderson Gneiss lithologies.

Sample #	MV-404-Oh	MV-655-Oh	MV-403-Oh	MV-1654-Oh
Lithology	HG	HG	HG	HG
# counted	991	1001	1011	1115
Quartz	5.9	25.9	21.3	15.8
Plagioclase	6.7 (An ₃₅₋₄₅)	21.2 (An ₃₅₋₄₅)	19.7 (An ₃₀₋₄₀)	22.6 (An ₃₅₋₄₀)
K-feldspar	6.1	12.6	15.4	7.1
Hornblende	3.7	0.7	1.9	2.3
Biotite	34.7	5.6	8.6	21.4
Muscovite	25.2	3.9	13.2	15.7
Chlorite	1.4	2.9	9.7	5.1
Sericite	12.5	22.2	7.2	8.5
Myrmekite	tr	4.0	2.0	0.7
Epidote	tr	tr	tr	tr
Garnet	—	—	0.3	—
Sillimanite	—	—	—	—
Sphene	0.5	0.4	0.5	0.4
Apatite	—	tr	tr	tr
Zircon	0.0	0.1	0.2	0.3
Monazite	0.6	tr	tr	tr
Rutile	—	—	—	—
Allanite	tr	tr	tr	tr
Calcite	—	—	—	tr
Opakes	1.9	0.6	0.1	0.1
totals	99.2	100.1	100.1	100.0

Trace (tr) minerals comprise less than 0.1% of the thin section. Plagioclase compositions were estimated using the Michel-Lévy method (Nesse, 1991). Point counting stage-step size was 0.3 mm for all samples. Abbreviations: MV=Moravian Falls Quadrangle; Oh=Ordovician Henderson Gneiss; ogn=orthogneiss; An=anorthite content; tr = present but not counted. Sections dominantly cut perpendicular to foliation.

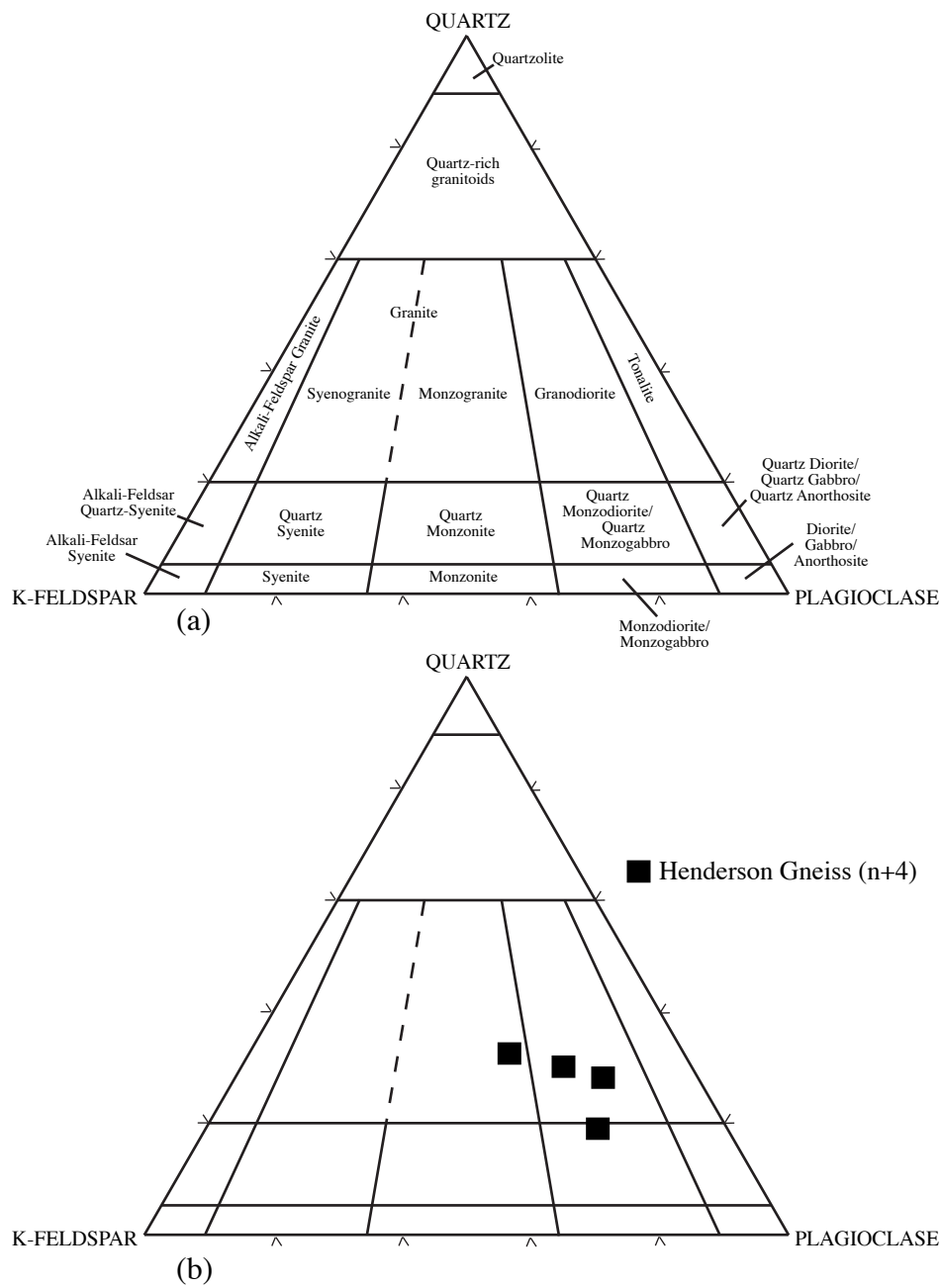


Figure 2-11. IUGS modal classification (Streckeisen, 1976) for Henderson Gneiss lithologies from the study area. (a) Streckeisen classification for felsic igneous rocks. (b) Modal analyses for the Henderson Gneiss from this study plotting in the monzogranite-granodiorite-quartz monzonite fields.

well with modal analyses of Henderson Gneiss samples from previous studies (Lemmon, 1973; Whisnant, 1975; Yanagihara, 1994; Bream, 1999). Textural differences across the suite of samples can be explained by varying degrees of mylonitization and grain-size reduction.

Five separable bodies of Henderson Gneiss occur in the hanging wall of the Tumblebug Creek fault in the study area (Fig. 2-4; Plate 1). Originally, northeastern IP Henderson Gneiss bodies were thought to occur as a series of lenticular outliers with no enclosing faults, as first noted by Reed (1964). More recent detailed mapping has indicated that the Henderson Gneiss is completely enclosed by the Tumblebug Creek fault (Davis, 1993a; Bream, 1999; Hill, 1999; Kalbas, 2003). Textural and contact relationships observed in this study also suggest a faulted contact between the Henderson Gneiss and the surrounding Tallulah Falls/Ashe Formation. Textures ranging from protomylonite in the interior portions of the lenticular outcrops to ultramylonite near the contacts, along with mylonitic fabrics in metasedimentary units in contact with the Henderson Gneiss, further support the conclusion that the Henderson Gneiss-Tallulah Falls Formation contact is faulted (Figs. 2-7, 2-9, and 2-10).

Many attempts utilizing zircon U-Pb and various whole-rock age dating techniques have been made over the past 20 years to obtain both crystallization and metamorphic ages of the Henderson Gneiss. Hatcher (1970) suggested that the Henderson Gneiss had a sedimentary protolith and is Late Proterozoic in age, citing the complexity of outcrop patterns and compositional variability. Based on zircon morphology, Lemmon (1973) inferred an igneous protolith for the Henderson Gneiss.

Zircon crystallization ages for the Henderson Gneiss range from $593 \pm ?$ Ma as a crystallization age for the upper intercept of a U-Pb discordia and metamorphic pulses at $456 \pm ?$ Ma and 360-390 Ma (Sinha and Glover, 1978), to $538 \pm ?$ Ma for a regressed suite of discordant U-Pb analyses (Odom and Fullagar, 1973), to a $490 \pm ?$ Ma ion microprobe age for Henderson Gneiss zircon rims, which is likely a metamorphic age (Carrigan et al., 2001). Attempts to determine the age of the Henderson Gneiss with whole-rock geochronological techniques have yielded ages of: 535 ± 27 Ma [Rb-Sr] for crystallization and 356 ± 8 Ma for metamorphism (Odom and Fullagar, 1973); 438 ± 22 Ma for mylonitic and 440 ± 22 Ma for undeformed Henderson Gneiss crystallization (Odom and Russell, 1975); 460 ± 9 Ma [Rb-Sr] for crystallization (Harper and Fullagar, 1981); and 513 ± 34 Ma for crystallization and 445 ± 20 Ma for metamorphism (Fullagar et al., 1997). Undoubtedly, successive tectonothermal events have complicated the geochronologic history of the Henderson Gneiss.

Lenoir Quarry migmatite

The uppermost portion of the Marion thrust sheet is occupied by an intensely migmatitic, compositionally heterogeneous L-S tectonite, situated in the immediate footwall of the Brindle Creek fault zone (Fig. 2-4; Plates 1 and 3). Numerous workers have documented the compositional heterogeneity of this unit. Originally, Reed (1964) documented this unit containing quartz diorite, granodiorite, and quartz-monzonite, with intermittent amphibolite bodies.

Rankin et al. (1972) recognized a large, northeast-trending, continuous gneissic biotite-muscovite quartz monzonite and granodiorite containing frequent layers and lenses of amphibolite, biotite-muscovite gneiss, sillimanite-mica schist and augen gneiss occupying the structural position between a Henderson Gneiss body and eastern IP metasedimentary units before ultimately terminating near Call, NC (Fig. 2-2). Furthermore, it has been recognized by Goldsmith et al. (1988) as migmatitic gneissic biotite granite to quartz diorite, with discontinuous septa of amphibolite, biotite gneiss and schist, and massive bodies of amphibolite and metagabbro.

Kalbas (2003) noted that mafic bodies associated with this unit are compositionally and temporally similar to Poor Mountain Amphibolite. He documented the structure, composition, age, and petrogenesis of migmatitic granodiorite and amphibolite lithologies associated with this unit, and informally named it the Lenoir Quarry migmatite. Merschat (2003) further delineated the geometry of this unit to the northeast across the Ellendale and Boomer quadrangles (Fig. 2-2; Plate 3).

Detailed mapping from this study in the northeastern Brushy Mountains has revealed the lateral continuation of a similar migmatitic tectonite in the immediate footwall of the Brindle Creek fault zone to the northeast. This unit consists of an ~5 km wide, northeast-striking, heterogeneous L-S tectonite composed primarily of migmatized intermediate to mafic metaigneous rocks in the Moravian Falls quadrangle. Mafic metaigneous bodies occur as massive blocks, boudin layers, lenses, and pods, and generally consist of dark gray to black, fine- to medium grained, hornblende-biotite-plagioclase-quartz amphibolite. Intermediate metaigneous lithologies dominate the overall composition of this unit. They consist of laterally continuous layers, generally composed of plagioclase-(An₂₀₋₄₀)-hornblende-biotite-quartz granodiorite, with minor occurrences of muscovite, myrmekite, epidote, and opaques (Table 2-3). Modal analyses of this lithology indicate a tonalite composition (Fig. 2-12). Felsic leucocratic layers contain mostly quartz and feldspar. Melanocratic layering is dominated by hornblende

Table 2-3. Modal mineralogy for western Inner Piedmont metaigneous units in the study area.

	Lenoir Quarry Migmatite			Brooks Crossroads Granite	
Sample #	MV-1604	MV-665	MV-607	MV-342-Sbc	MV-362-Sbc
Lithology	amph	mig amph	mig amph	ggn	ggn
# counted	989.0	1022.0	1039.0	993	1054
Quartz	17.3	15.3	12.2	18.5	21.1
Plagioclase	33.3 (An ₂₀₋₃₀)	39.6 (An ₂₀₋₃₀)	35.7 (An ₃₀₋₄₀)	26.4 (An ₂₅₋₃₅)	39.7 (An ₃₀₋₄₀)
K-feldspar	—	—	—	17.5	19.7
Hornblende	46.9	43.2	47.7	—	—
Biotite	—	—	—	8.5	8.3
Muscovite	—	—	—	11.5	5.9
Chlorite	—	—	—	—	—
Sericite	2.2	1.2	3.5	17.1	4.2
Myrmekite	—	—	—	0.1	0.4
Epidote	—	—	—	—	—
Garnet	—	—	—	—	—
Sillimanite	—	—	—	—	—
Sphene	—	—	—	—	—
Apatite	—	—	—	—	—
Zircon	0.9	0.2	0.6	tr	tr
Monazite	—	—	—	tr	tr
Rutile	—	—	—	tr	tr
Allanite	—	tr	tr	—	—
Calcite	—	—	—	—	—
Opaques	—	0.5	0.3	tr	tr
totals	100.6	100.0	100.0	99.6	99.3

Trace (tr) minerals comprise less than 0.1% of the thin section. Plagioclase compositions were estimated using the Michel-Lévy method (Nesse, 1991). Point counting stage-step size was 0.1 mm for granitic samples and 0.3 mm for amphibolite samples. Abbreviations: MV=Moravian Falls Quadrangle; mgw=metagraywacke; ss=sillimanite schist; cs=calc-silicate; An=anorthite content; tr = present but not counted. Sections dominantly cut perpendicular to foliation.

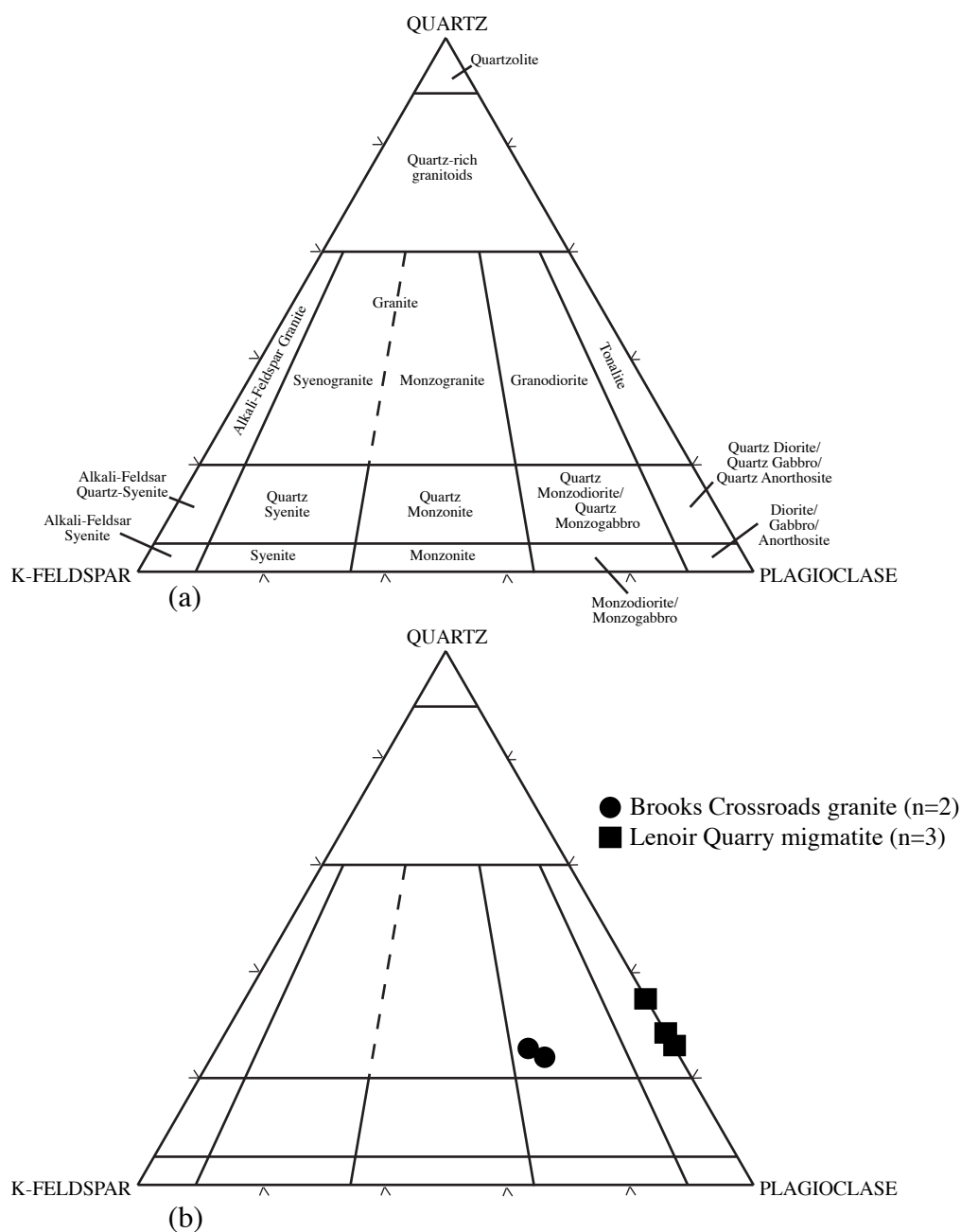


Figure 2-12. IUGS modal classification (Streckeisen, 1976) for western IP igneous and metaigneous lithologies from the study area. (a) Streckeisen classification for felsic igneous rocks. (b) Modal analyses for the Brooks Crossroads granite plotting in the granodiorite field and Lenoir Quarry migmatite plotting in the tonalite field.

and plagioclase. All primary and migmatitic layering is transposed into the dominant S_2 foliation. Lithologic heterogeneity and compositional characteristics of this unit indicate a bimodal volcanic protolith for this lithology, possibly correlative with Middle Ordovician Poor Mountain metavolcanic rocks to the southwest.

Brooks Crossroads Granite

Rankin et al. (1972) and Espenshade et al. (1975) delineated a large granitic gneiss body near the Sauratown Mountains anticlinorium and just southwest of the northeastern terminus of the IP (Fig. 2-2). This unit was informally named the Brooks Crossroads pluton. Several workers have recognized it as a muscovite-biotite granitoid, frequently containing xenoliths of migmatitic biotite gneiss, aluminous schist, and amphibolite.

The Brooks Crossroads granite in the Moravian Falls quadrangle exhibits a variable texture and a distinctive composition. It exists as a light gray (frequently stained to light orange on exposed surfaces) medium- to coarse-grained, weakly deformed (although locally strongly lineated), poorly foliated to massive, hololeucocratic to leucocratic, plagioclase (An_{25-40})-K-feldspar-quartz-biotite-muscovite granitic gneiss, with accessory myrmekite, hematite, zircon, monazite, and opaques (Table 2-3). Modal analyses plot entirely in the granodiorite field on a Q-A-P classification for felsic igneous rocks (Fig. 2-12). Textures range from massive and undeformed in the interior portions of the pluton to mylonitic and strongly lineated near contacts with eastern IP lithologies.

Although different, crystallization ages for the Brooks Crossroads pluton prohibit correlation with the eastern IP igneous/metavolcanic suite. A whole-rock Rb-Sr age of ~427 Ma was determined for samples collected within the Brooks Crossroads pluton in Wilkes County, NC (Harper and Fullagar, 1981). Vinson (1999) reported a U-Pb SHRIMP (sensitive high-resolution ion microprobe) crystallization age of ~461 and ~490 Ma for zircons from the Brooks Crossroads pluton. Regardless of which of these is the true age, both prohibit an intrusive contact between eastern IP lithologies and the Brooks Crossroads pluton. Structural patterns, contact relationships, textural variation, geochronologic data, and geochemical relationships (Wilson, 2006) also preclude an intrusive or unconformable relationship and support the conclusion that this contact is faulted.

Hibriten mylonite (BCFZ)

Recent detailed mapping in the southwestern Brushy Mountains has recognized the presence of a garnet and locally amphibole-bearing, foliated, inequigranular, biotite-quartz-plagioclase granitoid, and amphibole-bearing quartz-plagioclase gneiss occupying the immediate hanging wall of the Brindle Creek thrust (Kalbas, 2003; Mersch, 2003). Kalbas (2003) documented a diagnostic texture of 0.25-1.0 cm rounded plagioclase and quartz porphyroclasts in a dark-gray biotite matrix, and informally named this unit the Hibriten granitoid.

New data from this investigation have provided insight into the nature and origin of the Hibriten gneiss. Structural, lithologic, petrologic, geochemical, and geochronologic data (Part IV, this study) suggest that the previously delineated Hibriten gneiss is a heterogeneous, invariably mylonitic lithology, composed of a combination of eastern and western IP lithologies in a crustal-scale shear zone (Fig. 2-13). Here, the BCFZ acts as a lithologic blending zone, juxtaposing igneous and sedimentary rocks of different affinities during the process of terrane accretion. Intense deformation accompanied by dynamic recrystallization has masked primary stratigraphies, while partial melting and transport have transformed existing lithologies. These processes, occurring during thrust sheet emplacement, have collectively developed the compositional heterogeneity and intensely mylonitic character of the BCFZ. Therefore, it is suggested here that this unit be renamed the Hibriten mylonite, based on its highly variable composition and structural position within the BCFZ.

The Hibriten mylonite in the northwestern Brushy Mountains consists of mylonitic western IP Lenoir Quarry migmatite and hornblende amphibolite, along with mylonitic eastern IP Walker Top Granite, sillimanite schist, and metagraywacke. Several transposed and crosscutting intrusives are also present within the fault zone. Mylonitic textures range from protomylonite to ultramylonite (Fig. 2-13) and exhibit evidence for both northwest-directed, followed by southwest-directed transport (Fig. 2-13). Isolated and discontinuous boudins, pods, and lenses of amphibolite, associated with mylonitic eastern and western IP lithologies, occur sporadically throughout this unit, frequently exhibiting block-in-matrix structure. The association of amphibolite with eastern IP lithologies within a shear zone, combined with a general lack of it in the Brindle Creek thrust sheet, and abundant amphibolite in the western IP, further supports the conclusion that the Brindle Creek thrust is a zone of crustal mixing.

Samples from the Moravian Falls and Kings Creek quadrangle (a distance of ~35 km along strike; Plate 3) were selected for zircon U-Pb age dating by SHRIMP

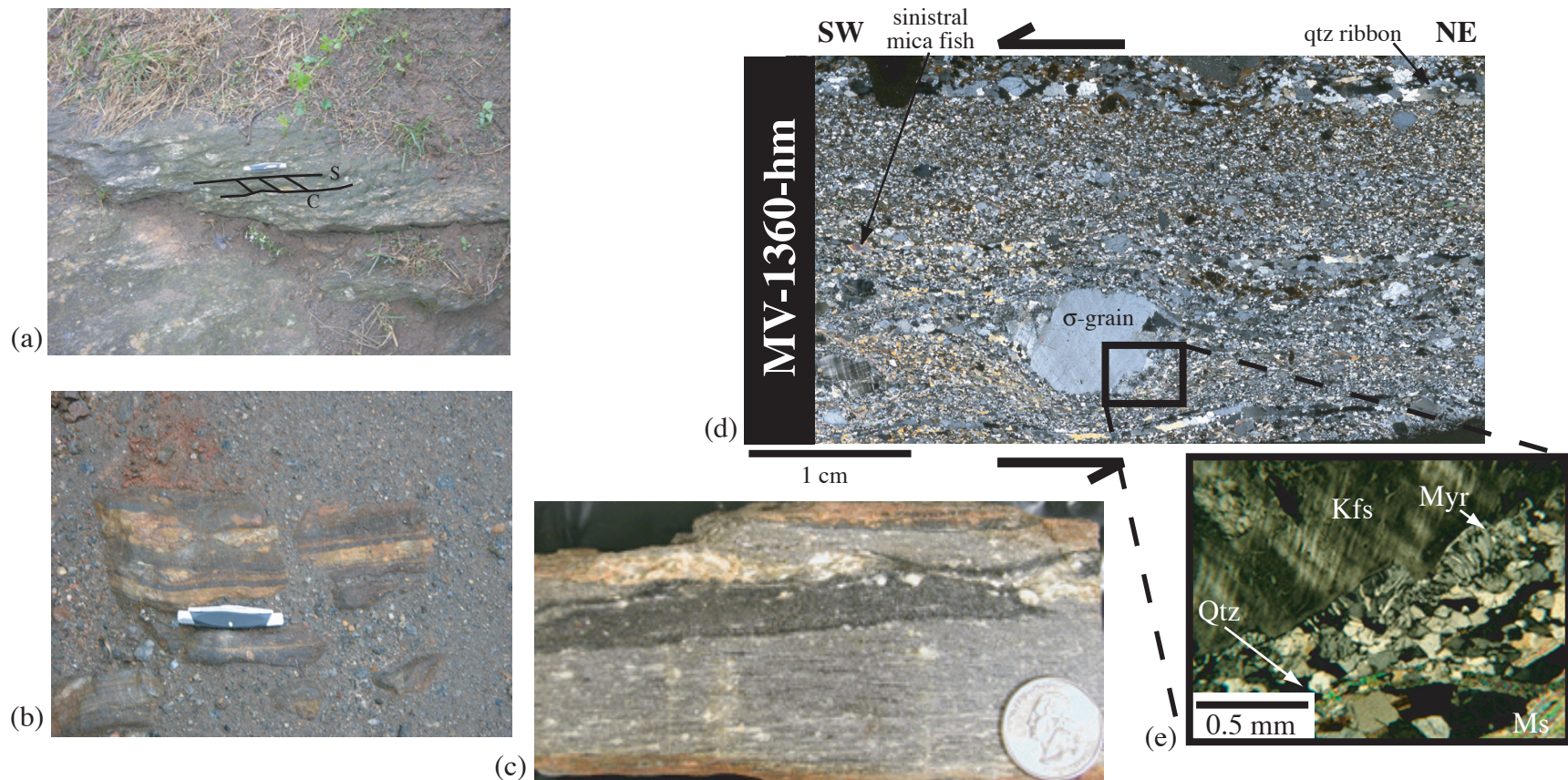


Figure 2-13. Field and petrographic characteristics of the Hibriten mylonite. (a) Hibriten mylonite from Hibriten mountain, containing a strong SW-vergent S-C fabric. Lithology consists of plagioclase-rich orthogneiss. (b) Field photograph of a stromatic migmatitic amphibolite from the same outcrop as (a), representing typical block-in-matrix structure of the hibriten lithology. (c) Mylonitic hand sample cut parallel to lineation from the BCFZ near Cub Creek, displaying a strong prolate L-S tectonite fabric. (d) Scanned ultramylonite thin section of Walker Top Granite protolith from the BCFZ near Cub Creek. Note the fine-grained recrystallized quartz and plagioclase in the matrix. (e) Photomicrograph of K-feldspar rim in (d) showing abundant myrmekite mantles and high-angle grain boundaries. Abbreviations (after Kretz, 1983): Qtz=quartz, Kfs=K-feldspar, Myr=myrmekite, Ms=muscovite.

ion probe methods (Part V, this study). Both samples were collected from the Brindle Creek fault zone and show high degrees of mylonitization. Lithologies consisted of western Inner Piedmont Lenoir Quarry migmatite and amphibolite. Samples yielded very similar zircon core crystallization ages of 434.7 ± 3.7 Ma, 444.0 ± 3.7 Ma and 448.7 ± 1.3 Ma. Metamorphic ages from zircon rim analyses produced ages of 364 ± 27 Ma for a discordia regression and 346.2 ± 2.1 Ma for concordant zircon rims. The textural and lithologic similarities and map-scale distance between the sample localities, along with the clustering of their ages, support the along-strike continuity of this unit as a map-scale shear zone including hanging wall and footwall lithologies in a crustal-scale lithologic mixing zone.

Brindle Creek Thrust Sheet (eastern IP)

Walker Top Granite

Located in the immediate hanging wall of the BCFZ, the Walker Top Granite displays a diagnostic porphyritic texture of myrmekite-rimmed anhedral to subhedral K-feldspar megacrysts in a medium-gray to black, medium-grained, biotite-quartz-plagioclase matrix, making it an easily distinguishable orthogneiss (Figs. 2-14 and 2-15; Giorgis, 1999; Vinson and Miller, 1999).

Goldsmith et al. (1988) also recognized the Walker Top Granite, but described it as less-deformed, garnetiferous Henderson Gneiss. Although some textural and compositional similarities exist, correlation with the Henderson Gneiss is precluded by megacrystic textural variation between augen gneiss and megacrystic gneiss (Figs. 2-9, 2-10, 2-14, and 2-15), modal mineralogical differences (Tables 2-2 and 2-4), geochemical variation (Giorgis et al., 2002; Part IV, this study), and geochronology (Part V, this study).

Detailed mapping from previous studies show that the Walker Top Granite occurs entirely in the eastern IP as a series of linear, laterally continuous and discontinuous bodies that parallel the regional structural trend throughout the South Mountains and Brushy Mountains, finally truncating ~25 km southwest of the Sauratown Mountains window (Fig. 2-4; Plates 1 and 3; Giorgis, 1999; Williams, 2000; Bier, 2001; Giorgis et al., 2002, Mersch, 2003; Wilson, 2006; Gatewood, this study).

The Walker Top Granite is continuous throughout the Brushy Mountains, from the Kings Creek quadrangle and across the Ellendale and Moravian Falls quadrangles, and ultimately truncates against the Brooks Crossroads pluton in the Gilreath quadrangle, near the easternmost boundary of the study area (Fig. 2-4; Plate 3). Large pavement-type



Figure 2-14. Field and hand samples of textural variations of the Walker Top Granite. (a) Mylonitic phase of the Walker Top Granite from near Bald Rock Mtn (photo by RDH). Note the asymmetric σ and δ porphyroclasts. (b) Garnet-bearing megacrystic phase of the Walker Top Granite from near Hidden Hollow, NC (photo by RDH). Note the subhedral to euhedral shape of the K-feldspar megacrysts. (c) Unmylonitic to protomylonitic phase of the Walker Top Granite from near Russel Gap, NC. Note that the porphyroclasts here lack a strong alignment. A SHRIMP U-Pb age of 406 ± 2.0 Ma was determined for this sample locality.

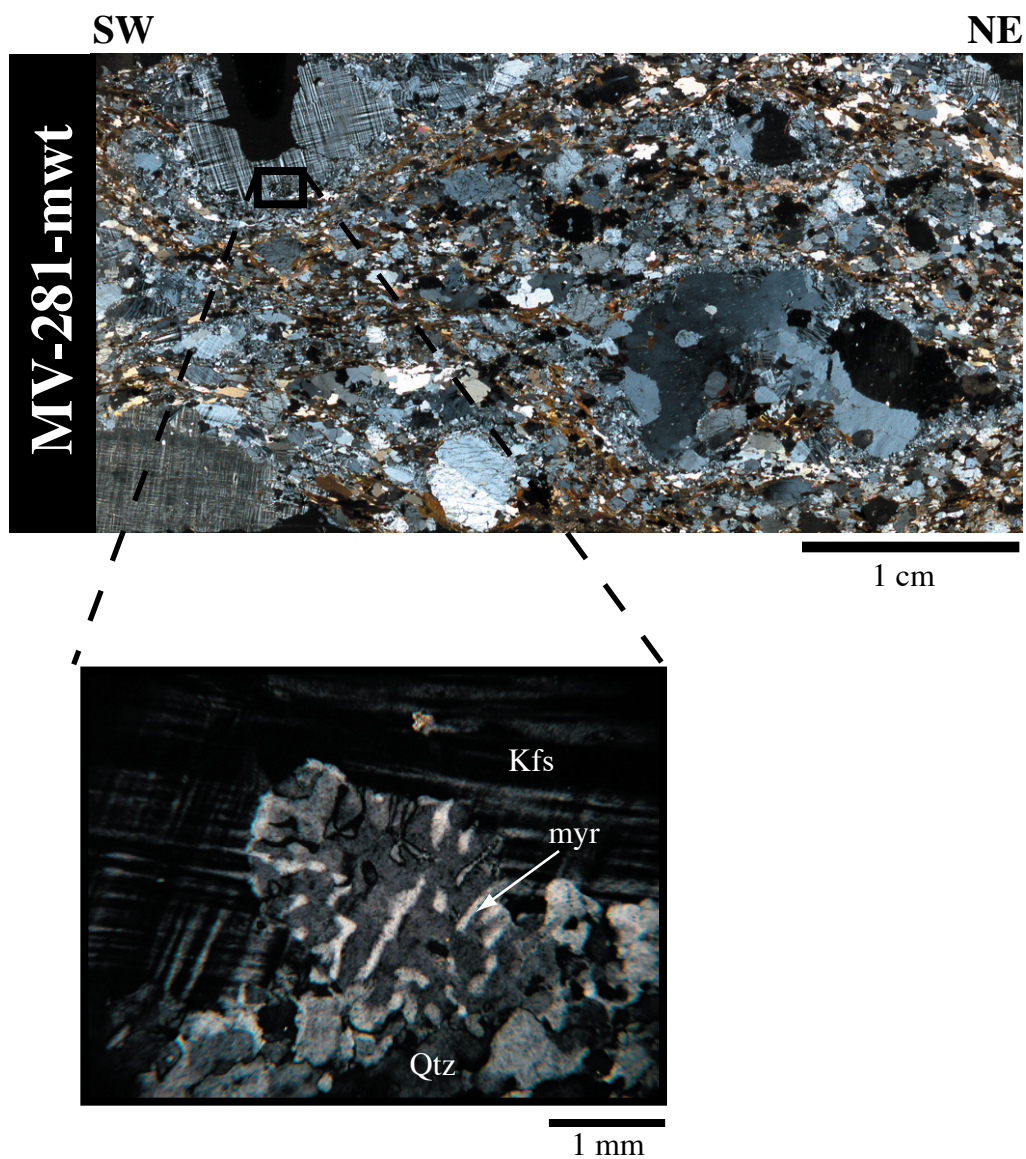


Figure 2-15. Petrographic characteristics of the Walker Top Granite from the study area. (a) Scanned thin section of typical protomylonitic Walker Top Granite. (b) Photomicrograph showing myrmekite embayment of K-feldspar megacryst in the Walker Top gneiss. Abbreviations (after Kretz, 1983): Kfs=K-feldspar, myr=myrmekite, Qtz=quartz.

Table 2-4. Modal mineralogy of Walker Top Granite samples.

Sample #	MV-281-WT	MV-19-WT	MV-566-WT	GL-1-WT*	GL-2-WT*
Lithology	ogn	myl ogn	myl ogn	myl ogn	myl ogn
# counted	1080	1018	952	930	1019
Quartz	21.8	24.5	13.0	21.6	19.1
Plagioclase	24.0 (An ₃₃)	24.6 (An ₃₇)	23.3 (An ₄₂)	24.8 (An ₃₅)	27.4 (An ₄₀)
K-feldspar	28.1	32.2	15.4	11.1	14.7
Hornblende	—	tr	—	—	—
Biotite	15.5	9.0	10.7	32.7	22.8
Muscovite	3.0	2.3	12.9	3.0	5.4
Chlorite	—	—	—	—	—
Sericite	—	0.1	tr	2.5	2.9
Myrmekite	7.0	7.1	4.1	1.5	6.8
Epidote	tr	—	tr	0.3	tr
Garnet	—	tr	0.7	tr	tr
Sillimanite	—	tr	tr	1.0	0.3
Sphene	0.6	tr	—	0.9	0.1
Apatite	tr	tr	tr	tr	tr
Zircon	tr	0.1	0.3	tr	tr
Monazite	tr	tr	tr	tr	tr
Rutile	tr	—	tr	tr	tr
Allanite	tr	tr	tr	tr	tr
Calcite	—	—	—	0.2	—
Opaques	tr	tr	tr	0.2	0.5
totals	100.0	99.9	99.9	99.9	100.0

*Sample selected for EMP analysis.

Trace (tr) minerals comprise less than 0.1% of the thin section. Plagioclase compositions were estimated using the Michel-Lévy method (Nesse, 1991). Point counting stage-step size was 0.3 mm for all samples. Abbreviations: MV=Moravian Falls Quadrangle; GL=Gilreath Quadrangle; WT=Walker Top gneiss; ogn=orthogneiss; An=anorthite content; tr = present but not counted. Sections dominantly cut perpendicular to foliation.

outcrops on ridge tops, combined with excellent exposures on hillsides and in streams, allow for easy identification and detailed descriptions of this unit.

The occurrence of traceable Walker Top Granite bodies within the Brindle Creek fault zone suggests that a sill-like body composed of this unit occupies the lowermost portion of the Brindle Creek thrust sheet (Fig. 2-4; Plate 1). Map patterns and associations of Walker Top Granite outcrops with shear zones further indicate the presence of this mechanical stratigraphy in the eastern IP. Contacts with surrounding metasedimentary units within the Brindle Creek thrust sheet are mostly concordant, migmatitic, and well exposed. Migmatitic layering, lithologic contacts, lenticular xenoliths and boudins, and megacrysts are transposed into parallelism with the dominant S_2 foliation. Based on megacrystic textures, acicular zircon morphology (Part V, this study), contact relationships, bulk chemistry (Part IV, this study), and the presence of abundant xenoliths, an igneous protolith is favored for Walker Top Granite.

Five representative samples, selected for modal analyses, revealed an assemblage of microcline, plagioclase (An_{35-45}), quartz, biotite, muscovite, $\pm$ garnet, $\pm$ hornblende, with minor and trace constituents of myrmekite, sericite, epidote, apatite, zircon, monazite, apatite, and opaques (Table 2-4). All samples display a porphyroclastic schistose texture, with microcline megacrysts in a biotite-, quartz-, plagioclase-rich matrix (Figs. 2-14 and 2-15). Strong planar fabrics result from the parallel alignment of biotite, quartzofeldspathic matrix material, and microcline megacrysts. Matrix plagioclase is mostly recrystallized and does not display twinning (Fig. 2-15). Megacrystic plagioclase and K-feldspar porphyroclasts commonly display Carlsbad and/or tartan twinning. Perthitic exsolution textures are common in alkali feldspar (Fig. 2-15). Compositionally, Walker Top Granite samples, from this and previous studies, range from syenogranite to monzogranite to granodiorite (Fig. 2-16). Modal variation can be explained by an irregular grain size distribution, mineralogical heterogeneity, and varying degrees of mylonitization.

Northeastern IP textural variations of this lithology range from protomylonite in the interior portion of Walker Top bodies, to mylonite in shear zones, to ultramylonite near contacts (Figs. 2-14 and 2-15, Part IV, this study). No euhedral megacrysts are observed within this unit in the study area, indicating that all occurrences of the Walker Top Granite in the northeastern Brushy Mountains are mylonitic.

Modern geochronologic techniques have been applied to two Walker Top Granite samples, one each from the South and Brushy Mountains. Mapes (2002) reported a 366 ± 3 Ma ion microprobe U-Pb zircon crystallization age for a sample of

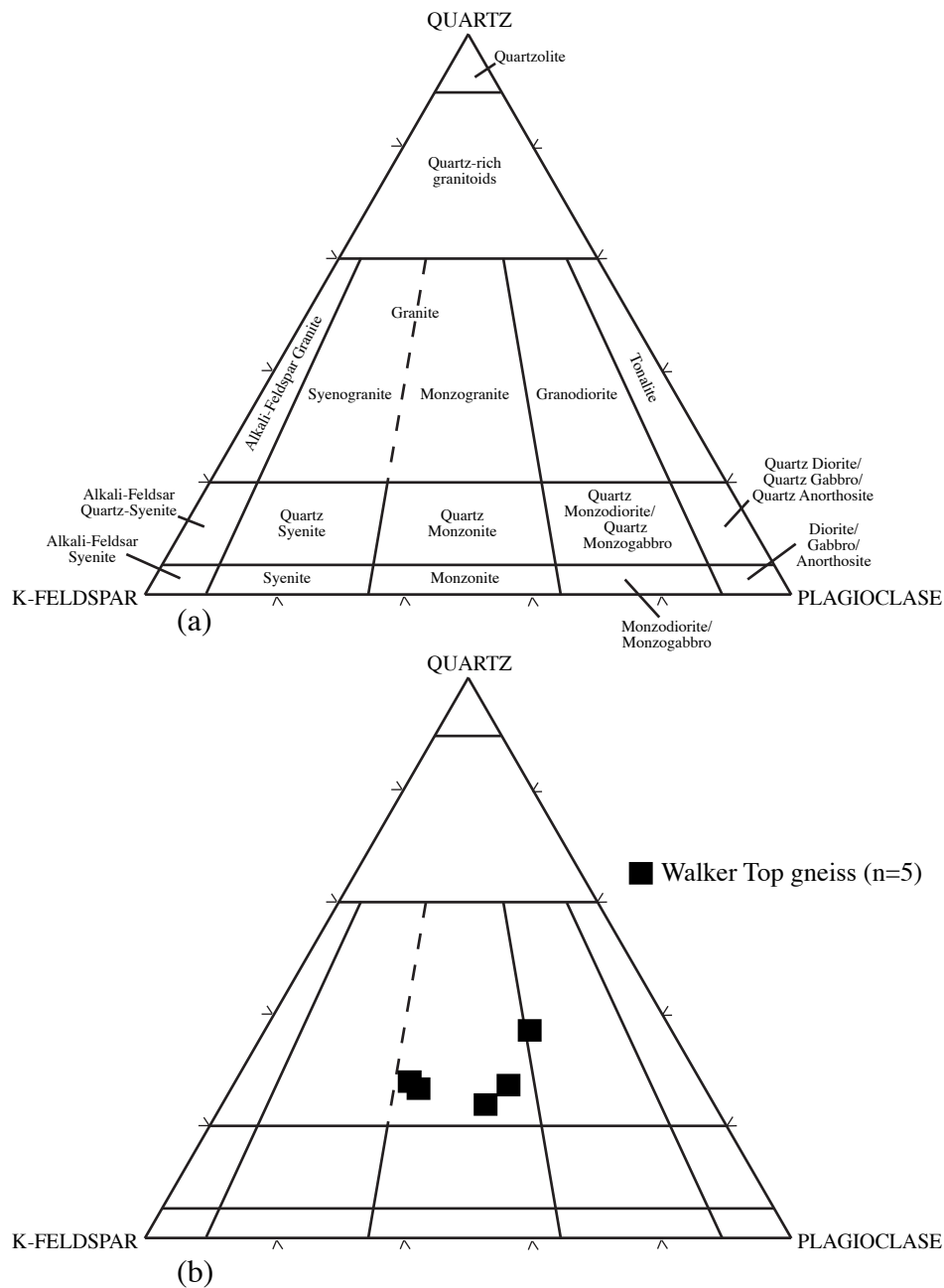


Figure 2-16. IUGS modal classification (Streckeisen, 1976) of the Walker Top Granite. (a) Streckeisen classification for felsic igneous rocks. (b) Modal analyses for the Walker Top gneiss plotting in the monzogranite-granodiorite fields.

Walker Top Granite collected near Icy Knob in the South Mountains. More recently, a U-Pb crystallization age of 406 ± 2 Ma has been obtained from the northeastern Brushy Mountains (Part V, this study). Either these orthogneisses do not share a common protolith, although spatially, texturally, and compositionally similar, or zircons from the South Mountains were reset during Neocadian high-grade metamorphism (Part V, this study).

Toluca Granite

Goldsmith et al. (1988) regionally correlated several eastern IP biotite granitoid bodies with the Toluca Granite, originally recognized by Griffiths and Overstreet (1952). Ion microprobe U-Pb zircon crystallization ages ranging from 375-380 Ma were reported by Mapes et al. (2001) for the Toluca Granite near the type locality. Merschat (2003) noted that lack of a contact areole, interlayering with encompassing metasedimentary units, truncation of intrusive contacts by the dominant foliation, and transposition of map-scale occurrences suggest that these are catazonal plutons. Mapes (2002) deduced, based on similarities of whole-rock chemistry and Sr, Nd, and O isotope data, that Toluca Granite bodies are derived from partial melting of surrounding metasedimentary units. Merschat (2003) interpreted sharp contacts between these metaigneous and enveloping metasedimentary lithologies in the southwestern Brushy Mountains, however, as evidence for fault transport of the Toluca bodies over the surrounding metasedimentary lithologies.

The Toluca Granite outcrops in the northeastern IP as a series of deformed and disconnected plutons, layers, and pods (Fig. 2-4; Plates 1 and 3). In the Moravian Falls quadrangle the Toluca Granite bodies consist of a dark-gray to white, medium- to coarse-grained to porphyritic, weakly foliated to mylonitic, leucocratic, muscovite and garnet bearing, biotite orthogneiss and granitic gneiss, with a garnet-feldspar gneiss, containing xenoliths of metagraywacke and aluminous schist. Deformational fabrics vary from strongly foliated to undeformed and massive. A variably present linear fabric is defined by parallel C-axes of feldspar and quartz. The Toluca granite in the northeastern Brushy Mountains is composed of quartz (30-40%), plagioclase (25-30%; An_{30-40}), K-feldspar (15-25%), biotite (10-15%), muscovite (2-5%), and trace sphene, apatite, zircon, monazite, rutile, and opaques (Table 2-5). Three samples selected for modal analyses plot within the monzogranite-granodiorite fields on a Q-A-P ternary diagram (Fig. 2-17).

Structural patterns and sharp mylonitic contact relationships between the Toluca Granite and surrounding metasedimentary lithologies in the northeastern IP further provide evidence for transport of these lithologies. This evidence alone, however, does

Table 2-5. Modal mineralogy for Toluca granite lithologies.

Sample #	Toluca Granite		
	MV-341-Dtg	MV-454-Dtg	MV-1035-Dtg
Lithology	ggn	ggn	ggn
# counted	1000	1011	1002
Quartz	38.8	38.0	31.7
Plagioclase	26.0 (An ₃₈)	28.3 (An ₄₁)	28.5 (An ₃₂)
K-feldspar	14.8	21.0	23.8
Hornblende	—	—	—
Biotite	15.6	10.1	12.8
Muscovite	4.2	1.8	2.0
Chlorite	—	—	—
Sericite	—	—	—
Myrmekite	—	0.2	0.6
Epidote	—	—	—
Garnet	—	—	tr
Sillimanite	—	—	—
Sphene	tr	tr	tr
Apatite	tr	tr	tr
Zircon	0.4	0.3	0.3
Monazite	0.1	0.2	0.1
Rutile	tr	tr	tr
Allanite	—	—	—
Calcite	—	—	—
Opakes	0.1	0.2	0.2
totals	100.0	100.1	100.0

Trace (tr) minerals comprise less than 0.1% of the thin section. Plagioclase compositions were estimated using the Michel-Lévy method (Nesse, 1991). Point counting stage-step size was 0.1 mm for all samples. Abbreviations: MV=Moravian Falls Quadrangle; Dtg=Devonian Toluca granite; ggn=granitic gneiss; ss=sillimanite schist; An=anorthite content; tr = present but not counted. Sections dominantly cut perpendicular to foliation.

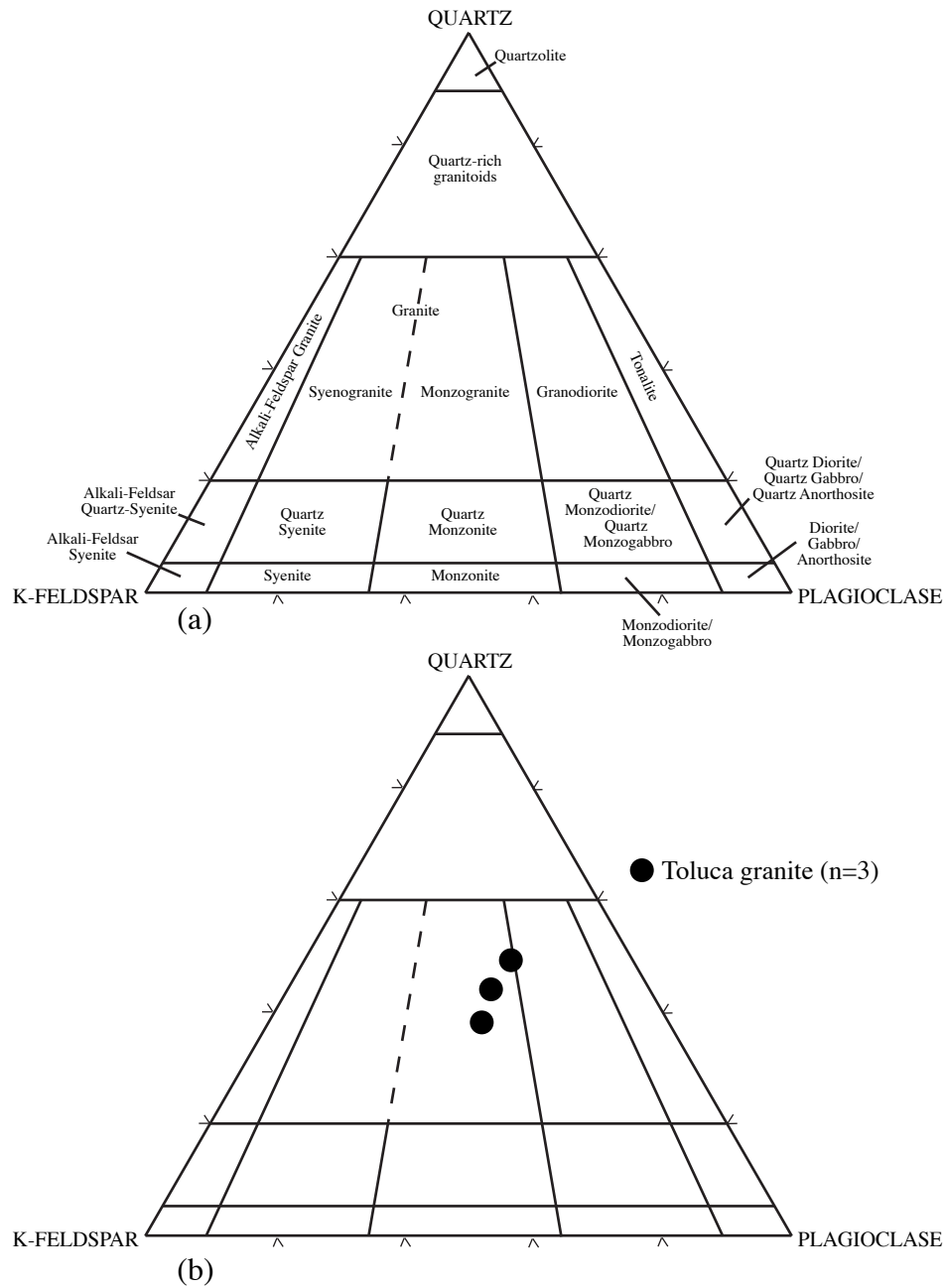


Figure 2-17. IUGS modal classification (Streckeisen, 1976) of the Toluca Granite. (a) Streckeisen classification for felsic igneous rocks. (b) Modal analyses for the Toluca Granite plotting in the monzogranite-granodiorite fields.

not indicate that the Toluca bodies originated from anything other than associated metasedimentary lithologies. Geochemical similarities and the presence of abundant xenoliths composed of lithologies identical to those of the surrounding metasedimentary units suggest local derivation of these igneous and metaigneous bodies from nearby country rocks. Moreover, mylonitic textures and contact relationships do not necessarily indicate large-scale transport. Continuity of mylonitic fabrics across lithologic contacts and shear-sense indicators suggests that transport of the Toluca and metasedimentary bodies occurred simultaneously.

Sillimanite Schist

An extensive body of aluminous schist is one of two metasedimentary units that dominate eastern IP metasedimentary lithologies (Fig. 2-4; Plates 1 and 3). In the Moravian Falls quadrangle, three bands of migmatitic biotite-muscovite-sillimanite-quartz-garnet-feldspar schist (referred to here as sillimanite schist) trend northeast-southwest throughout the study area (Fig. 2-4; Plate 1). This unit is easily recognizable in outcrop by its weathering characteristics, including a diagnostic brown to reddish-brown coloration and fissile texture (Fig. 2-18).

Several distinct assemblages and compositional layering between mica-rich and quartz-feldspar rich layers occur within these schist units, although neither primary structures nor an identifiable stratigraphy were observed. Mersch (2003) noted the presence of three lithologies within eastern IP aluminous schist in the Ellendale quadrangle: (1) a coarse-grained, poikiloblastic muscovite-sillimanite schist; (2) a migmatitic sillimanite schist, containing >50 percent leucosome; and (3) a garnet-biotite-sillimanite schist. These lithologies are also recognized within the sillimanite schist units in the Moravian Falls and Gilreath quadrangles.

Modal analyses reveal an assemblage of biotite, quartz, muscovite, plagioclase ($\sim\text{An}_{20}$), $\pm$ garnet, $\pm$ sillimanite, with minor contributions from epidote, chlorite, apatite, sericite, zircon, monazite, and opaques (Table 2-6). Sillimanite and garnet contents are highly variable. Sillimanite schist lithologies generally display a poikiloblastic to lepidoblastic texture. Poikiloblastic and embayed garnets preserve previous internal fabrics, and appear to be rotated and pulled apart into smaller grains within the foliation. Sillimanite typically occurs as fibrolitic needles, bladed pseudomorphs after kyanite, and less-commonly microscopic prismatic varieties (Fig. 2-18). Planar schistose, S-C fabrics, and S-C-C' fabrics result from a parallel alignment of biotite, primary muscovite, quartzofeldspathic material, and sillimanite. Muscovite laths frequently overgrow

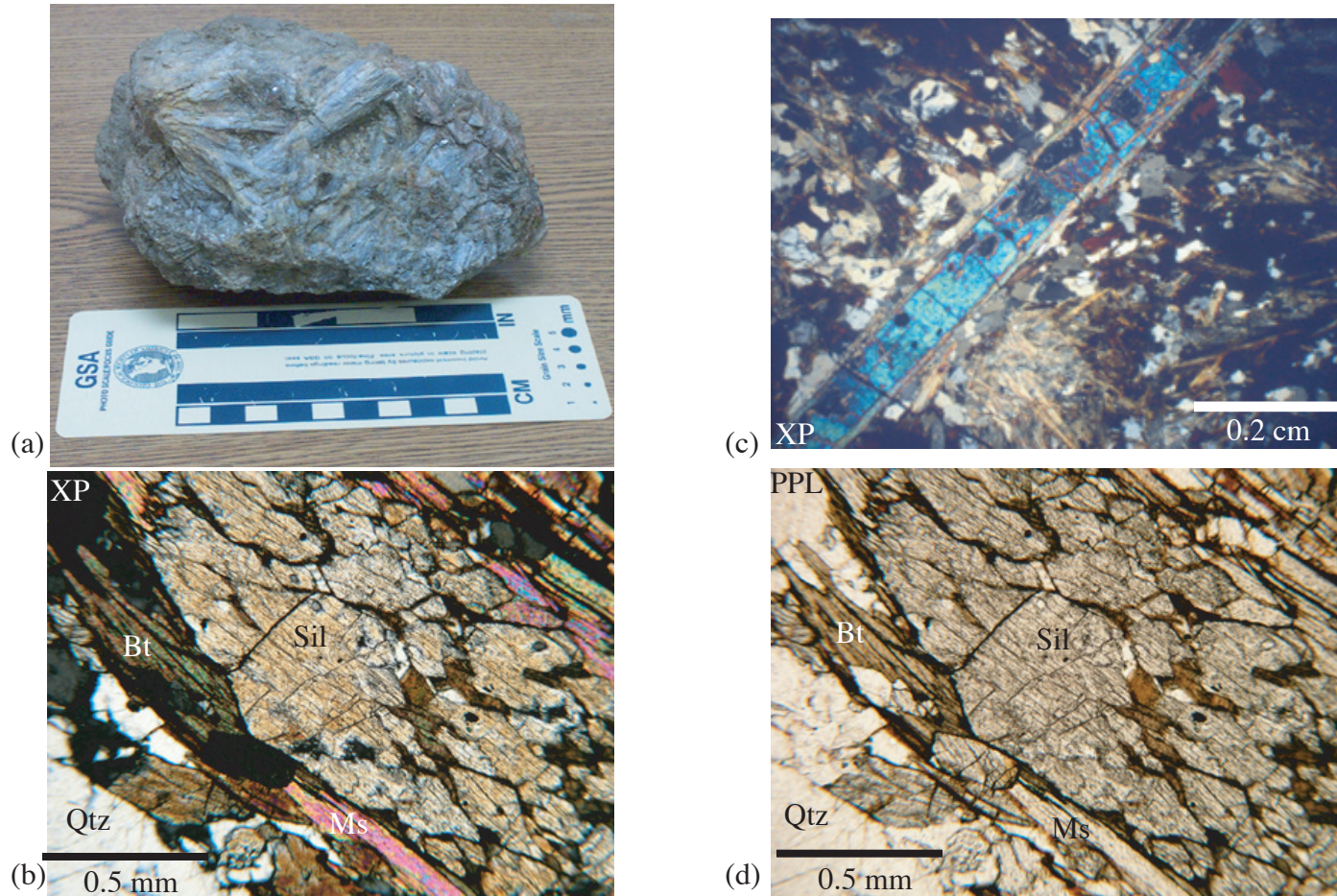


Figure 2-18. Petrographic characteristics of aluminous schist units from the study area. Note that all occurrences of pelitic schist in the study area do not contain sillimanite. (a) Hand sample from near the BCFZ, displaying large euhedral sillimanite pseudomorphs of kyanite. (b) Scanned thin section from near Pores Knob, showing concordant and discordant sillimanite blades and needles. (c) Crossed polars photomicrograph of pelitic schist from near Moravian Creek, showing large sillimanite pseudomorphs of kyanite. (d) Plane polarized view of (b). Note the very high relief of the sillimanite blades. Abbreviations (after Kretz, 1983): Sil=sillimanite after kyanite, Ms=moscovite, Bt=biotite, Qtz=quartz.

Table 2-6. Modal mineralogy for eastern Inner Piedmont metasedimentary units in the study area.

	Sillimanite Schist			Metagraywacke					Calc-Silicate
Sample #	MV-369-ss	MV-1252-ss	MV-112-ss	MV-374-mgw	EL-2-mgw	MV-355-mgw	MV-336-mgw	MV-827-mgw	T-792-cs
# points counted	1033	900	1004	1000	975	1066	988	1029	976
lithology	ss	ss	ss	mgw	mgw	mgw	mgw	mgw	cs
Quartz	27.2	23.8	13.3	54.8	60.8	53.5	54.8	61.7	68.8
Plagioclase	3.7 (An ₂₀)	1.4	3.2 (An ₂₀)	9.6 (An ₃₀₋₄₀)	14.1 (An ₂₅)	15.9 (An ₃₀)	12.3 (An ₃₀)	11.6 (An ₂₅₋₃₅)	3.6
K-feldspar	—	—	—	1.2	—	0.2	0.4	—	—
Hornblende	—	—	—	11.6	—	—	—	3.7	5.8
Biotite	41.7	32.4	31.7	22.4	12.6	23.5	23.1	22.0	—
Muscovite	20.8	14.9	9.0	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—	—	—	—
Sericite	—	7.4	6.0	0.4	—	—	—	—	—
Epidote	—	—	—	tr	11.6	6.6	8.7	tr	20.7
Garnet	2.6	—	tr	—	—	—	—	—	—
Sillimanite	3.6	17.9	36.5	—	—	—	—	—	—
Sphene	—	—	—	—	0.4	0.2	—	0.2	0.7
Apatite	tr	—	tr	—	tr	tr	—	tr	tr
Zircon	tr	tr	tr	tr	0.3	0.2	0.2	0.2	tr
Monazite	tr	tr	tr	tr	0.1	tr	0.1	tr	—
Rutile	tr	—	tr	tr	tr	tr	—	tr	—
Calcite	—	—	—	—	—	—	—	0.4	—
Opakes	0.4	2.1	0.4	—	0.4	—	0.4	0.3	0.4
totals	100.0	99.9	100.1	101.2	100.3	100.1	100.0	100.1	100.0

Trace (tr) minerals comprise less than 0.1% of the thin section. Plagioclase compositions were estimated using the Michel-Lévy method (Nesse, 1991). Point counting stage-step size was 0.1 mm for metagraywacke and calc-silicate samples and 0.3 mm for sillimanite schist samples. Abbreviations: MV=Moravian Falls Quadrangle; mgw=metagraywacke; ss=sillimanite schist; cs=calc-silicate; An=anorthite content; tr = present but not counted. Sections dominantly cut perpendicular to foliation.

foliation planes (Fig. 2-18). A common crenulation cleavage present in the schist developed from kink folding of mica- and sillimanite-rich layers.

Metagraywacke

The most areally extensive metasedimentary unit in the northeastern IP consists of migmatitic K-feldspar-plagioclase-muscovite-biotite-quartz gneiss (metagraywacke or metapsammite), which frequently contains calc-silicate and less frequently amphibolite. Several northeast-trending bands are exposed in the study area (Fig 1-4; Plate 1). Weathering of this lithology produces a light red to tan saprolite with light tan to white leucocratic material often occurring as transposed layers, boudins, and disconnected pods. Although mesoscopic compositional banding can be seen in outcrop scale, no map-scale primary stratigraphy can be recognized.

Although textural similarities between metagraywacke lithologies are invariable, mineralogical variations most likely result from differing protoliths or differing degrees of migmatization. Generally, the metagraywacke is composed of quartz, biotite, muscovite, K-feldspar, and plagioclase (An_{20-35}), with minor components of clinozoisite, garnet, sillimanite, hornblende, apatite, sphene, and opaques (Table 2-6). Leucocratic layers consist of quartzofeldspathic material and muscovite. All metagraywacke lithologies plot within the graywacke-feldspathic sandstone-quartzose sandstone fields (Fig. 2-19).

Calc-Silicate

A mappable body of calc-silicate outcrops in the northwestern portion of the Taylorsville quadrangle (Fig. 2-4; Plates 1 and 3). It is light- to greenish-gray, porphyroblastic, diopside-epidote-hornblende-plagioclase-biotite-quartz gneiss, and is easily recognized by distinctive hornblende and epidote porphyroblasts in a fine-grained quartz and biotite matrix. Mersch (2003) originally recognized this unit and delineated its geometry across the Ellendale quadrangle to the southwest (Plate 3). Other small calc-silicate pods and layers are sporadically present throughout the study area, but are not mappable and are always associated with metagraywacke lithologies.

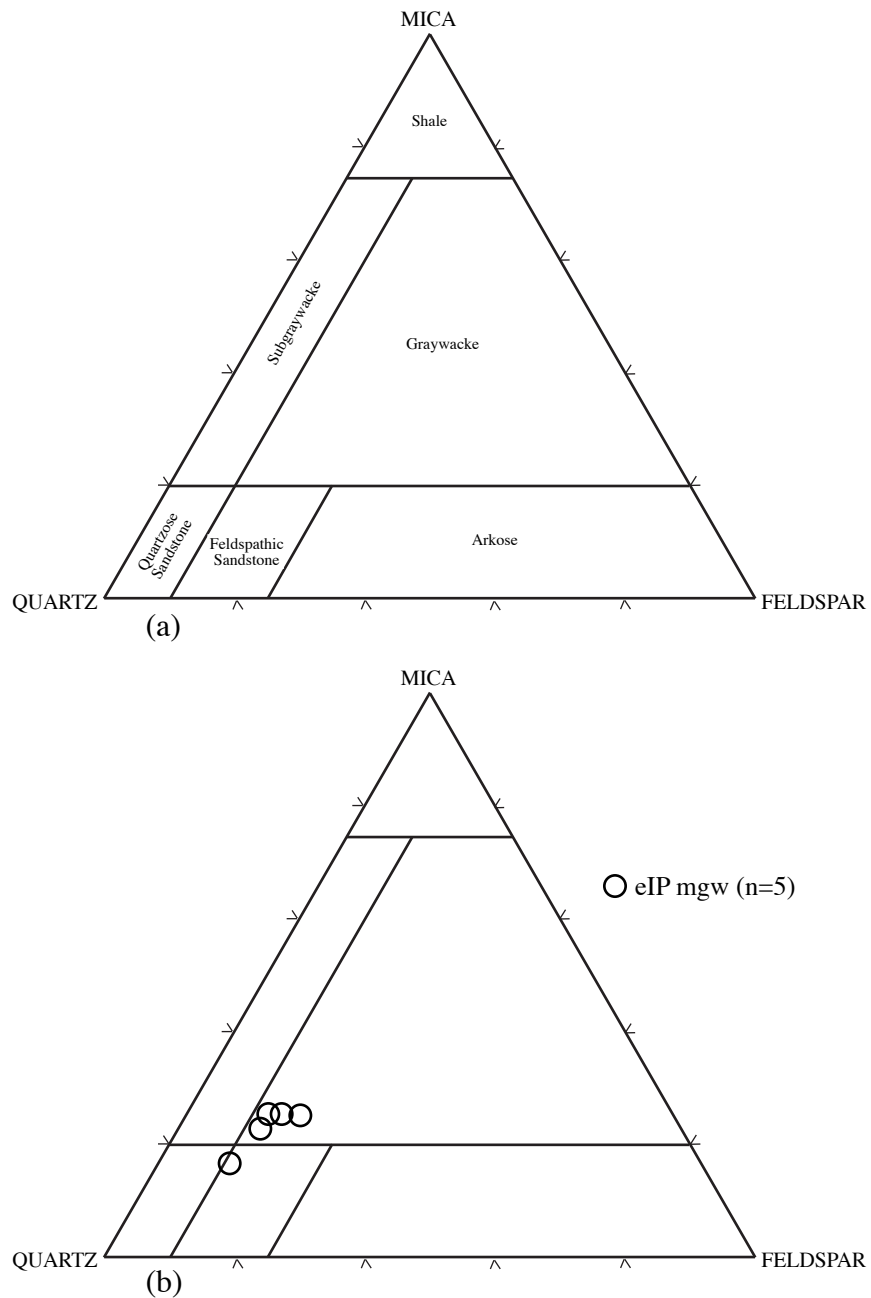


Figure 2-19. Quartz-feldspar-mica ternary diagram comparing the modal composition of eastern IP metagraywacke lithologies. (a) Modified sandstone classification from Pettijohn (1949). (b) Q-F-M ternary plot of northeastern IP metagraywacke lithologies plotting in the graywacke-feldspathic sandstone-quartzose sandstone fields.

METAMORPHIC RELATIONSHIPS FROM THE NORTHEASTERN BRUSHY MOUNTAINS

Inner Piedmont Metamorphism

The Neoacadian metamorphic core of the southern Appalachians, the eastern Blue Ridge and IP, has long been recognized as a stack of westward-verging crystalline thrust sheets containing predominantly high-grade metamorphic rocks (Griffin, 1969; Hatcher, 1969). In North Carolina, the IP is dominated by an ~60 km wide zone of kyanite- to sillimanite I- and locally sillimanite II grade ortho- and paragneisses. Metamorphic grade increases from low-grade rocks on the flanks to high-grade (middle- to upper-amphibolite facies) near the core (Fig. 2-20; Butler, 1991). The western flank of the IP contains a fault-related inversion of metamorphic isograds, which places sillimanite-grade rocks over kyanite- and upper greenschist-grade assemblages southeast of the Brevard fault zone (Hopson and Hatcher, 1988). Upright metamorphic isograds occur along the eastern flank of the IP (Fig. 2-20).

Several recent metamorphic studies from the IP have yielded peak estimates of kyanite- and sillimanite-grade conditions for the eastern and western IP. Davis (1993a), Yanagihara (1994), and Mirante and Patino-Douce (2000) have documented sillimanite-grade assemblages for western IP lithologies (Fig. 2-21). Hill (1999) recognized a prograde progression of sillimanite after kyanite (Fig. 2-21). Bier (2001) determined similar peak P-T estimates for eastern IP metaigneous and metasedimentary lithologies (Fig. 2-21). P-T estimates for western IP migmatites range from 600 to 700° C and 3.0 to 7.7 kbar (Kalbas, 2003). Merschat (2003) recognized the presence of localized second-sillimanite assemblages in eastern IP aluminous schist lithologies from the southwestern Brushy Mountains. The presence of local sillimanite II peak metamorphic conditions for the Brushy Mountains was further supported by thermobarometric calculations yielding near granulite facies P-T estimates for eastern IP metasedimentary lithologies (Fig. 2-21).

Methodology

Mineral assemblages for northeastern IP lithologies were recorded for >1800 stations during detailed geologic mapping of the study area (Fig. 2-4; Plate 1). Petrographic and modal mineralogical analyses were performed for selected samples from all recognized lithologies. Locations of recognized metamorphic assemblages were plotted on the geologic map, and a metamorphic map for the northeastern Brushy Mountains was compiled (Fig. 2-22).

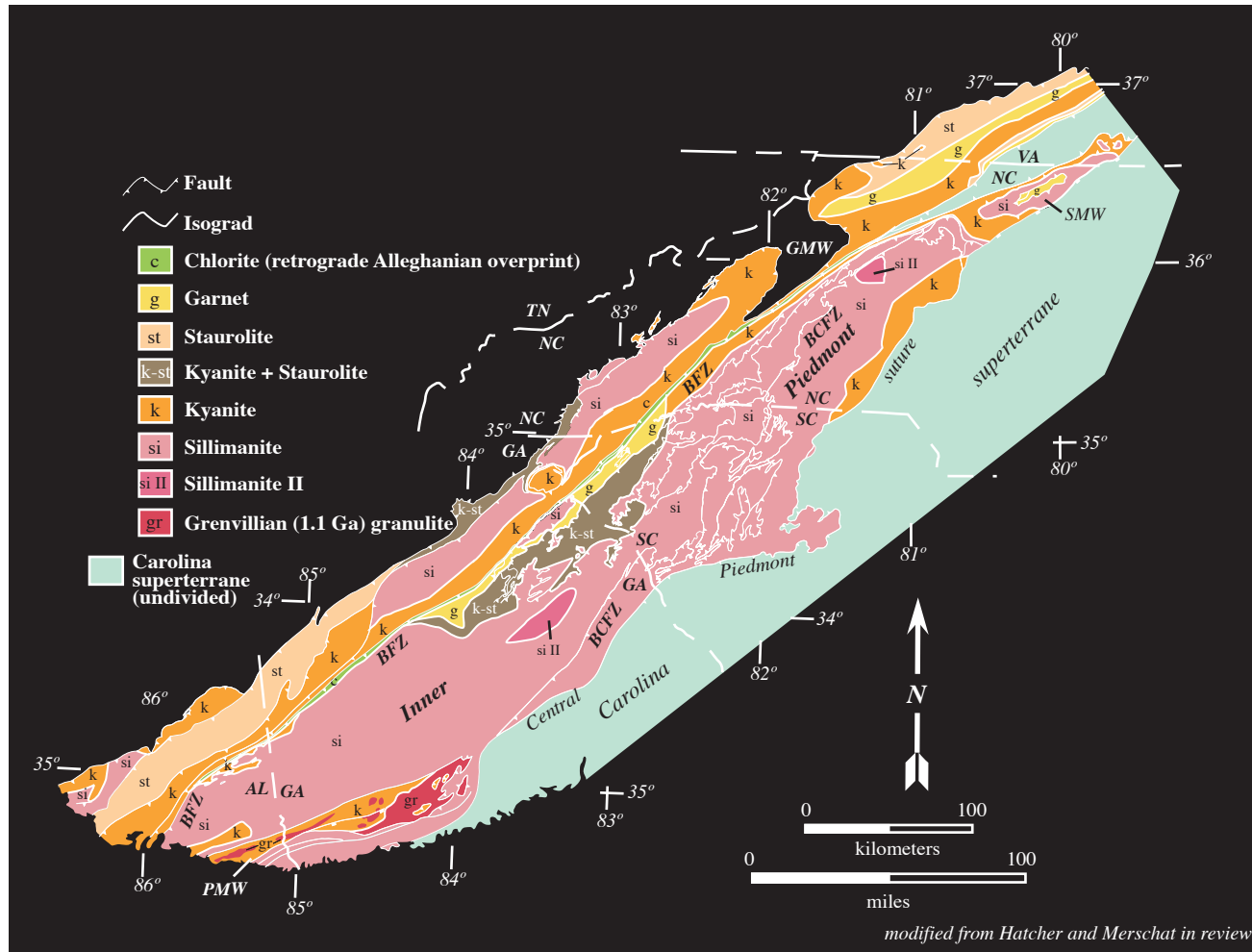


Figure 2-20. Metamorphic isograd map of the southern Appalachian crystalline core. Abbreviations: PMW=Pine Mountain window; BFZ=Brevard fault zone; BCFZ=Brindle Creek fault zone; GMW=Grandfather Mountain window; SMW=Sauratown Mountains window. Figure modified from Hatcher and Merschat, in press.

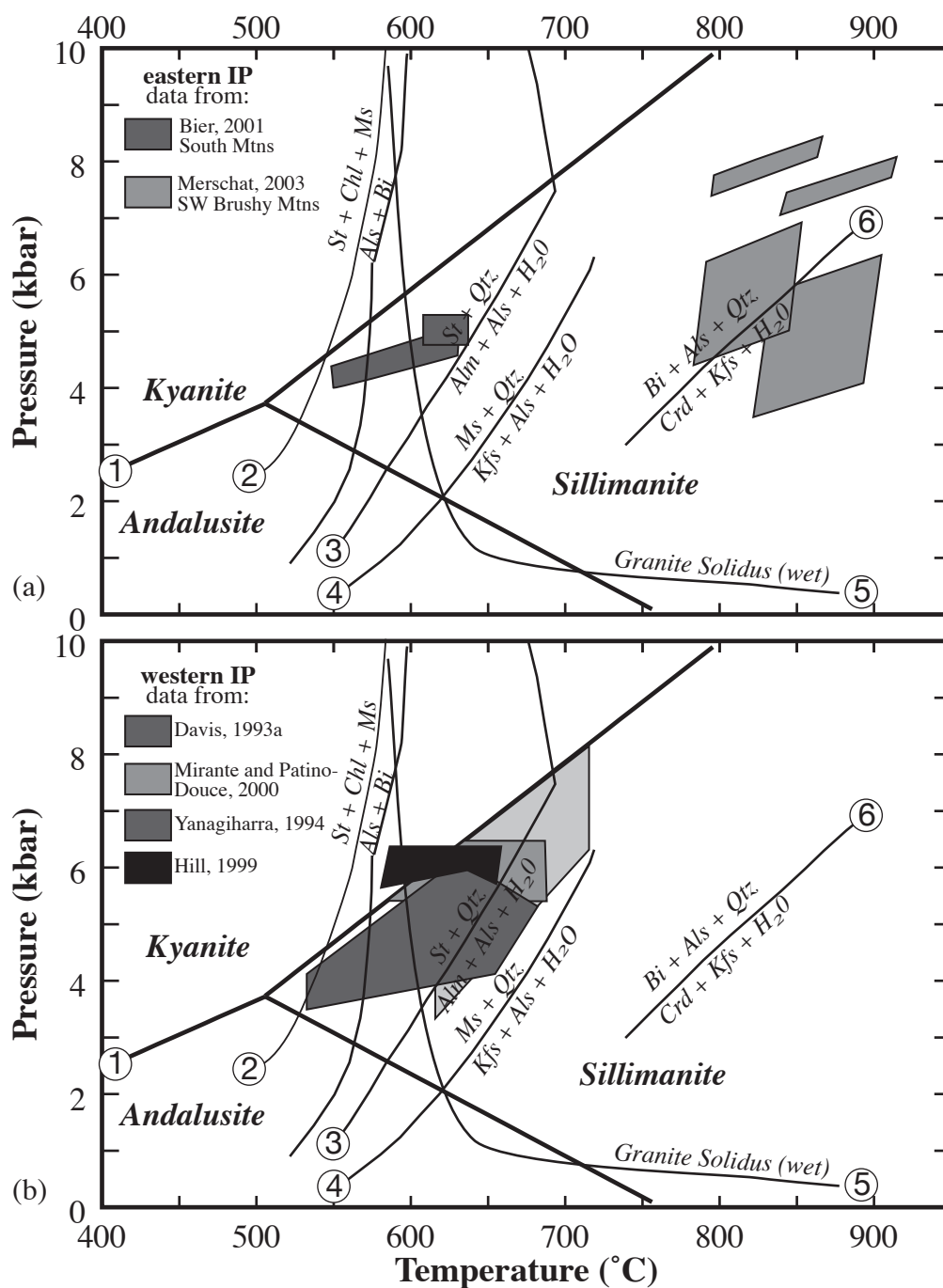


Figure 2-21. Metamorphic P-T estimates plotted for recent IP studies. (a) P-T estimates for eastern IP lithologies. (b) P-T estimates for western IP lithologies. Univariant curves plotted are: (1) Holdaway (1971); (2) Albee (1965); (3) Pigage and Greenwood (1982); Chatterjee and Johannes (1974); (5) Luth et al. (1964); and (6) Holdaway and Lee (1977). St=staurolite, Chl=chlorite, Ms=muscovite, Als=aluminum silicate, Bi=biotite, Qtz=quartz, Alm=almandine, Kfs=potassium feldspar, Crd=cordierite.

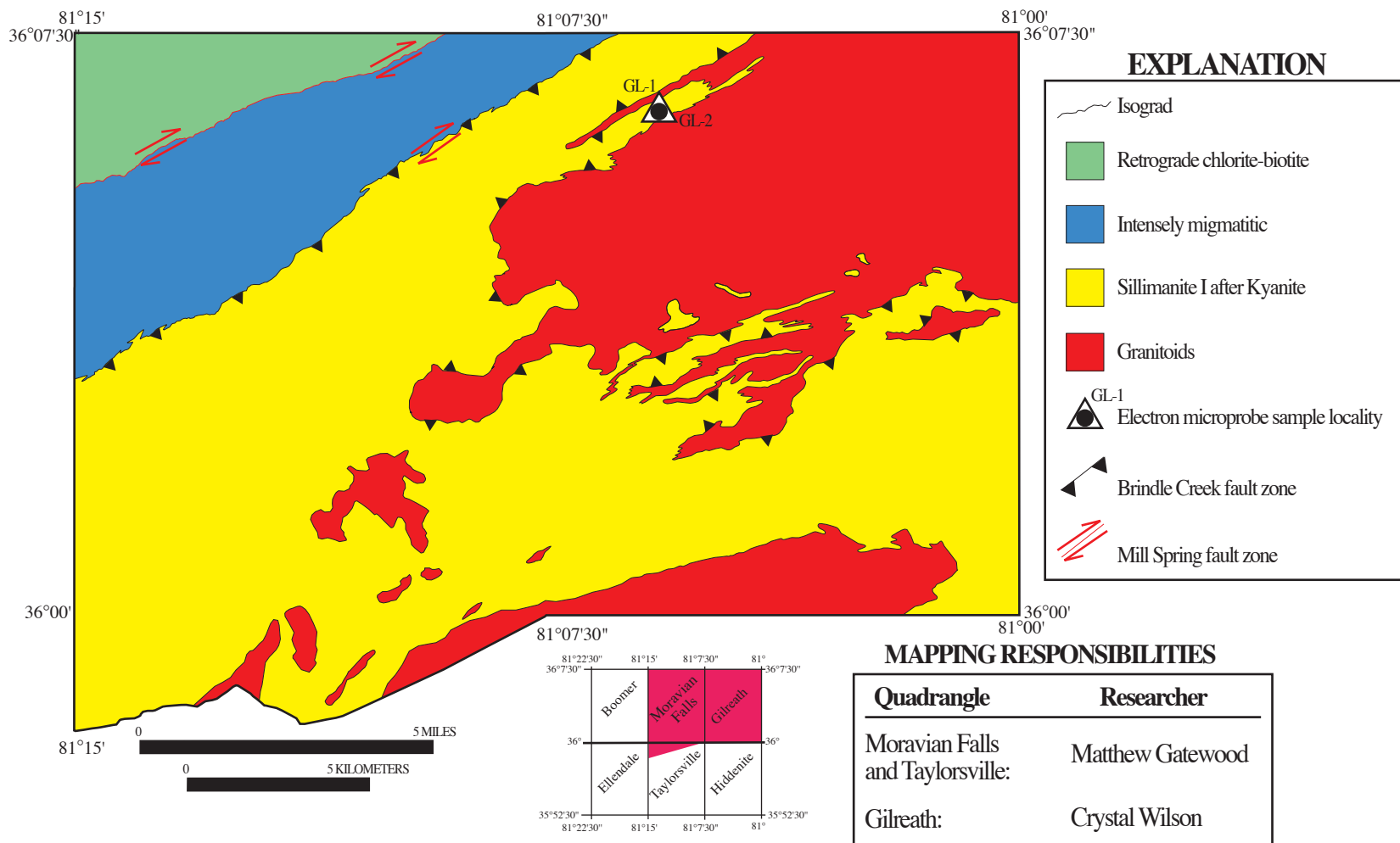


Figure 2-22. Metamorphic isograd map of the northeastern Inner Piedmont. The sillimanite I assemblage was recognized by the occurrence of biotite+ muscovite + quartz + sillimanite. Map-scale retrograded assemblages are restricted to the Brevard fault zone. Locations of drill core samples from the Vulcan Materials 115 Quarry selected for electron microprobe analyses are indicated. Brindle Creek and Mill Spring fault zones shown for reference.

For electron microprobe samples, four thin sections were made, cut, and polished sub-perpendicular to foliation. Samples were examined petrographically for mineralogy, texture, fabric, etc (Fig. 2-23; Table 2-4). Before quantitatively analyzing the samples, all phases were evaluated semi-quantitatively by EDS spectrometry for their elemental compositions.

Mineral chemistry was determined quantitatively using a four-spectrometer CAMECA SX-50 electron microprobe (EMP) at the University of Tennessee electron microprobe facility. Run conditions consisted of 20 keV for the accelerating voltage, with a beam current of 20 nA for all analyses except feldspar, for which a beam current of 10 nA was utilized. Beam size was varied, depending on mineralogy, from 1 - 5 μm , with counting times of 20 seconds. Both natural and synthetic standards were used, and all microprobe data were fully reduced using the CAMECA ZAF (PAP) software.

Data collection methods varied according to locations and purposes of analyses. Spot analyses, automated line traverses, and X-ray maps were utilized in obtaining mineral composition and examining chemical zonation patterns in garnet. Line traverses within and between grains were performed. Intragranular line traverses were generally oriented perpendicular to grain boundaries and, whenever possible, to transect the entire grain. Intergranular line traverses were performed to obtain information about reactions occurring along phase boundaries. Spot analyses were performed for specific areas of phases, grain boundaries, inclusions, etc.

Data obtained in the above-mentioned analyses were used in calculating P-T estimates for the samples. For estimating values of P and T, the computer program Thermobarometry v. 1.9, developed by Spear and Kohn (1989), was utilized. This program determines values for P and T by plotting experimental reaction curves on a petrogenetic grid, based on cation number. Estimates for P-T conditions were calculated for garnet analyses along with biotite for thermometry, or plagioclase for pressure estimates (Appendix A). P-T estimates were then compared with mineral assemblage data to verify their validity.

Sample Descriptions

The deep erosion levels of the southern Appalachian IP make the sample selection process crucial to obtaining accurate results. Large pavement outcrops, road cuts, streams, and rock quarries often contain fresh material available for chemical analyses. Samples analyzed in this study were collected from a drill core taken from a Vulcan Materials quarry (115 quarry) near Wilkesboro, NC (Fig. 2-23). The availability of a drill



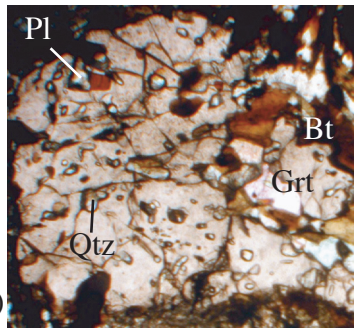
(a) photo by RDH

GL-1-WT



(b)

GL-1-WT-grt C



(d)

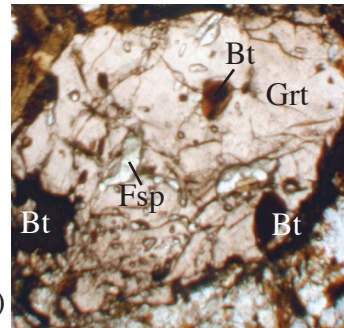
1 mm

GL-2-WT



(c)

GL-2-WT grt A



(e)

1 mm

Figure 2-23. Representative lithologies from the Vulcan Materials 115 Quarry sample locality. (a) Quarry block of mylonitic Walker Top gneiss. Note the prominent shear zone. (b) GL-1-WT core sample selected for EMP analysis. (c) GL-2-WT core sample selected for EMP analysis. (d) GL-1-WT-garnet (Grt) C photomicrograph. (e) GL-2-WT-garnet (Grt) A photomicrograph. Note the prominent inclusions of biotite (Bt), quartz (Qtz), Plagioclase (Pl), and Feldspar (Fsp) (abbreviations from Kretz, 1983).

core sample (depth ~110 ft.) provided the opportunity to examine rock that has not been significantly altered by weathering, like those exposed at the surface. Also, the proximity of the sample locality to the BCFZ (Fig. 2-20) should allow for peak P-T values to be obtained, yielding representative estimates for the environmental conditions during crystalline thrust sheet emplacement.

Both samples selected for EMP analyses were taken from 1.5-inch diameter drill core. In hand sample and thin section these samples consist of a medium- to coarse-grained inequigranular mylonitic biotite-augen gneiss. Recrystallized quartzofeldspathic material in the matrix, rounded feldspar porphyroclasts, myrmekitic rims on feldspars, S-C fabrics, disconnected boudins, and quartz-feldspar ribbons indicate a high-temperature mylonitic texture in the sample (Figs. 2-23 and 2-24). Quartz shows evidence for grain boundary migration and subgrain formation with high-angle grain boundaries (Fig. 2-24). Transposed migmatitic compositional layering can be easily recognized in hand sample, with quartz and feldspar being the major constituents of the leucocratic layers. Several melt layers display distinct boudinage. Migmatitic areas of the sample were purposely avoided during sample preparation to eliminate the effects of migmatization. The characteristic texture of the sample consists of 0.5-1.0 cm diameter rounded feldspar, and to a lesser extent quartz porphyroclasts in a fine-grained dark-gray biotite matrix. The biotite in the sample, along with quartz, defines the foliation and wraps other phases.

Distinct textural and mineralogical features of this sample correspond to a mylonitic phase of the Walker Top Granite. This unit can be traced across the study area along-strike for several kilometers to the southwest (Plate 3). Recent mapping has shown that the Walker Top Granite is continuous throughout the Brushy Mountains until ultimately truncating against the BCFZ to the northeast (Fig. 2-4; Plates 1 and 3). Proximal to fault zones and map-scale shear zones, textures of the Walker Top Granite become increasingly mylonitic (Part IV, this study).

Primary phases in selected samples consist of: biotite (30-35%), quartz (20-25%), plagioclase (20-25%), and K-feldspar (10-15%) (Table 2-4). Accessory phases present include muscovite, garnet, myrmekite, sericite, sillimanite, sphene, epidote, monazite, zircon, ilmenite, apatite, rutile, cordierite, siderite, calcite, pyrite, and opaques (Table 2-4).

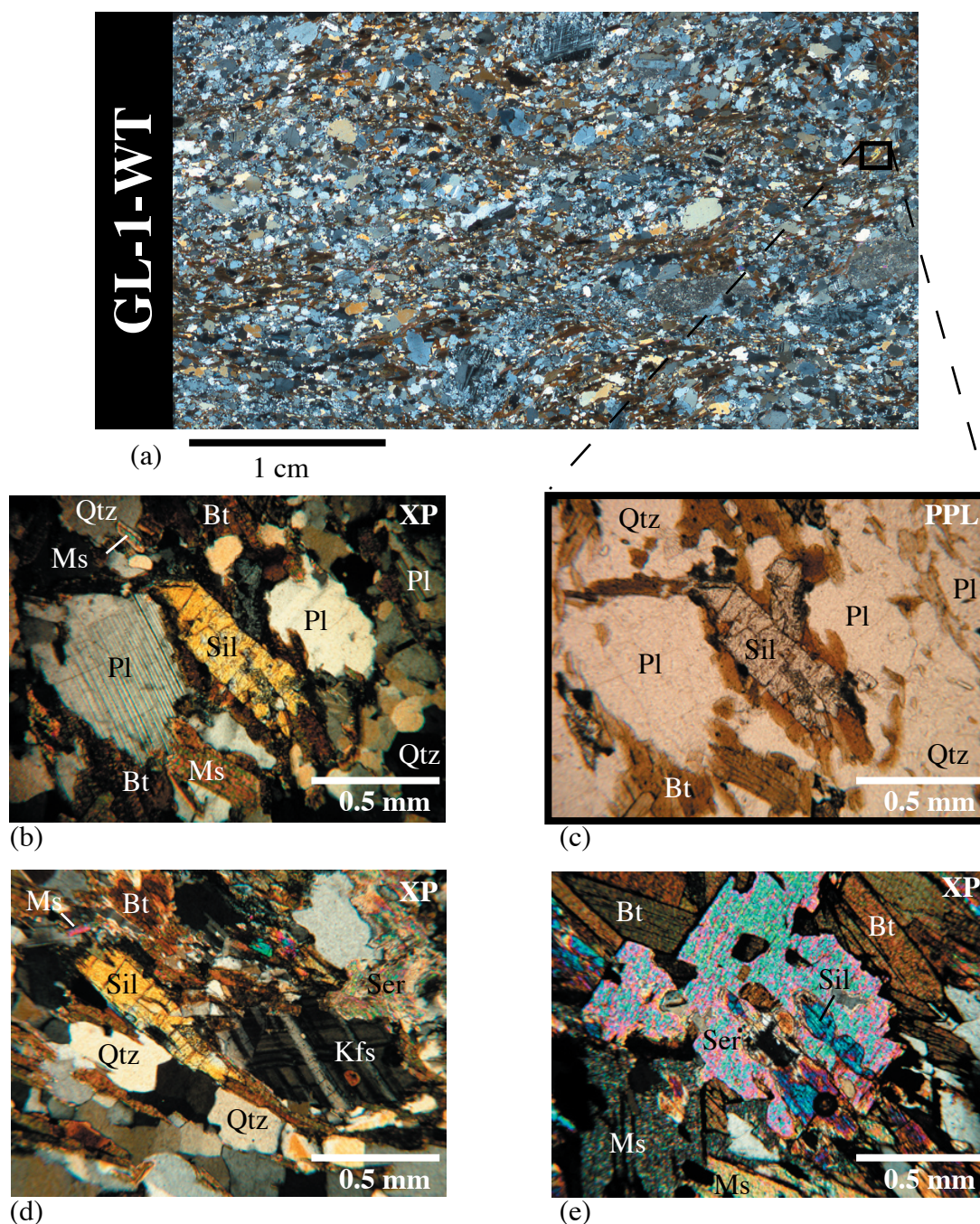


Figure 2-24. Petrographic characteristics of EMP samples. (a) Scanned thin section of GL-1-WT. (b) Photomicrograph of sillimanite blade after kyanite. Note the parallel extinction of the bladed crystal. (c) PPL view of (b). Note the high relief of the sillimanite. (d) Bladed sillimanite pseudomorph of kyanite in sample GL-2-WT. The K-feldspar is igneous in this sample. Note the alteration to sericite in the upper right corner. (e) Alteration of sillimanite to sericite in sample GL-2-WT. Abbreviations (after Kretz, 1983): Sil=sillimanite, Ser=sericite, Kfs=K-feldspar, Qtz=quartz, Bt=biotite, Ms=muscovite, Pl=plagioclase.

Mineralogy

Garnet

Accessory garnet constitutes 2-5 percent of representative samples selected for analysis. Anhedral to subhedral garnet porphyroblasts range from 0.25-0.5 cm in diameter, are highly fractured, and are flattened into the dominant foliation (Fig. 2-23). Garnet grain boundaries may be distinct or embayed by quartz, feldspar, and biotite (Fig. 2-23). Some minor alteration is present along fractures. No optical zoning or preservation of internal fabrics was observed in any of the garnets. All garnets contain numerous inclusions consisting of: quartz, biotite, feldspar, apatite, zircon, epidote, ilmenite, rutile, calcite, and siderite. Semi-quantitative identification of accessory inclusion phases was determined by EDS spectrometry.

Chemical zonation patterns within the garnets can be seen in Figures 2-25, 2-26, and 2-27. Analyses reported in Appendix A show elements analyzed in the garnets. Formula totals for selected garnet analyses (Appendix A) show no indication of the presence of Fe^{3+} . Some analyses may indicate the presence of minor Fe^{3+} near the rim of garnet GL-1-grt A (Appendix A). Sobolev et al., (1999), however, showed that values for $\text{Fe}^{3+}/\Sigma\text{Fe}$ calculated from EMP analyses are inaccurate, and therefore no attempt was made to quantify the amount of Fe^{3+} . Cr_2O_3 and Na_2O are present only in trace quantities (usually < 0.03 wt%; Appendix A).

Some chemical zonation can be seen in the garnets, especially near the rims (Figs. 2-26 and 2-27). Garnet compositions are mostly almandine, but also have significant pyrope, spessartine, and grossular components. The largest variations occur in the contents of FeO, MnO, and MgO (Fig. 2-25). Garnet rims are characterized by large increases in FeO and MnO contents, and a decrease in MgO content (Fig. 2-25). Garnet cores show higher contents of MgO and lower concentrations of MnO and FeO. The CaO components of the garnets are weakly zoned to homogeneous, with slight increases near cores and rims (Figs. 2-25, 2-26 and 2-27). All garnets analyzed display similar zonation patterns, which are typical of garnets that have undergone volume diffusion (Spear, 1993; Figs. 2-26 and 2-27). The diffused nature of the garnets in these samples greatly affects the results of P-T estimates and will be taken into account and discussed further below.

Biotite

Biotite defines the dominant foliation in all samples, is subhedral, and ranges from 0.1-10 mm in diameter. The biotite defining the foliation tends to wrap around

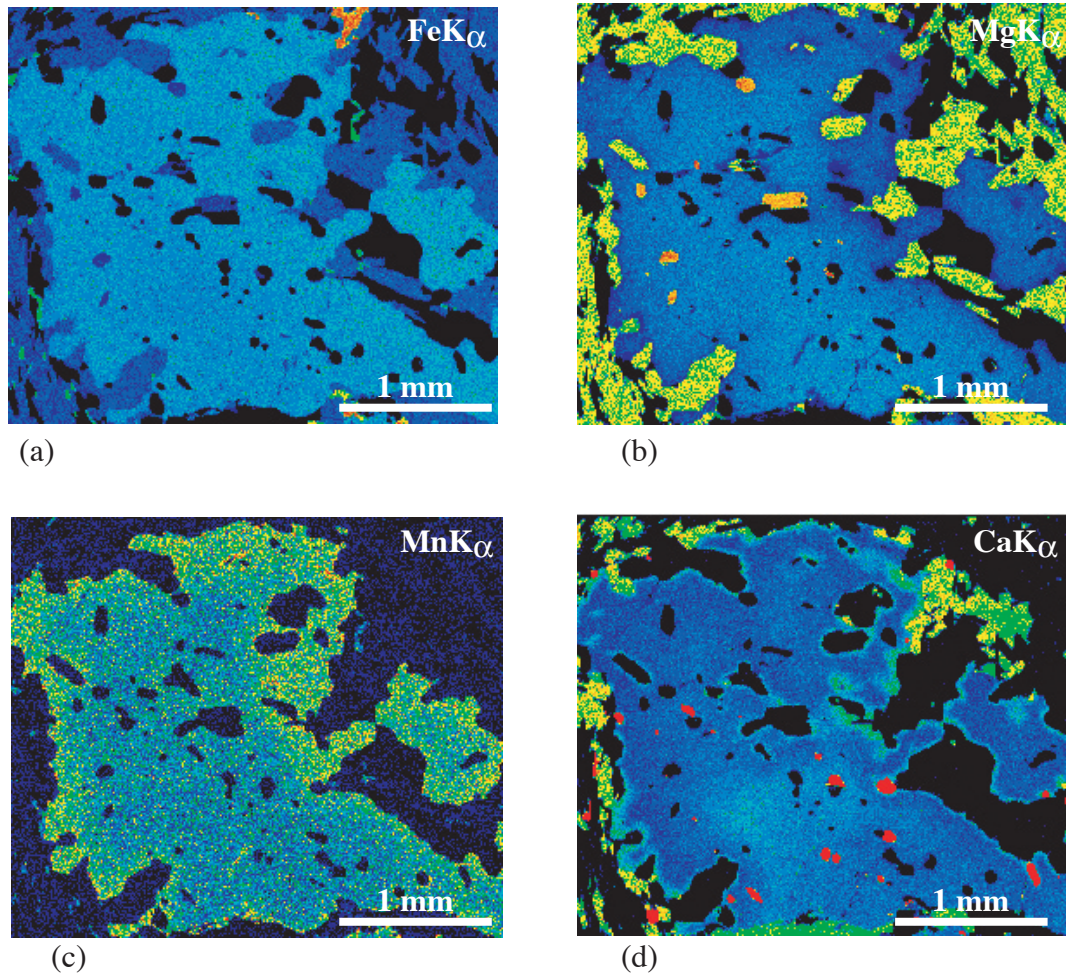


Figure 2-25. X-ray maps showing zonation of Fe, Mg, Mn, and Ca for sample GL-1 garnet C. (a) At this scale, Fe does not appear to be zoned within the garnet, except for just around the rim, where the lighter blue color shows a slightly higher content than in the core. Matrix and inclusion biotite has a lower Fe content than garnet and is shown in dark blue. Fe-poor phases (quartz, feldspar, muscovite, and aluminum silicates) are black. A large ilmenite grain is present near the top of the garnet, shown in orange. (b) Dark blue color shows higher Mg in the core, with a substantial decrease in Mg content near the rim. The decrease in Mg near the rim corresponds to an increase of Fe. Notice high values in (a) corresponding to low values in (b). Matrix biotite has a lower Mg content (yellow-green) than inclusion biotite (red-orange). All other phases shown in black. (c) Drastic increase in Mn content near the rim. (d) Light-blue color indicates higher Ca values in the garnet core and rim, with decreased Ca content between the core and rim. Plagioclase inclusions are shown in red and have a significantly higher Ca content than matrix plagioclase (shown in yellow-green).

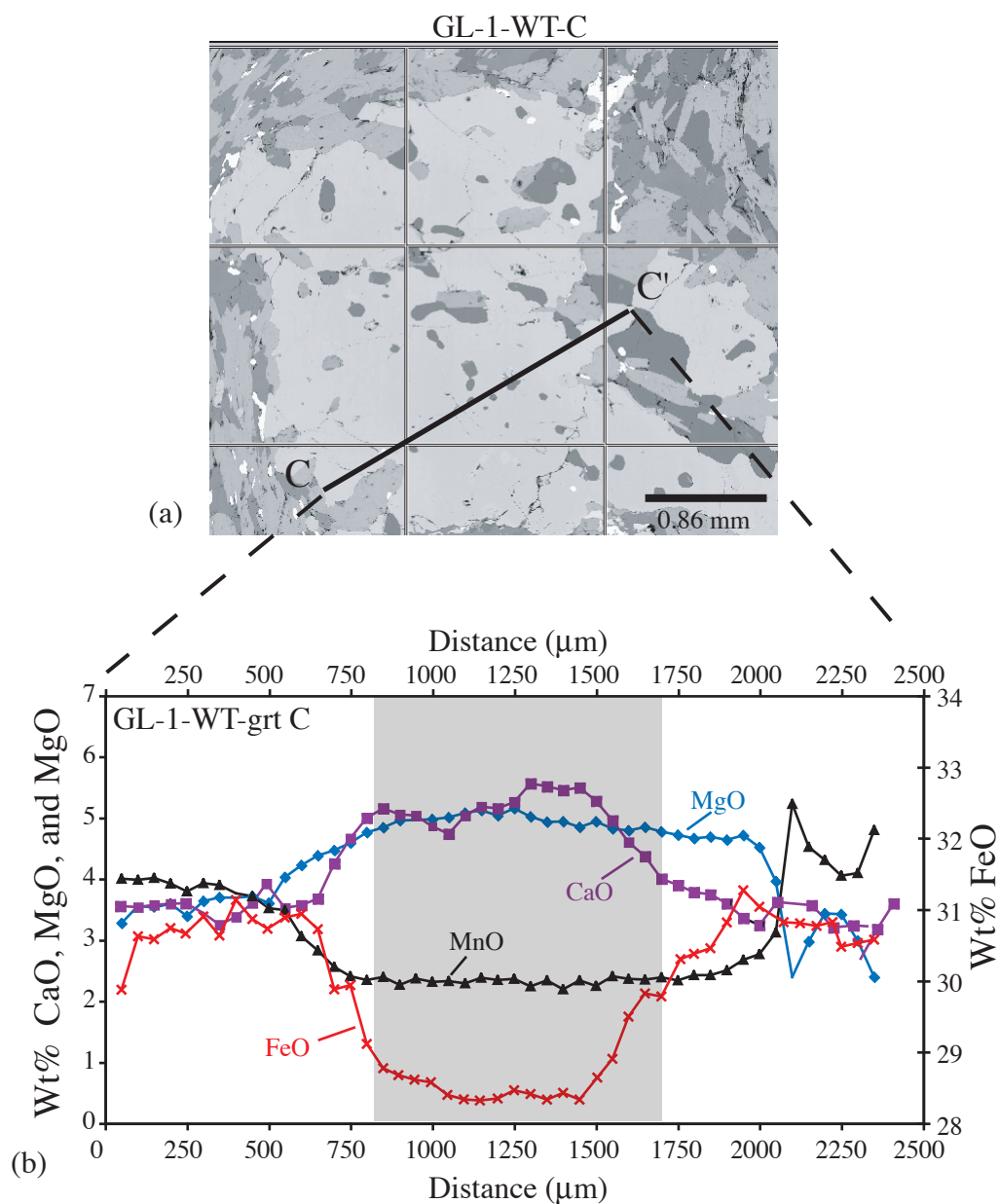


Figure 2-26. Chemical zoning profile from sample GL-1-WT. (a) Back-scattered electron image of garnet C from GL-1-WT. Solid black line represents line traverse C - C' for garnet C. Spot analyses were spaced $\sim 60 \mu\text{m}$ apart along traverse C - C'. (b) Chemical zoning profile of garnet C from GL-1-WT. Note that FeO is plotted at a different scale on the secondary y-axis. Gray shaded region represents the area interpreted to be the garnet core. Note the increase in the concentrations of FeO and MnO from the core to rim and the overall decrease in MgO from the core to rim.

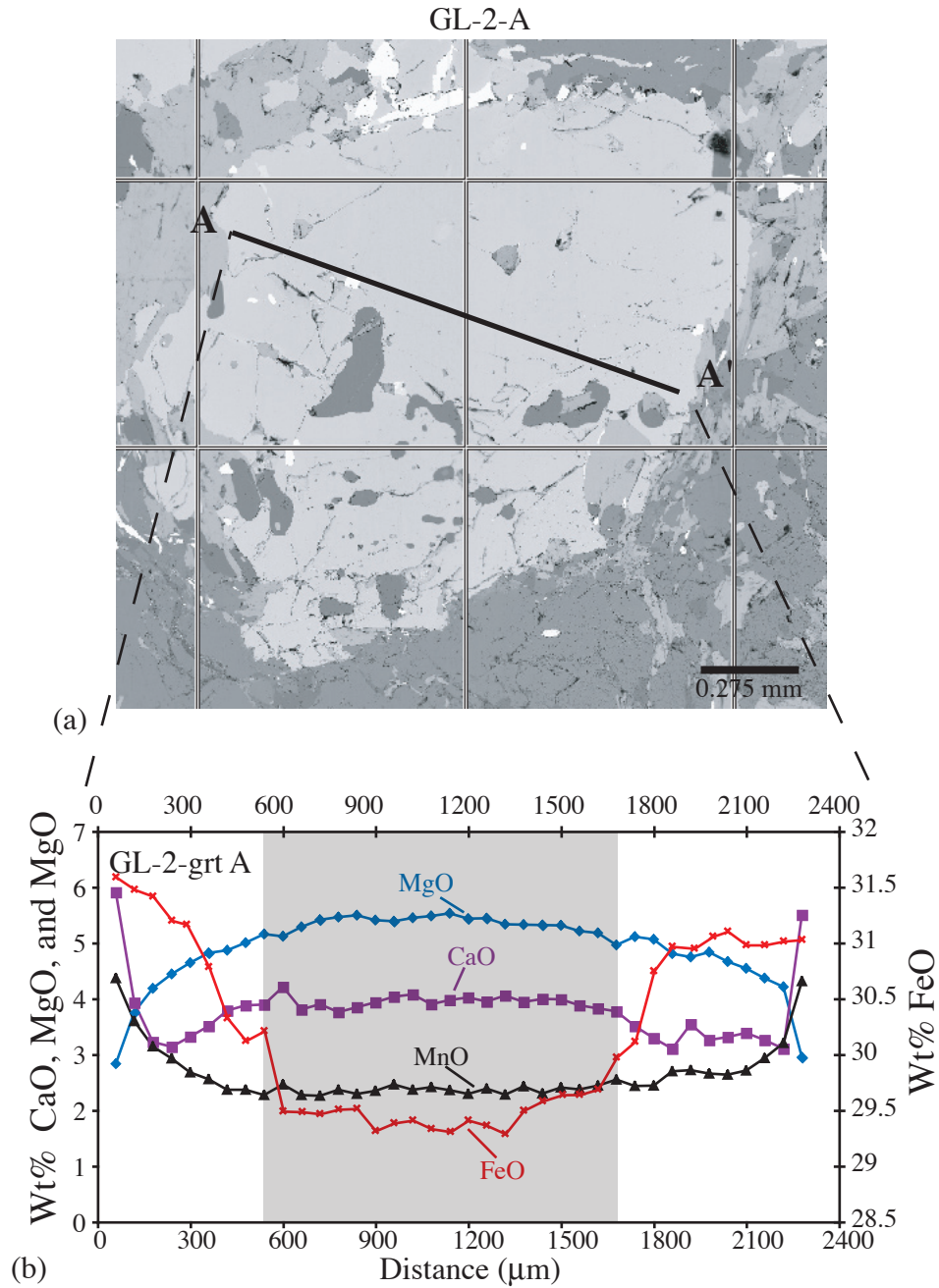


Figure 2-27. Chemical zoning profile from sample GL-2-WT. (a) Back-scattered electron image of garnet A from GL-1-WT. Solid black line represents line traverse A - A' for garnet A. Spot analyses were spaced ~65 μm apart along traverse A - A'. (b) Chemical zoning profile of garnet A from GL-2-WT. Note that FeO is plotted at a different scale on the secondary y-axis. Gray shaded region represents the area interpreted to be the garnet core. Note the increase in the concentrations of FeO and MnO from the core to rim and the overall decrease in MgO from the core to rim.

coarser-grained phases. Compositionally, the biotite grains vary somewhat with respect to where they are located within the sample. Some compositional variation can be seen between the matrix biotite and the biotite inclusions in the garnets (Fig. 2-25). Matrix biotite appears to be more homogeneous than biotite inclusions in the garnets. Biotite inclusions are higher in TiO_2 , MgO , and Na_2O , and lower in FeO and K_2O than their matrix equivalents. Compositional variation between matrix and included biotite may have important consequences for thermobarometry and is discussed further below.

Plagioclase

Plagioclase feldspar porphyroclasts in the sample range in size from 0.25-1 cm in diameter. In hand specimen, the plagioclase has a rounded shape, with the rims altered to sericite. The plagioclase in these samples has a composition of An_{48-60} . Matrix plagioclase is not twinned and does not show compositional zoning (Fig. 2-25). Plagioclase inclusions in the garnets, however, have a much higher CaO content and show weak compositional zoning. This may be related to growth zoning and/or volume diffusion within the garnets.

K-feldspar

K-feldspar porphyroclasts have a characteristic rounded (0.5-1 cm) diameter shape and are ubiquitously rimmed with myrmekite (Figs. 2-15 and 2-24). K-feldspar composition appears to be homogeneous with an orthoclase content of 89-92 percent. The presence of K-feldspar has recently been used to interpret sillimanite II conditions in lithologies from the northeastern IP. In this case, however, the K-feldspar is igneous and not an indicator of metamorphic grade. Furthermore, the presence of muscovite in contact with sillimanite indicates a sillimanite I assemblage.

Sillimanite

Sillimanite occurs mostly as bladed pseudomorphs of kyanite, with rare needles and fibers aligned within the dominant foliation (Fig. 2-24). In some cases, sillimanite shows partial alteration to sericite (Fig. 2-24). All sillimanite occurrences in these samples indicate a prograde metamorphic replacement of kyanite. Sillimanite is assumed to be a pure phase in all samples.

Accessory Phases

Ilmenite and rutile occur as inclusions in garnet and as minor constituents of matrix phases. Ilmenite inclusions are generally subhedral and contain rutile cores. Matrix ilmenite crystals are generally anhedral and aligned with the dominant foliation.

Northeastern IP Regional Metamorphism

Important metamorphic mineral assemblages observed in the field include biotite-muscovite-quartz-garnet-sillimanite for the aluminous schist, and biotite-muscovite-plagioclase-K-feldspar-quartz-garnet-sillimanite for the Walker Top Granite. The abundance of micas indicates that water was present during metamorphism. Lack of metamorphic K-feldspar and the presence of muscovite in pelitic lithologies suggest that peak P-T conditions remained below the second sillimanite isograd (Fig. 2-18). Sillimanite invariably occurring as pseudomorphs of kyanite in both pelitic metasedimentary and metaigneous lithologies reflects a prograde metamorphic P-T path for eastern IP lithologies (Figs. 2-18 and 2-24).

Ubiquitous migmatitic textures observed for all lithologies indicate that minimum metamorphic conditions were at or above the wet granite solidus. Furthermore, the Walker Top and Toluca Granite bodies have been interpreted to have magmatic origins (Giorgis, 1999; Mapes, 2002), and because of their aluminum contents, may be the product of regional-scale migmatization (Part IV, this study). Observed assemblages and lower peak P-T estimates obtained for this study area (see below) yield lower P-T conditions and do not indicate the presence of sillimanite II conditions during peak metamorphism, as recognized by Merschat (2003) (Fig. 2-22).

Petrogenesis of EMP Samples

Mineral assemblages present in all samples correspond to those indicative of the upper amphibolite facies for pelitic rocks (Spear, 1993). The absence of staurolite indicates that P-T conditions were above the staurolite stability field. Coexisting phases of sillimanite and muscovite, and the absence of metamorphic K-feldspar suggest peak conditions below the second sillimanite isograds. Intense migmatization is indicative of pressures and temperatures well above minimum melt conditions. Assemblages plot in the muscovite-biotite-quartz-sillimanite stability field, constraining P-T conditions to $\geq 600^{\circ}\text{C}$ and ≥ 2 kbar (Fig. 2-28).

The lack of second sillimanite grade assemblages indicates either that conditions did not reach those required for intense dehydration, or that assemblages have been

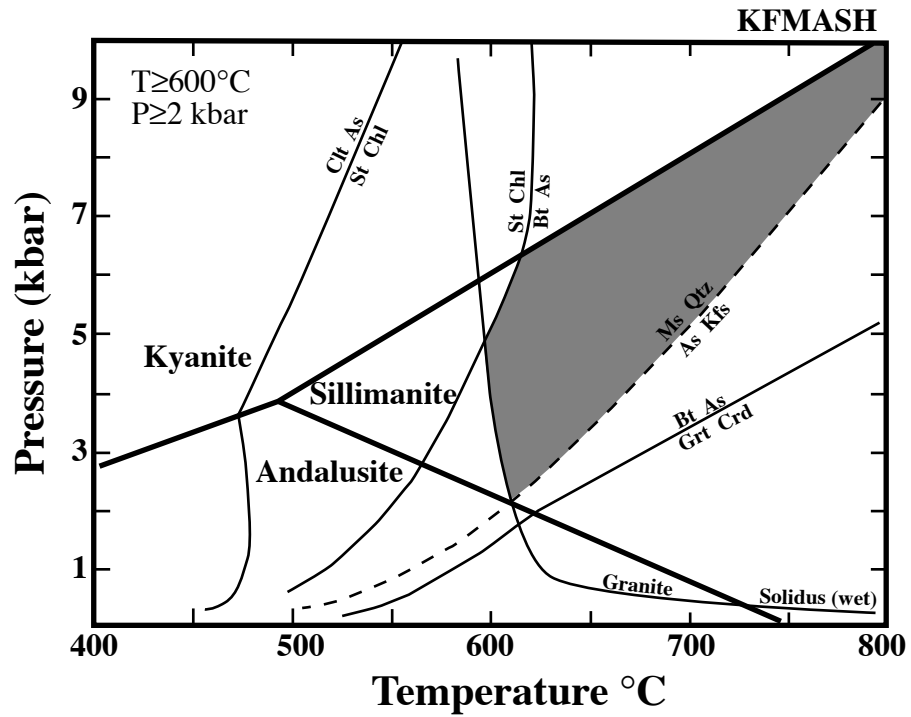
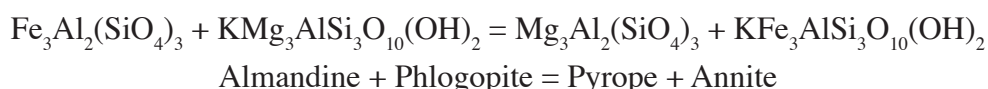


Figure 2-28. Simplified petrogenetic grid for the KFMASH system (after Spear, 1993). Dashed line represents muscovite dehydration. Shaded area corresponds to peak P-T field for EMP samples based on mineral assemblages observed in thin section.

retrograded. Evidence for retrograde reactions is provided by the subhedral appearance and embayments of garnet by quartz, biotite, and muscovite. Although some overgrows the dominant foliation, most muscovite appears to be primary and is concordant with planar fabrics. It is unlikely that retrograde muscovite would develop parallel to earlier fabrics.

Thermobarometry

One thermometer and one barometer were used in estimating P-T, based on assemblages present in the samples. The thermometer used was the garnet-biotite thermometer of Ferry and Spear (1978). The garnet-biotite thermometer is a widely used exchange thermometer utilizing the Fe-Mg exchange between garnet and biotite in the following reaction:



Pressures were estimated using the GASP, garnet-aluminum silicate-plagioclase-quartz, net-transfer equilibria barometer of Hodges and Spear (1982). GASP barometry is based on the following net-transfer reaction:



The GASP barometer is popular for calculating pressure estimates, because it requires a common assemblage in pelitic rocks. Philpotts (1990) noted, however, that erroneous estimates may result because it is a temperature-sensitive barometer that depends on the activities of anorthite and grossular components, and estimates may only be accurate within ± 0.8 kbar.

These geobarometers and geothermometers were systematically applied to collected EMP data to obtain estimates of prograde and peak metamorphic conditions. Several analyses were made for each garnet. First, average core compositional values for garnets were used with averaged biotite and plagioclase inclusion compositional data for each garnet. Next, data collected from near the rims of the garnets were applied with matrix biotite and plagioclase.

Data from sample GL-1-WT garnet cores yield average P-T estimates of 650°C and 6.7 kbar (Fig. 2-29). Rim compositional data combined with matrix biotite and plagioclase phase data yield estimates of 630°C and 4.6 kbar (Fig. 2-29). The lower P-T estimates obtained when using garnet rim and matrix phase data can most likely be attributed to diffusion along the rims of the garnets and retrograde metamorphism during

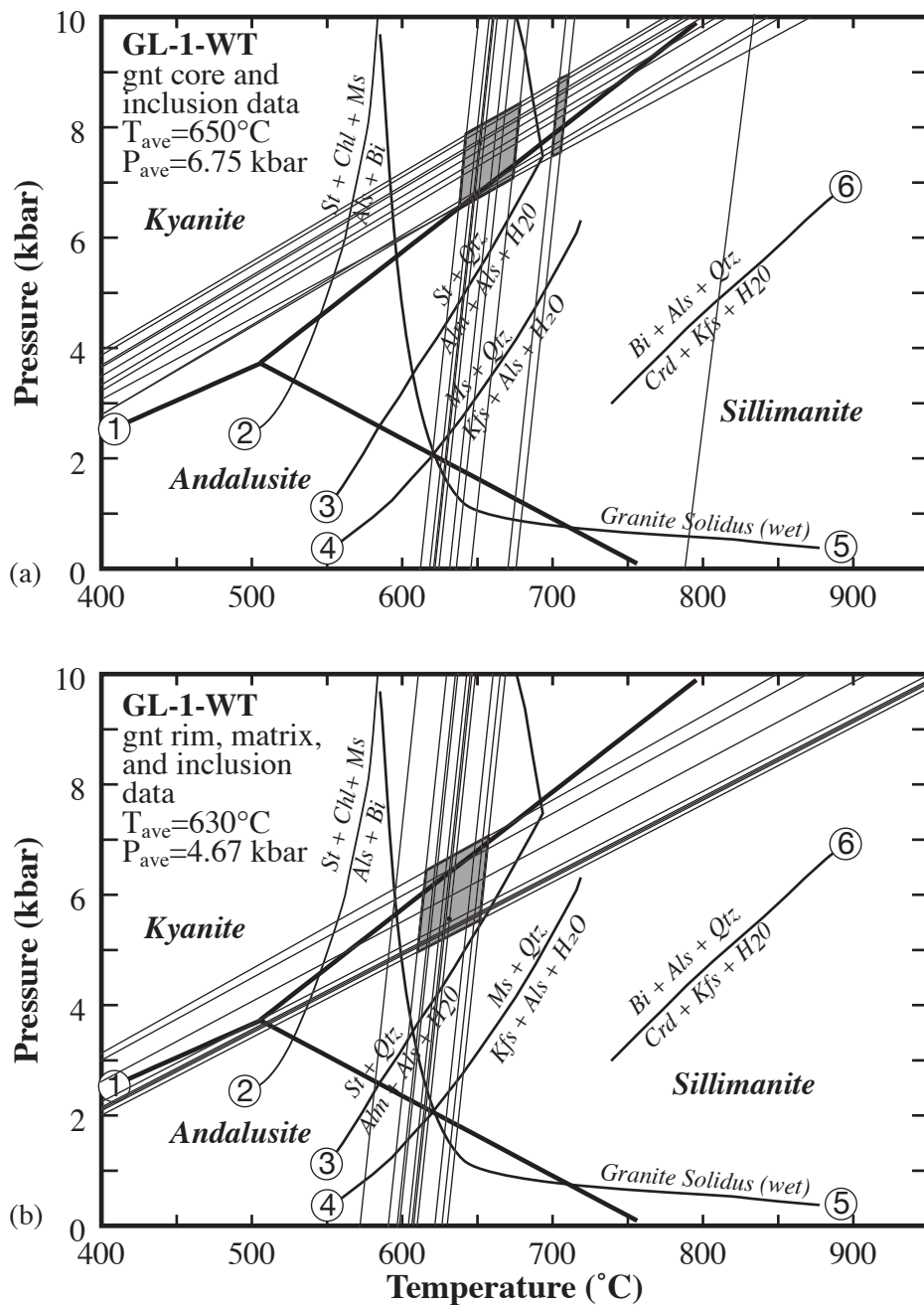


Figure 2-29. Temperature and pressure estimates for sample GL-1-WT. (a) Average garnet core compositions are used with average biotite and feldspar inclusion data for thermobarometry. (b) Average garnet rim compositions were used with matrix biotite and feldspar composition data for thermobarometry. Univariant curves plotted are: (1) Holdaway (1971); (2) Albee (1965); (3) Pigage and Greenwood (1982); (4) Chatterjee and Johannes (1974); (5) Luth et al. (1964); and (6) Holdaway and Lee (1977). St=staurolite, Chl=chlorite, Ms=moscovite, Als=aluminum silicate, Bi=biotite, Qtz=quartz, Alm=almandine, Kfs=potassium feldspar, Crd=cordierite.

cooling, indicating these conditions lie mostly within the kyanite stability field (Fig. 2-29). The absence of kyanite in the sample may suggest disequilibrium or erroneous barometry calculations. Textural evidence (Fig. 2-24) suggests that these P-T estimates are representative of a prograde metamorphic path from the kyanite to sillimanite stability fields, however, and that garnet cores equilibrated with near-core inclusions under these conditions. Flat MgO and FeO zoning profiles for sample GL-1-WT garnet cores (Fig. 2-26), which are interpreted to represent areas of original homogeneous growth zoning in the garnets.

Analyses from sample GL-2-WT produced estimates of 680°C and 7.1 kbar for garnet core average values, when used in conjunction with near-core inclusion compositional data (Fig. 2-30). Peak conditions were determined from garnet rim and matrix compositional data, which yielded average estimates of 745°C and 7.0 kbar (Fig. 2-30). These values are also taken to represent a prograde metamorphic path within the sillimanite field.

Use of the data from garnet cores in conjunction with near-core inclusion data, and garnet rim data, combined with near-rim inclusion phase data, may represent a more useful method for attempting to obtain metamorphic conditions than using garnet rim with matrix phase data. Spear (1991) noted that above the staurolite zone ($T > 550^{\circ}\text{C}$) peak mineral compositions become altered by diffusion, thus hindering P-T estimate calculation. Compositional data suggest that all garnets analyzed have undergone considerable diffusion (Figs. 2-26 and 2-27). Zoning profiles, however, indicate that significant exchange of Fe, Mg, and Mn has occurred between the garnets and adjacent phases. Embayments in garnets by biotite, quartz, and plagioclase point to net-transfer and exchange reactions that occurred to alter the garnet rim chemistry. Compositional differences between matrix and inclusion phases (Fig. 2-25), and diffused garnet rim compositions (Figs. 2-26 and 2-27) suggest that inclusion phases more realistically represent an equilibrium assemblage with the garnets than matrix phases. Therefore, P-T estimates calculated using garnet compositions with inclusion phases are preferred for thermobarometry in this study.

P-T Paths

Mineral assemblages and P-T estimate calculations often represent prevailing thermal gradients that are retained for a particular moment in time during the petrogenesis of metamorphic rocks. However, rocks may also retain mineralogical and compositional features acquired early in their development, in addition to further changes occurring

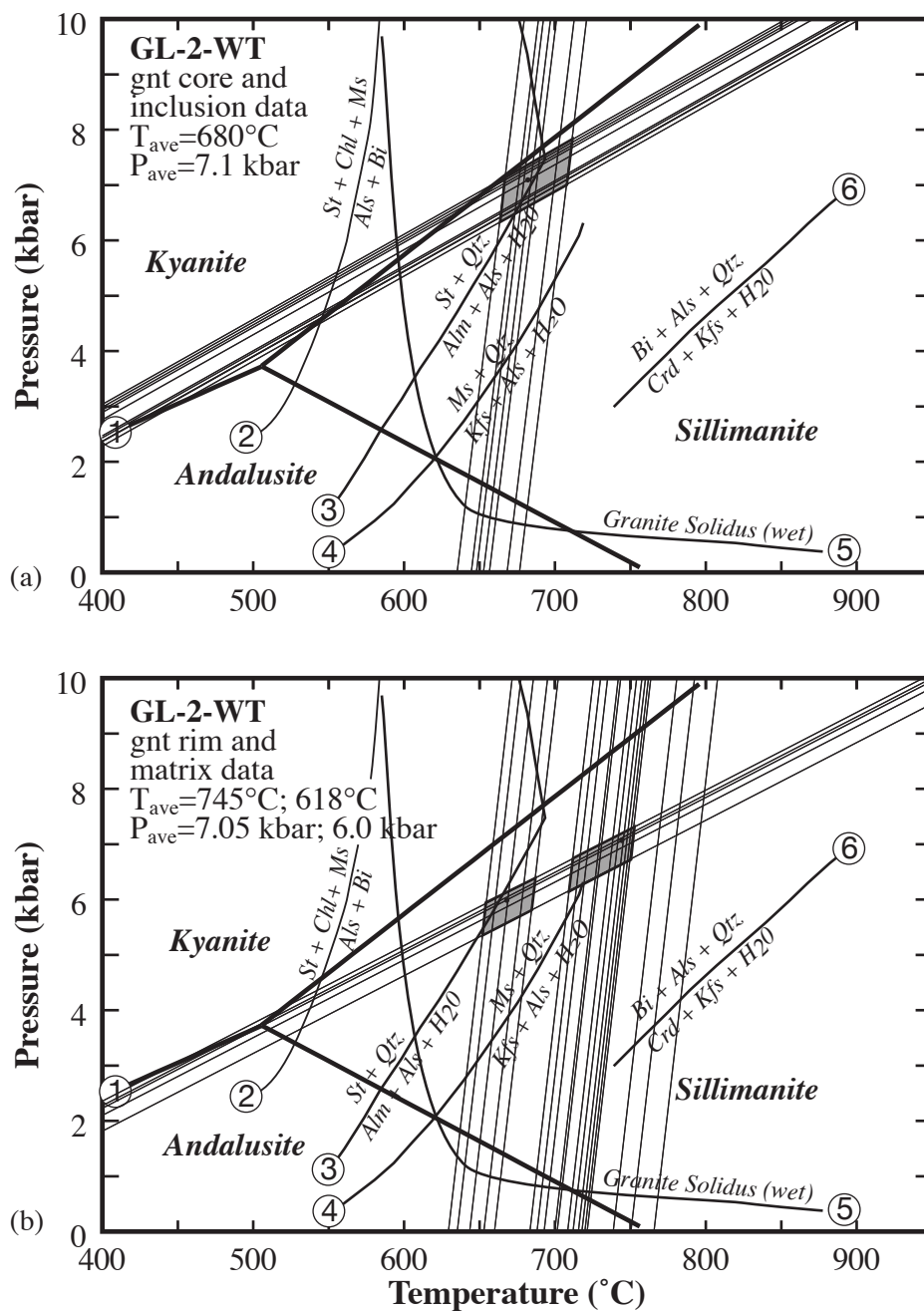


Figure 2-30. Temperature and pressure estimates for sample GL-2-WT. (a) Average garnet core compositions are used with average biotite and feldspar inclusion data for thermobarometry. (b) Average garnet rim compositions were used with matrix biotite, matrix feldspar, and near-rim biotite and feldspar composition data for thermobarometry. Univariant curves plotted are: (1) Holdaway (1971); (2) Albee (1965); (3) Pigage and Greenwood (1982); (4) Chatterjee and Johannes (1974); (5) Luth et al. (1964); and (6) Holdaway and Lee (1977). St=staurolite, Chl=chlorite, Ms=moscovite, Als=aluminum silicate, Bi=biotite, Qtz=quartz, Alm=almandine, Kfs=potassium feldspar, Crd=cordierite.

during progressive metamorphism. Assuming that garnets in all samples continuously developed during progressive metamorphism, a P-T path can be constructed by comparing P-T estimates from different zones within the garnet (i.e., comparing garnet core estimates with garnet rim estimates).

Analyses selected for P-T estimates were separated into three distinct groups based on the position of the phases relative to the garnet: (1) garnet core and near-core inclusion phase data, yielding high pressure/high temperature conditions lying in the kyanite stability field; (2) garnet rim and near-rim inclusion data, yielding higher pressure/higher temperature than group 1 and plotting near the kyanite-sillimanite stability field boundary; and (3) garnet rim and matrix phase data, yielding lower temperature/lower pressure estimates than groups 1 or 2 and falling in the sillimanite stability field exclusively (Fig. 2-31). When combined, all three groups represent a clockwise prograde metamorphic path recording an initial high pressure phase, followed by a high temperature/high pressure phase, followed by a lower temperature/lower pressure phase during garnet growth. The validity of this prograde P-T path is supported by the recognition of prograde assemblage relationships (sillimanite pseudomorphing kyanite [Figs. 2-18 and 2-24]).

In attempts to characterize metamorphic belts in orogenic cores, several authors have presented models to describe the process of progressive metamorphism during orogenesis. England and Richardson (1977), in considering the thermal consequences of crustal thickening and accretionary processes during metamorphism, concluded that rocks beneath a large thrust undergo an initial rapid increase in pressure, followed by a gradual increase in temperature. Furthermore, uplift produces a drop in pressure, followed by cooling during unroofing and exhumation. Conditions of initial high pressures, followed by high temperatures and lower pressures produce a clockwise P-T path, representing prograde metamorphism. Yardley (1989) noted that, whenever possible, P-T paths should be mimicked by mineral assemblage associations. Further modeling has shown that clockwise P-T paths are typical of regions in which continental crust has been overthickened and successively cooled by uplift and exhumation (e.g., England and Thompson, 1984; Thompson and England, 1984).

Timing of Metamorphism

Polymetamorphic terranes often preclude a simple interpretation of their temporal characteristics due to overprinting and retrograding processes. Recent advances in geochronologic techniques have significantly improved constraints on the timing of

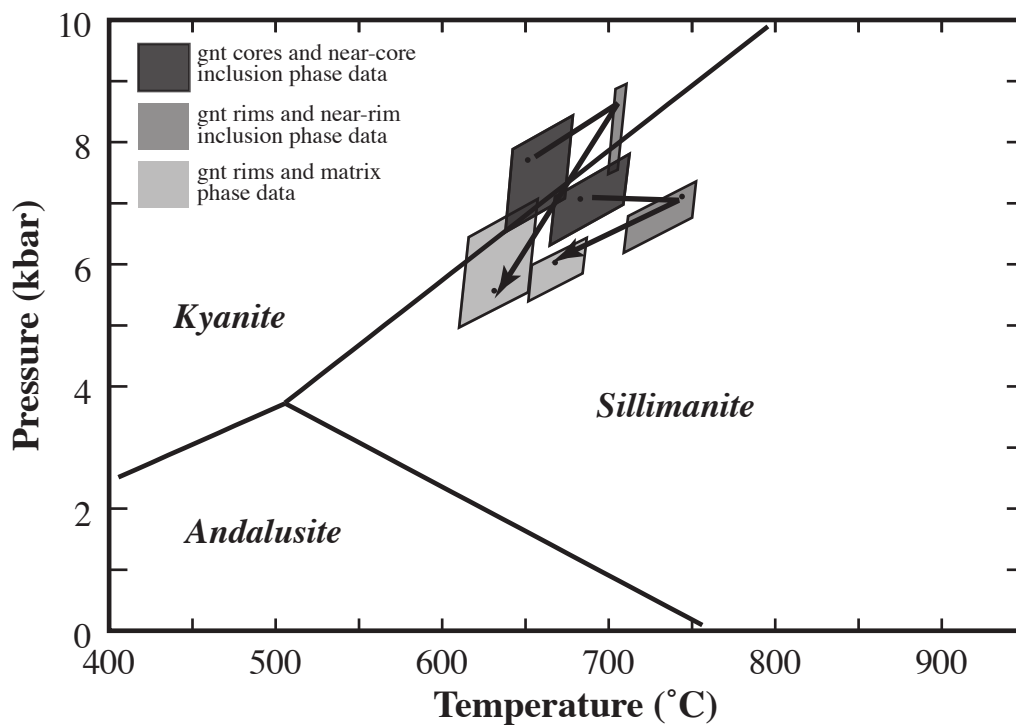


Figure 2-31. P-T path for eastern IP lithologies from the study area. A the prograde clockwise path is indicated for all samples when divided into groups based on position of phases relative to the associated garnet. Note that the prograde progression from kyanite to sillimanite is supported by petrographic textures.

metamorphism in the IP, however, and greatly increased our understanding of the timing of crystalline thrust sheet emplacement in the IP. Several recent studies have employed a variety of methods for delimiting the timing of IP metamorphism, such as U-Pb TIMS (thermal ionization mass spectrometry) monazite ages (e.g., Dennis and Wright, 1997a, 1997b; Mirante and Patino-Douce, 2000), $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende cooling ages (e.g. Dallmeyer, 1988), and SHRIMP U-Pb zircon rim analyses (e.g. Bream, 2003; Part V, this study). Consistent igneous and metamorphic age dates for IP lithologies indicate significant igneous and metamorphic events occurred from 360-340 Ma and from 320-330 Ma. Based on the recognition of a 360-340 Ma thermal event in the IP, Kohn (2001) suggested the term “Neoacadian” be employed. Pre-Neoacadian tectono-thermal events are also recognized in each terrane, although significantly overprinted. The Neoacadian is now recognized as the first shared thermal event between the eastern and western IP.

Eastern and western IP lithologies share a common Barrovian-style metamorphic history for the Neoacadian and Alleghanian orogens. P-T estimates and geochronology from both indicate that similar environmental conditions were experienced by each at approximately the same time. Therefore, it is likely that both experienced upper-amphibolite facies metamorphism during the Neoacadian (360-340 Ma) orogeny. Terrane accretion is likely synmetamorphic and associated with the emplacement of the BCFZ.

CONCLUSIONS

1. New mapping indicates that units originally recognized in the southwestern Brushy Mountains are continuous to the northeast.
2. Two lithotectonic packages are recognized for the northeastern IP and consist of fourteen distinctive lithologies.
3. The three-part stratigraphy of the Tallulah Falls Formation can be recognized in the study area, consisting of upper and lower graywacke-amphibolite units separated by a thin garnet-aluminous schist member.
4. Outcrop patterns and mylonitic textures proximal to lithologic contacts indicate a fault contact between disconnected pods and map-scale boudins of Henderson Gneiss and the underlying Tallulah Falls Formation.
5. The Brindle Creek fault is continuous throughout the Moravian Falls quadrangle and folded to the northeast, exposing western IP lithologies in a reentrant.
6. Textural evidence suggests that the contact between the Silurian Brooks Crossroads pluton and the Brindle Creek thrust sheet is faulted, and the pluton is exposed in a window.

7. The Hibriten gneiss is located entirely within the BCFZ, consists of various eastern and western IP lithologies, displays prominent block-in-matrix structure, contains lithologies ranging from mylonite to ultramylonite, and represents a crustal-scale lithologic blending zone. These relationships warrant renaming of this lithology to the Hibriten mylonite.
8. The Walker Top Granite occurs within the BCFZ in the northeastern IP, indicating a sill-like intrusive body located along the base of the Brindle Creek thrust sheet, exposed along deep crustal shear zones and faults.
9. Metamorphic mineral assemblages, pseudomorph textures, and ubiquitous migmatization suggest a prograde metamorphic path from kyanite-grade conditions to sillimanite-grade conditions.
10. Sillimanite II assemblages are not present in pelitic metasedimentary or metaigneous units in the study area. Only sillimanite I assemblages were observed in hand sample and thin section.
11. Retrograde greenschist metamorphic overprint is restricted to the Alleghanian BFZ northwest of the Mill Spring fault.
12. Garnets from selected EMP samples are chemically zoned with respect to FeO, MgO, CaO, and MnO, and display chemical zonation profiles typical of thermal diffusion.
13. P-T estimates from the Walker Top Granite yield peak-metamorphic conditions of 745°C and 7.1 kbar, during Neocadian metamorphism.
14. A prograde, clockwise (Barrovian) metamorphic path, reaching upper-amphibolite facies is recorded by garnets from the base of the Brindle Creek thrust sheet. The validity of this path is supported by prograde mineral assemblage textures of sillimanite pseudomorphing kyanite.

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PART III

Structural Geology of Part of the Northeastern Inner Piedmont: New Mapping Reveals Important Structural and Timing Relationships

ABSTRACT

Structural observations and fabric analyses from the northeastern Inner Piedmont (IP) reveal a polyphase deformational history and retain evidence for six orogenic pulses. Fabric and crosscutting relationships from four map-scale fault zones provide direct information about successive deformation sequences. The presence of the Neoacadian Brevard fault zone (BFZ) and the Neoacadian Brindle Creek fault zone (BCFZ) provides an opportunity to study the interactions between two crustal-scale fault zones in the northeastern IP. The Tumblebug Creek fault zone (TCFZ) placed mylonitic Henderson Gneiss over metasedimentary lithologies of the Tallulah Falls Formation and is discontinuous across the northwestern portion of the study area. The Mill Spring fault zone (MSFZ) is recognized as a late dextral strike-slip fault related to strike-slip movement along the Alleghanian BFZ. The BCFZ, a Neoacadian terrane boundary, is continuous from SW to NE across the study area and is embayed to the NE, exposing a western IP Ordovician pluton in a reentrant. The Poplar Springs shear zone (PSSZ) is an internal shear zone to the eastern IP and is composed of map-scale sheath folds cored by transposed Devonian anatectic granitoids.

Timing constraints are provided by crosscutting relationships at the meso- and macroscales. Western IP map-scale F_1 folds developed pre-TCFZ emplacement, which must have occurred 490-360 Ma. Truncation of the PSSZ by the BCFZ indicates the development of ~407 Ma macroscale sheath folds prior to BCFZ emplacement. Dismemberment of the TCFZ must have occurred after ~360 Ma and is likely a product of Neoacadian pure shear followed by orogen-parallel transport during Alleghanian strike-slip motion along the BFZ.

Northeastern IP structures correspond to respective deformation episodes. Three Paleozoic accretionary tectonic pulses correspond to four ductile deformation episodes and were succeeded by two late extensional-dominated events. Eastern and western IP lithologies experienced spatially and temporally distinct D_1 events as indicated by fold styles, crosscutting relationships, and geochronologic constraints. D_2 and D_3 structures result from initial NW- followed by SW-directed thrusting, ductile extrusion, and terrane accretion during the Neoacadian. Deformational styles indicate a progression from ductile-to-brittle deformation during D_3 and D_4 . D_4 fabrics are invariably SW-vergent and correspond to dextral strike-slip reactivation of previously developed northeastern IP fault zones and overprint all earlier ductile fabrics. D_5 and D_6 brittle structures reflect uplift and extension

during continued uplift and Mesozoic rifting.

Three structural domains were identified. Domain I structures are strongly NE-SW oriented with southeasterly dips and correspond to a zone of constricted alignment. Domain II contains a reentrant into the Brindle Creek thrust sheet and is recognized by the deflection of planar fabrics near the fault zone. Domain III is similar to domain I, but structures dip both NW and SE, likely due to late folding episodes.

Observations and analyses from this study provide evidence for a developmental model similar to those previously developed by others. Here, western IP D_1 structures were produced by a pre-Neoacadian orogenic pulse, likely related to the 380-360 Ma Taconic orogeny. Eastern IP D_1 structures result from long-term subduction of the Cat Square terrane beneath the Carolina terrane before BCFZ emplacement, causing regionally inhomogeneous simple shear from SW-directed ductile extrusion of eastern IP lithologies and the development of map-scale sheath folds. The Neoacadian orogeny produced NW-vergent structures and produced the dominant fabrics in the IP during D_2 and D_3 . SW-vergent dextral shear fabrics were produced during D_4 resulting from Alleghanian strike-slip reactivation of existing thrust faults. Finally, brittle folding and fracturing events overprint all earlier fabrics, and result from late Alleghanian uplift, and Mesozoic and Cenozoic extensional and rifting events.

INTRODUCTION

Detailed structural studies from exhumed metamorphic cores of orogenic belts provide direct information on the internal workings of mountain chains. The Inner Piedmont comprises part of the Neoacadian and Alleghanian crystalline core of the southern Appalachians, providing an opportunity to study an exhumed Paleozoic orogenic core. Studies of deep levels of the continental crust require situations such as these for study. Numerous investigations into the structure and composition of the IP have been undertaken over the past century, which have effectively resolved apparent regional lithostratigraphies (Part II, this study), determined overall structural and kinematic trends, and produced models for comparison with studies from other orogens (e.g., Overstreet et al., 1963a, 1963b; Lemmon and Dunn, 1973a, 1973b; Heyn, 1984; Hopson and Hatcher, 1988; McConnell, 1990; Davis, 1993a; Yanagihara, 1994; Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Mersch, 2003). These studies are crucial for interpretation of the structural development of metamorphic cores.

The southern Appalachian mountain belt is the end product of three Paleozoic accretionary orogenic events, followed by late Paleozoic-early Mesozoic rifting and finally late Mesozoic and Cenozoic uplift. Paleozoic terrane accretion developed the IP and Kiokee belt as part of the Neoacadian and Alleghanian igneous and metamorphic crystalline core of the southern Appalachians. The IP is composed of an exhumed, structurally complex, polydeformed stack of transpressional type-F ductile thrust sheets. Multiple deformational events and transposition accompanied by simultaneous high-grade metamorphism during Paleozoic crystalline thrust sheet emplacement complicate deciphering its orogenic history. Overprint by semi-brittle and brittle deformational structures further complicate matters. Nevertheless, studies that incorporate integration of techniques (detailed structural mapping and analysis, combined with geochemical, geochronologic and petrological analytical techniques) have revolutionized approaches to complex problems such as these. Utilization of these techniques has led to the development of increasingly appealing tectonic models for the spatial and temporal evolution of the southern Appalachians (e.g., Bream, 2003). This study is designed to incorporate these techniques for ultimately producing a coherent model for the structural and kinematic development of the northeastern IP.

STRUCTURAL SETTING AND LOCATION OF THE STUDY AREA

The IP is a large NE-SW trending belt of high-grade para- and orthogneisses extending from eastern Alabama to northern North Carolina (Fig. 3-1). It is bounded to the northwest and southeast by large faults (Fig. 3-1). Based on recent detailed field studies from the South Mountains and Brushy Mountains in North Carolina (e.g., Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Merschat, 2003), the IP has been subdivided into eastern and western components. The Brindle Creek thrust, originally described by Giorgis (1999), was recognized by Bream et al. (2001) as the southern Appalachian Neoacadian (360-340 Ma) terrane boundary separating the eastern IP Cat Square terrane from the western IP (eastern Tugaloo terrane) (Fig. 3-1).

Western IP units lie entirely between the BFZ to the northwest and the BCFZ to the southeast (Fig. 3-1). Lithologies consist of late-Neoproterozoic to early-Paleozoic paragneisses along with Ordovician-Silurian(?) meta-igneous, -volcanic, and -sedimentary packages. Structurally, the western IP can be characterized as a stack of successive, thin, strongly northeast-southwest oriented, shallowly to moderately southeast-dipping thrust sheets (Griffin, 1969; Hatcher, 1969; Osberg et al., 1989;

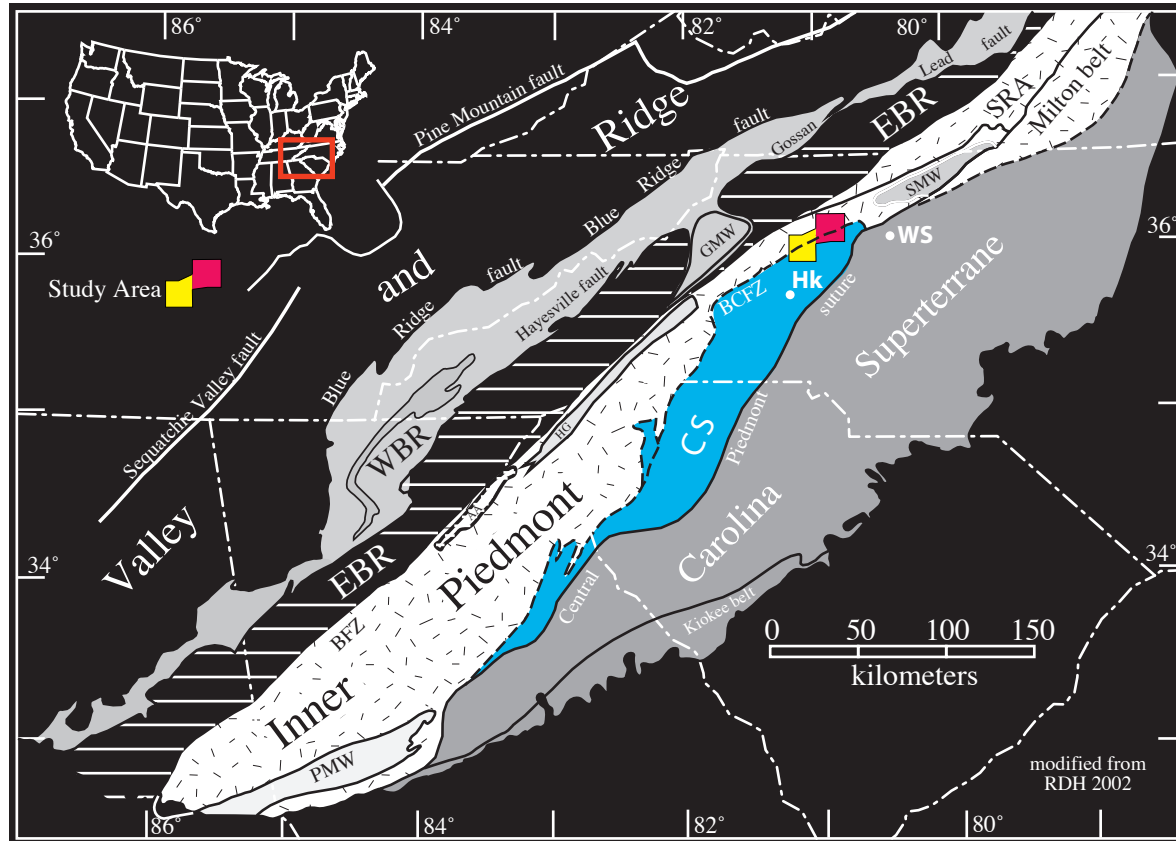


Figure 3-1. Generalized tectonic map of the southern Appalachians. Red box represents the location of present study area. Yellow box represents the location of previous detailed geologic mapping in the Brushy Mountains from Kalbas (2003 and Merschat (2003). Tectonic map of the southern Appalachians (modified from Hatcher, 2002) shows the major lithotectonic units. CS—Cat Square terrane. EBR—Eastern Blue Ridge. WBR—Western Blue Ridge. GMW—Grandfather Mountain window. PMW—Pine Mountain window. SMW—Sauratown Mountains window. BFZ—Brevard fault zone. BCFZ—Brindle Creek fault zone. AA—Alto allochthon. HG—Henderson Gneiss. SRA—Smith River allochthon. WS—Winston-Salem. Hk—Hickory.

Hatcher and Hooper, 1992; Davis, 1993; Hatcher, 1993). Micro-, meso-, and map-scale structures display consistent northeast-southwest alignment across the belt.

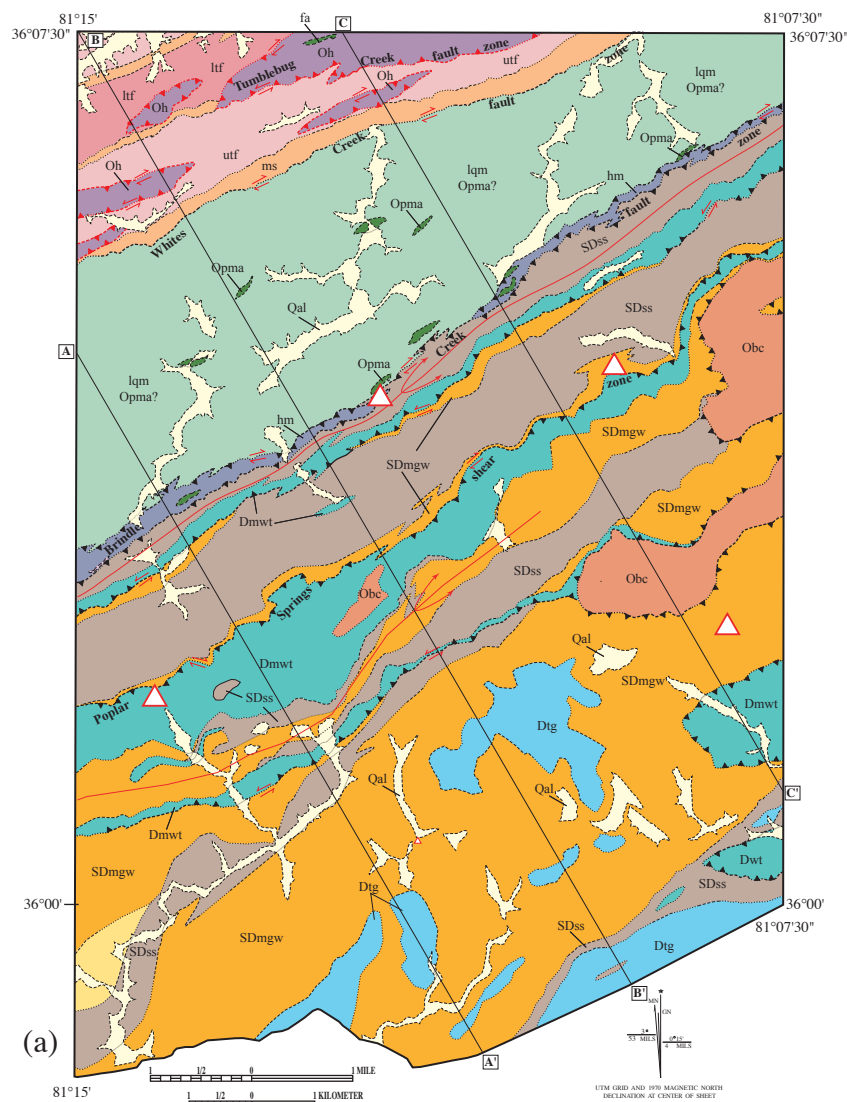
Eastern IP units are bounded by the BCFZ to the northwest and the Central Piedmont Suture to the southeast (Fig. 3-1). The Brindle Creek thrust sheet is the only lithotectonic package recognized within the eastern IP. It is composed of Silurian-Devonian metasedimentary and Devonian-Mississippian metaigneous lithologies. Several internal shear zones occur within the Brindle Creek thrust sheet. Changes in the orientations of structures from strong NE-SW alignment proximal to the BCFZ, to E-W, to N-S further to the southeast, exist across the terrane.

The Moravian Falls and Taylorsville 7.5-minute quadrangles are located in the central and northeastern Brushy Mountains, ~65 km NNE of Hickory and ~50 km W of Winston-Salem, NC (Fig. 3-1). Moderate relief and good exposure permit detailed examination of structurally complex fabrics. Large roadcuts, rock quarries, clear cut ridges, creeks, and exfoliation surfaces provide fresh exposures for detailed study. Recent property development has provided new road access to remote areas. Access to many foot traverses is provided by hunting trails, logging roads, and creek beds.

The structural geology and tectonic history of the study area make it an ideal location for studying a structurally complex area containing multiple ductile and successive brittle deformational events. This area contains a segment of the BCFZ and terrane boundary, the northeastern part of the PSSZ, and a portion of the Neocadian BFZ to the northwest, including the MSFZ, and the TCFZ (Fig. 3-2; Plate 1). The presence of four map-scale shear zones within a single 7.5-minute quadrangle provides an excellent opportunity to study several Paleozoic ductile fault zones. The close proximity of the BCFZ and the Neocadian BFZ allows for analyses of the multi-phase interaction between these crustal-scale structures, which is unique to this study. The characteristics of and relationships between these large-scale shear zones provide insight into the developmental history and workings of polyphase northeastern IP ductile deformation during successive crystalline thrust sheet emplacement.

METHODS

A detailed geologic map of the Moravian Falls quadrangle and the northwestern portion of the Taylorsville quadrangle were constructed during the course of the 2003 and 2004 field seasons (January-July). Additional field excursions were conducted as necessary for sample collection and field reviews during 2005. Field mapping utilized standard 1:24,000- and enlarged 1:12,000-scale USGS topographic quadrangles as



LITHOLOGIES

Qal Quaternary alluvium/colluvium

WESTERN INNER PIEDMONT

- Obc Ordovician Brooks Crossroads granitoid
- Lqm Opma? Lenoir Quarry migmatite/Ordovician Poor Mtn Amphibolite?
- Opma amphibolite (Ordovician Poor Mountain equivalent)
- Oh Ordovician Henderson Gneiss
- utf Upper Tallulah Falls/Ashe Formation (Cambrian?)
- ms garnet-aluminous schist
- ltf Lower Tallulah Falls/Ashe Formation (Cambrian?)
- hm hibriten mylonite

EASTERN INNER PIEDMONT

- Dwt Devonian Walker Top Granite
- Dmwt Devonian mylonitic Walker Top Granite
- Dtg Devonian Toluca Granite
- SDmgw Silurian-Devonian metagraywacke
- SDss Silurian-Devonian sillimanite schist
- SDcs Silurian-Devonian calc-silicate
- ggn granitic gneiss

MAP SYMBOLS

- Lithologic contact
- Neoacadian (~366 Ma) thrust fault (teeth located on hanging wall)
- Early Neoacadian thrust fault (teeth located on hanging wall)
- Oblique-slip fault (arrows indicate shear sense)
- Possible sheath fold axis (arrows point in direction of shear sense)
- △ Sample collected for SHRIMP geochronologic analysis

Figure 3-2. (a) Simplified geologic map of the Moravian Falls and a portion of the Taylorsville 7.5-minute quadrangles, Wilkes and Alexander Counties, North Carolina.

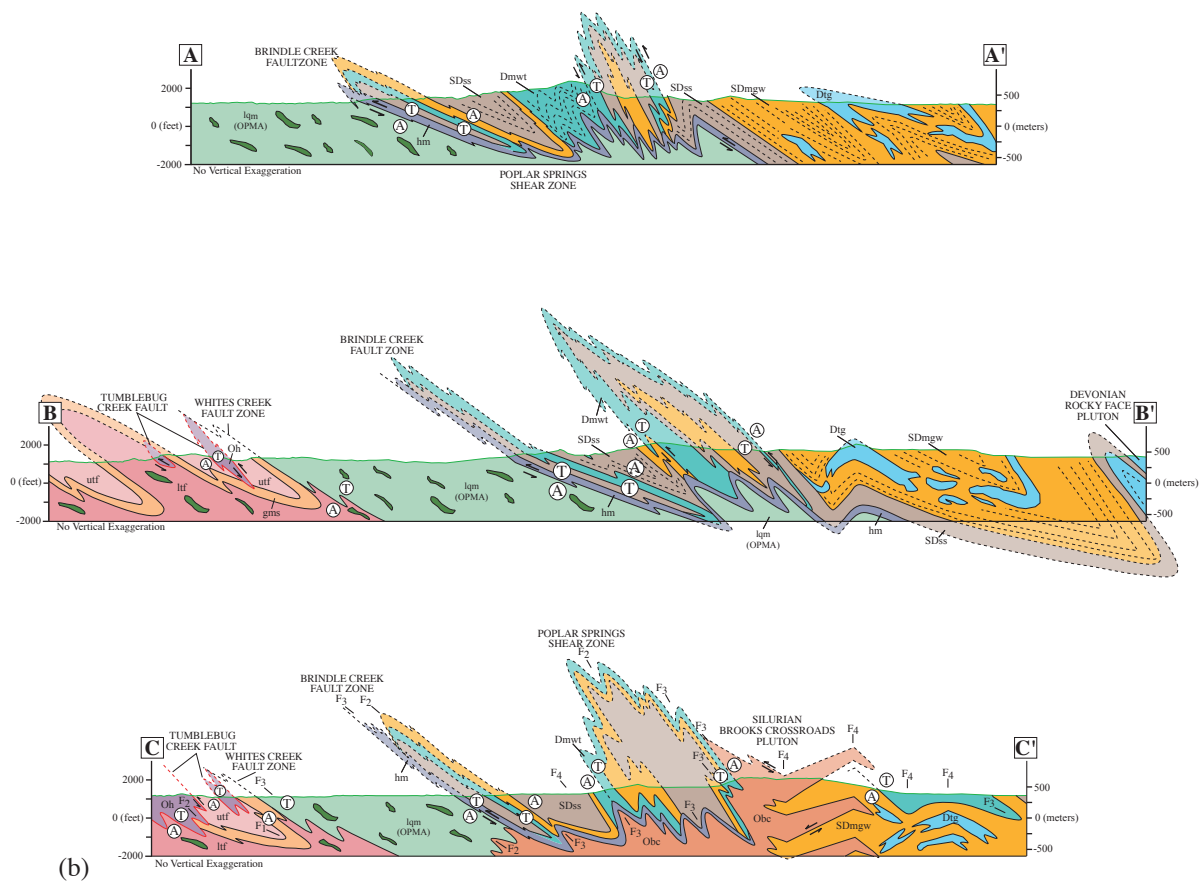
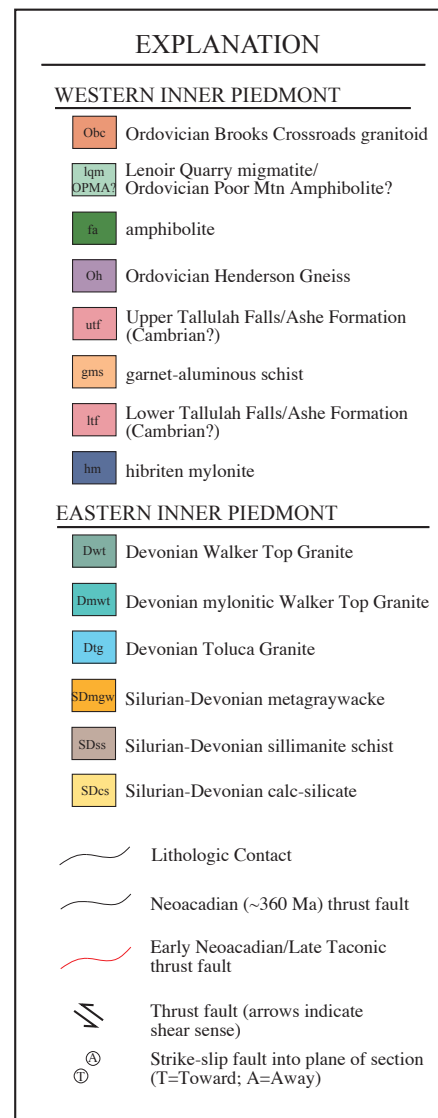


Figure 3-2 continued. (b) Cross sections A-A', B-B', and C-C'.



base maps. Structural and lithologic data were recorded at >1,700 stations (Plate 2). Orientations of structural fabrics were measured with a BruntonTM pocket transit. All structural and lithologic data, interpreted contacts, observed contacts, and float lithologies were manually plotted in the field before compiling a spreadsheet database in Microsoft ExcelTM (Appendix B) and a digital geologic map in Adobe IllustratorTM (Plate 1). All data were then georeferenced using MAPublisherTM software for Adobe IllustratorTM. Scaled field sketches were constructed, digital photographs were taken, and samples were collected for selected outcrops and cataloged by station number (Plate 2).

Structural analyses of all data were conducted on completion of all fieldwork. Coeval structures were initially grouped by their relative timing based on field observations, crosscutting relationships, and orientations. Structural domains were then identified from characteristic homogeneous and heterogeneous planar fabric orientations and separated on form-line maps. Planar and linear fabric orientations were grouped into respective domains and plotted on fabric diagrams constructed with GeoorientTM software (Holcombe, 2005). Fabric data were contoured using the percent per percent area method.

Oriented samples were collected from selected outcrops for microstructural analyses. Microstructures and petrofabrics were examined and interpreted for oriented standard (2.4 x 4.6 cm) and oversized (5.08 x 7.62 cm) thin sections.

DEFORMATION EVENTS AND TIMING

Six deformation events (D_1 - D_6) can be resolved in the study area based on field observations and structural analysis (Table 3-1). Deformation events recognized here mostly correspond to those outlined by previous workers in the IP with some modifications (e.g., Davis, 1993; Yanagihara, 1994; Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Mersch, 2003). D_1 structures were truncated and folded by later fabrics, but evidence for this is limited due to the pervasive nature of D_2 , D_3 , and D_4 fabrics. D_2 and D_3 fabrics are the most prominent in the study area and likely represent evolution of a single ductile deformational event evolving over the course of the Neoacadian orogeny. D_4 structures correspond to mylonitic fabrics associated with post-Neoacadian dextral strike-slip reactivation of large fault zones in the northeastern IP. The D_5 and D_6 events in the study area are late regional folding episodes, which are correlative with fracture and joint formation.

Relative timing constraints are provided by field observations of crosscutting relationships and orientation analyses. Modern geochronologic techniques, however,

Table 3-1. Deformation hierarchy and relative timing of deformation events in the northeastern IP, North Carolina*.

			STRUCTURES			METAMORPHIC CONDITIONS	REGIONAL EVENTS	OROGENY & TIMING
			FABRICS	FOLDS	FAULTS			
DEFORMATION EVENTS	D₁	D_{1wIP}	S ₁ local foliation preserved in boudins	F _{1wIP} : intrafolial, rootless folds; folds preserved in boudins; map-scale folds in TCFZ footwall	TCFZ emplacement	moderate pressure and temperature	arc accretion to Laurentian margin and deposition of western IP Ordovician bimodal volcanics	Taconian Orogeny 409-390 Ma
		D_{1eIP}	S ₁ regional axial planar foliation	F _{1eIP} : intrafolial and rootless folds; folds preserved in boudins; refolded recumbant, and isoclinal folds	development of CPS	high pressure, upper amphibolite, kyanite-grade; above minimum melt conditions	initial subduction of Cat Square terrane sediments beneath Carolina terrane	Acadian Orogeny intrusion of ~407 Ma Walker Top Gneiss in eIP, followed by development of PSSZ
	D₂		S ₂ : penetrative foliation; L ₂ : mineral lineation	F ₂ : reclined, tight to isoclinal, and recumbant folds; meso- and macroscale SW-vergent passive flow sheath folds	emplacement of BCFZ and truncation of PSSZ; early movement along Neoacadian BFZ	high temperature, upper amphibolite (granulite?) facies; sillimanite I and II grade; first shared thermal event between eIP and wIP	transpressional accretion of eastern IP and Carolina terrane; SW-directed ductile extrusion and crustal flow of IP	Neoacadian Orogeny 360-340 Ma
	D₃		S ₃ : rare mesoscopic foliation, subparallel to S ₂	F ₃ : folding of BCFZ; reclined, open to tight, NW-vergent folds	continued movement along ductile fault zones; initial SW-deflection of IP thrust sheets	high temperature, lower pressure conditions; sillimanite I grade	continued emplacement of eastern IP and Carolina terrane; uplift, unroofing, and cooling of IP	Late Neoacadian Orogeny
	D₄		dextral S-C and shear-related fabrics in WCFZ, TCFZ, BCFZ, and PSSZ	F ₄ : Inclined to upright, tight to closed, NW-SE trending, SW-vergent folds	ductile reactivation of BFZ; dextral oblique-slip motion on WCFZ and BCFZ in northeastern IP	lower pressure and temperature retrograde greenschist conditions	emplacement of composite Blue Ridge-Piedmont type C thrust sheet; regional dextral strike-slip motion along large faults	Alleghanian Orogeny ~325 Ma
	D₅		Joints	F ₅ : regional open, broad, trend NE & NW	brittle reactivation and dextral strike-slip motion along BFZ	low pressure and temperature brittle conditions	regional uplift, unroofing, and cooling followed by rifting	Mesozoic extension
	D₆		Joints	F ₆ : regional broad, open folds, trend NE	Meso- and macroscale normal faults	low pressure and temperature brittle conditions	continued rifting and uplift	Cenozoic uplift

*Modified from Davis, 1993; Yanagihara, 1994; Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; and Merschat, 2003. BCFZ=Brindle Creek fault zone; BFZ=Brevard fault zone; CPS=Central Piedmont suture; WCFZ=Whites Creek fault zone; PSSZ=Poplar Springs shear zone; TCFZ=Tumblebug Creek fault zone.

permit determination of absolute timing constraints. Detrital zircon geochronology has revealed the presence of a terrane boundary in the IP by indicating differing provenances for eastern and western IP metasedimentary lithologies (Bream, 2003). Additionally, igneous geochronologic data suggest that eastern and western IP terranes contain temporally distinct plutonic suites (Vinson, 1999; Mapes, 2002; Bream, 2003; Part V, this study). Crystallization age dates of IP metaigneous lithologies, combined with textural, geometric, and crosscutting relationships, delimit timing relationships for IP fabric development and orogenic pulses.

D₁ Deformation

Although the penetrative nature of successive deformational events has transposed and almost completely masked D₁ structures and fabrics in the study area, meso- and macroscale relationships convey some information about early deformational characteristics. Map-scale crosscutting relationships and differences in deformational style indicate that separate D₁ deformation events occurred for eastern and western IP terranes before emplacement of the BCFZ.

Truncated macroscale isoclinal folds in the footwall of the discontinuous TCFZ provide the best evidence for D₁ in the western IP (Fig. 3-2; Plate 1). Mesoscopic folding of the Tallulah Falls Formation stratigraphy in the western IP must have occurred prior to TCFZ emplacement, which likely occurred during the late Taconic or early Neocadian orogeny.

Eastern IP D₁ map-scale shear zones and sheath folds (PSSZ and Big Warrior sheath fold of Mersch et al., 2005) show truncation by the BCFZ (Fig. 3-2; Plate 1), indicating development of these structures prior to BCFZ emplacement. Map-scale sheath folding during regional SW-directed inhomogeneous simple shear likely developed during the early stages of D₂, and their truncation by the middle- to late-D₂ BCFZ does not imply that these are D₁ structures. Rootless and intrafolial folds along with oblique foliations preserved in boudins provide additional evidence for D₁ in both eastern and western IP terranes.

D₂ Deformation

D₂ is the most pervasive deformation event in the northeastern IP. D₂ is characterized by a strong foliation (S₂), a prominent mineral lineation (L₂), and reclined to recumbent apparent NW-vergent isoclinal folds (F₂), and is responsible for the first shared deformation and thermal event between the eastern and western IP. The apparent

NW-vergence of D_2 folds likely corresponds to parasitic folds on the northwest limb of a NE-SW trending macroscale sheath folds. The transpressive nature of D_2 caused initial W- followed by SW-directed crustal flow during the emplacement of the BCFZ. D_2 penetrative deformation produced S-L tectonites proximal to SW-directed map-scale shear zones and S-tectonites away from shear zones. Strong transposition and reorientation of earlier fabrics occurred during D_2 deformation. All D_2 fault zones appear to have developed along attenuated limbs of ductile folds, corresponding to the Type-F thrusts of Hatcher and Hooper (1992). Also, reactivation of the PSSZ and TCFZ likely took place during D_2 . NW-vergent F_2 folds are isoclinal and gently inclined to recumbent and present at micro-, meso-, and macroscales throughout the entire study area. Initial emplacement of the BCFZ and associated Neoacadian terrane accretion processes likely produced D_2 fabrics.

D_3 Deformation

D_3 deformation structures, primarily folds, are oriented parallel and subparallel to D_2 structures, and likely represent a continuation of D_2 deformation (Kalbas, 2003). F_3 folds have inclined to steeply dipping axial surfaces and more open geometries than F_2 folds. Furthermore, the distinction between F_2 and F_3 can easily be made at the outcrop scale, as Type-3 interference patterns are common between F_2 and F_3 folds. Similar orientations of F_2 and F_3 fold axes, however, suggest they are genetically related (discussed below).

Although D_3 structures are inherently different from D_2 structures, they most likely result from the later stages of a mid-Paleozoic Neoacadian event that initially produced D_2 structures. Cooling and uplift during continued thrust sheet emplacement could have altered deformational styles and rheologies, thus producing D_3 structures.

D_4 Deformation

D_4 fabrics are the result of dextral strike-slip fault zones occurring within and between large thrust sheets. SW-vergent folds (F_4) and NW-SE-trending crenulations indicate SW-directed transport. Mylonitic S-C fabrics in shear zones overprint earlier D_2 and D_3 structures. Undulose extinction and retrograde metamorphic textures in completely recrystallized mylonites indicate that this episode of deformation took place under much lower temperature conditions than previous deformational events. Furthermore, D_4 fabrics result from different deformational styles than prior deformation events; very little evidence exists for low-temperature strike-slip motion between thrust

sheets before D_4 . D_4 features can largely be attributed to late-Neoacadian to Alleghanian strike-slip movement on the BFZ, causing reactivation and development of other large fault zones in the northeastern IP.

D_5 and D_6 Deformation

The transition from ductile to brittle deformational styles most likely occurred between late D_4 and early D_5 events. Refolded macro- and mesoscopic fold geometries, dome-and-basin fold interference patterns, and brittle structures resulted from D_5 and D_6 deformation (Plate 1; Table 3-1). D_5 is a late folding event that produced upright open folds oblique to D_4 structures and sub-parallel to D_2 and D_3 structures. Deformation occurring during D_5 and D_6 events is coeval or prior to the development of joint sets observed in all outcrops in the study area and is likely related to Mesozoic rifting and/or Cenozoic uplift after the Alleghanian orogeny.

MACROSCOPIC STRUCTURES

Macroscopic structural relationships in the study area are best illustrated by the cross sections in Plate 1. These structures, excluding the F_1 folds in the footwall of the TCFZ and map-scale sheath folds in the PSSZ, can mostly be attributed to ductile deformation and faulting occurring during D_2 , D_3 and D_4 . Map-scale features include large folds, faults, and lithostratigraphic relationships, and provide timing constraints for northeastern IP orogenic events. Transposition of lithologies and fabrics is evident from the along-strike continuity of units and structures (Plate 1). Polyphase deformation is manifested by map-scale truncation and multi-phase folding of structures and lithologies. At the regional scale, map patterns reveal the dominance of ductile D_2 and D_3 structures in the study area.

Western Inner Piedmont (Marion thrust sheet)

Western IP units present in the study area include the Tallulah Falls Formation stratigraphy, the Ordovician Henderson Gneiss, and a migmatitic bimodal volcanic equivalent of the Poor Mountain Formation (Fig. 3-2; Plate 1). Map patterns and petrographic characteristics reveal the presence of the Tallulah Falls Formation stratigraphy in the northwesternmost portion of the study area. Stratigraphic relationships indicate that these units are folded into map-scale northeast-plunging anticline-syncline pairs (Plate 1). Observation of map-scale folding is consistent with map patterns observed in the South Mountains (IP) (e.g., Bream, 1999; Hill, 1999) and in the eastern

Blue Ridge of northeast Georgia and northeastern South Carolina.

The Henderson Gneiss overlies the Tallulah Falls Formation everywhere in fault contact. It is the most areally extensive igneous body of the North and South Carolina IP. However, the nature and origin of the Henderson Gneiss has been a topic of considerable interest and debate among southern Appalachian geologists for the past few decades, despite numerous studies undertaken to resolve this issue. Several workers have attempted to provide petrogenetic and structural interpretations of the Henderson Gneiss and its relationship to the BFZ (e.g., Reed and Bryant, 1964; Bryant and Reed, 1970; Lemmon, 1973; Odom and Fullagar, 1973; Roper and Dunn, 1973; Lemmon and Dunn, 1975). More recent detailed studies in the Columbus Promontory (e.g., Davis, 1993), and from the South Mountains (e.g., Bream, 1999; Hill, 1999) have concluded that Henderson Gneiss bodies within the Marion thrust sheet are completely enclosed by the TCFZ.

Although considerable effort has been made to resolve the nature of the Henderson Gneiss, few studies have been undertaken northeast of the main outcrop body. Kalbas (2003) interpreted Henderson Gneiss lithologies to be fault bounded just NW of the southwestern Brushy Mountains, although very little of this lithology was mapped in detail (Plate 3). Textural and contact relationships from the northeastern Brushy Mountains observed in this study indicate that the contact with the underlying metasedimentary units is a fault zone. Sharp contacts, mylonitic textures, truncation of map-scale structures and mesofabrics, and outcrop patterns indicate that a fault contact envelopes Henderson Gneiss bodies recognized in this study.

A series of disconnected lenticular bodies of Henderson Gneiss occurs in the northwestern Moravian Falls quadrangle (Fig. 3-2; Plate 1). Considering the age and polydeformational history of the Henderson Gneiss, it is likely that this map pattern is the product of several deformational events. Crystallization ages, petrologic characteristics, and fabrics suggest that the Henderson Gneiss is likely an early Paleozoic intrusive body that has been successively deformed and metamorphosed (Odom and Fullagar, 1973; Sinha and Glover, 1978; Harper and Fullagar, 1981; Fullagar et al., 1997; Carrigan et al., 2001; Merschat et al., 2005).

Map-scale features in the western IP provide important relative controls on the timing of deformational events. Relationships of Henderson Gneiss bodies with Tallulah Falls Formation stratigraphy, crosscutting faults, and stratigraphic relationships afford first-order relative timing constraints.

Truncation of map-scale F_1 folds in the Tallulah Falls Formation suggests that the Henderson Gneiss was intruded elsewhere and then thrust over western IP lithologies

during a later, possibly unrelated, thrusting event (Hatcher, 2002; Merschhat et al., 2005). Considering the age of the Tallulah Falls Formation (Neoproterozoic-Cambrian) and Ordovician crystallization ages of the Henderson Gneiss (~490 Ma; Carrigan et al., 2001), western IP map-scale folding is likely the result of pre- to syn-Taconian (480-460 Ma) deformation. Thus, the timing of fault emplacement of the Henderson Gneiss would be restricted to syn- to post-Taconian time, with the early Neoacadian a likely possibility. Additionally, folded fault contacts, petrofabrics, and outcrop patterns suggest that after thrust emplacement, the Henderson Gneiss and Tallulah Falls stratigraphy were deformed together, developing the observed map-scale boudinage patterns due to strain partitioning between these units. Neoacadian thrust emplacement of the Brindle Creek sheet is a likely candidate for causing this style of deformation. If initial Neoacadian thrusting was northwest-directed, then A-type subduction of western IP lithologies beneath the eastern IP and Carolina terrane could have produced structures such as these by causing extensive pure shear and northeast-southwest extension. Additionally, dextral strike-slip movement between northeastern IP thrust sheets during D_4 could have further dismembered these bodies by reactivating earlier fault zones. Evidence for strike-parallel transport under moderate P-T conditions can be seen in meso- and microscale structures along the TCFZ (discussed below).

Map-scale lenses and boudins resulting from northeast-southwest extension are successively pulled apart along the Neoacadian BFZ. Dextral strike-slip movement between the Neoacadian BFZ and BCFZ could have produced this style and pattern of deformation. Mylonitic fabrics observed in the Tallulah Falls Formation and all occurrences of Henderson Gneiss invariably display top-to-the-SW shear sense, indicating dextral strike-slip motion along the mid-Paleozoic BFZ. Also, ubiquitous top-to-the-SW kinematic indicators throughout the study area suggest a strike-slip component of dextral shear for all thrust sheets of the BFZ and BCFZ. Furthermore, truncation of map-scale lenses of Henderson Gneiss by the MSFZ (Plate 1) provides an upper bound on the timing of juxtaposition between the Henderson Gneiss and Tallulah Falls Formation in the northeastern IP, indicating that the MSFZ is younger than the TCFZ. Additionally, truncation of the chlorite isograd in the western IP indicates that the MSFZ is younger than the retrograde greenschist metamorphism in the Neoacadian BFZ.

Finally, provided that stratigraphic correlations are correct, the MSFZ cannot thrust Ordovician Poor Mountain Formation metavolcanic equivalents over the older (Neoproterozoic-Cambrian?) Tallulah Falls Formation stratigraphy. S-C intersection lineations mostly plunge down dip within the fault zone (discussed below), indicating

dextral (top-to-the-SW) strike-slip movement along the MSFZ, and provide little evidence for thrust motion. This evidence, combined with the steep (60-65°) dip of the fault zone, further supports strike-slip motion along the MSFZ. Therefore, I suggest that the MSFZ in the northeastern IP is a late (Alleghanian?) strike-slip fault, juxtaposing Ordovician metavolcanic packages with disconnected Henderson Gneiss bodies and Tallulah Falls Formation metasediments of the Marion thrust sheet.

Eastern Inner Piedmont (Brindle Creek thrust sheet)

The BCFZ, a terrane boundary, juxtaposes high-grade metasedimentary and metaigneous rocks of mixed affinity against western IP lithologies of Laurentian affinity (Giorgis, 1999; Williams, 2000; Hatcher, 2002; Bream, 2003). Field observations of lithologic relationships, block-in-matrix structures, and shear zone fabrics indicate that the BCFZ is a crustal-scale shear zone in which mixing of eastern and western IP lithologies has occurred. Outcrop patterns indicate that the frontal boundary of the BCFZ is a mylonite zone, continuous across the study area from southwest to northeast, juxtaposing eastern IP lithologies against western IP metavolcanic packages (Fig. 3-2; Plate 1). To the east and northeast, however, the Brindle Creek thrust sheet is juxtaposed against a different western IP metaigneous unit, exposing a large portion of the ~427 Ma Brooks Crossroads pluton in a reentrant (Fig. 3-2; Plate 1).

Also present within the Brindle Creek thrust sheet is the PSSZ, an internal shear zone to the eastern IP (Fig. 3-2; Plate 1). The PSSZ is recognized by the presence of mylonite zones within map-scale bodies of the Walker Top Granite. As with the Henderson Gneiss in the western IP, the nature and origin of the Walker Top Gneiss in the eastern IP has been a recent topic of considerable interest (Giorgis, 1999; Giorgis et al., 2002; Mapes, 2002). Early reconnaissance mapping recognized the Walker Top Gneiss, but correlated it with the Henderson Gneiss, based on textural and mineralogical similarities (e.g., Rankin et al., 1972; Goldsmith et al., 1988). New mapping and modern geochronology have demonstrated that the Walker Top Granite is not spatially or temporally correlative with the Henderson Gneiss, and is restricted to the eastern IP (Giorgis, 1999; Williams, 2000; Bier, 2001; Giorgis et al., 2002; Mapes, 2002; Kalbas, 2003; Mersch, 2003; Wilson, 2006).

The nature of contacts bounding the Walker Top Granite is an important relationship to consider in determining its petrogenesis and relationship to other eastern IP lithologies. Map patterns, field evidence, and contact relationships from this study suggest an initial intrusive contact between the Walker Top Granite and

enclosing metasedimentary lithologies, followed by ductile flow and faulting during the development of shear zones and map-scale sheath folds during D_1 . Map geometries of continuous tabular-shaped bands (Plate 3), sharp and concordant contacts with enveloping metasedimentary units, and the presence of abundant xenoliths infer that initial intrusive contacts have been successively transposed into a sill-like body. Mylonitic textures and crosscutting fabrics suggest that transposed sills of Walker Top Granite are in fault contact with the metasedimentary lithologies. The occurrence of a band of Walker Top Granite within the BCFZ and its repetition at map-scale from northwest to southeast implies that tabular sills of this lithology exist near the lowermost Brindle Creek thrust sheet, which is re-imbricated several times to the southeast (Plates 1 and 3). A discernable mechanical stratigraphy for the eastern IP is not evident, because imbricated units are not repeated in an ordered succession (Plate 1). This is likely a result of mechanical transposition of stratigraphies followed by dismemberment and transport resulting from inhomogeneous simple shear during intense ductile deformation within the eastern IP.

Four bands of Walker Top Granite are laterally continuous across the Moravian Falls quadrangle (Fig. 3-2; Plate 1), including the band present in the BCFZ. Northwesternmost bands are associated with the BCFZ, while additional laterally continuous bands are restricted to the PSSZ (Fig. 3-2; Plate 1). Additional lenticular-shaped pods that parallel the regional trend are also sporadically present throughout the study area (Fig. 3-2; Plates 1 and 3). Mersch (2003) and Mersch et al. (2005) interpreted similar geometries to the SW as map-scale sheath folds, based on map patterns and deformational styles. Walker Top Granite bodies in the northeastern Brushy Mountains are exclusively mylonitic. This evidence supports the interpretation of an imbricated Brindle Creek thrust sheet raising sill-like bodies of Walker Top Granite from near the bottom of a mechanical stratigraphy. This evidence, however, may also support the macroscale sheath fold interpretation. Regardless of which interpretation of these geometries is correct, tabular bodies of Walker Top Granite are exposed in map-scale shear zones in the northeastern IP. Therefore, cross-section interpretations showing Walker Top Granite bodies associated with map-scale sheath folds are based on map patterns, deformational style, and recognition of outcrop-scale structures of this nature (Plate 1).

The restriction of the PSSZ and related shear zones to the eastern IP has temporally significant consequences. My mapping initially recognized the truncation of the PSSZ by the BCFZ, exposing the Brooks Crossroads pluton near the eastern boundary

of the Moravian Falls quadrangle (Fig. 3-2; Plate 1). This relationship provides two important constraints on the timing of BCFZ emplacement: (1) the BCFZ must post-date the age of the Brooks Crossroads pluton (~461 Ma; Vinson, 1999); and (2) transposition of the Walker Top Granite bodies into regional fabrics, development of the PSSZ during imbrication of the Brindle Creek thrust sheet, and emplacement of the BCFZ must postdate crystallization of the Walker Top Granite (~407 Ma; see Part V). Furthermore, folded map patterns indicate that later folding of the Brindle Creek thrust sheet and western IP lithologies took place simultaneously after BCFZ emplacement.

A large body of the Devonian Toluca Granite outcrops in the southern portion of the study area (Fig. 3-2; Plate 1). Correlation of this lithology with a granitic body located in the southern portion of the Ellendale quadrangle (Plate 3), is based on textural and compositional similarities to units described by Merschat (2003). A missing contact aureole, interfingering margins with metasedimentary units, transposition of structures, and continuous fabrics across lithologic contacts, suggest that these bodies are catazonal plutons. Merschat (2003) inferred that Toluca Granite bodies in the central Brushy Mountains are fault-bounded, based on sharp contacts with encompassing metasedimentary units. Mapes (2002), citing geochemical similarities, concluded that Toluca Granite bodies in the IP are the result of voluminous anatexis of adjacent metasedimentary units, and that the contact is intrusive. Map patterns from this study show similar geometries to those present to the southwest (Plate 3), although an alternative structural interpretation is possible.

Map patterns of Toluca Granite bodies in the northeastern Brushy Mountains suggest that tabular-shaped intrusive bodies have been transposed into the regional structural trend, successively folded, and dismembered contemporaneously with enveloping metasedimentary assemblages (Plates 1 and 3). Abundant xenoliths, sharp and interlayered contacts with adjacent metasedimentary units, high-grade metamorphic and migmatitic country rock, and transposition of structures also infer catazonal plutons. Mylonitic fabrics truncate lithologic contacts, however, indicating that Toluca Granite bodies were intruded and then deformed simultaneously with adjoining metagraywacke and schist lithologies. Preferred geometric interpretations of Toluca Granite outcrops included in this study therefore show a transposed, folded, and dismembered intrusive body, accounting for observed map patterns (Plate 1).

MESOSCOPIC AND MICROSCOPIC STRUCTURES

Outcrop-scale relationships provide the most direct and accessible means of resolving deformation sequences in polydeformed terranes. Overprinting and crosscutting relationships can be readily observed in many exposures in the study area. Mesoscale observations are of particular importance for resolving associations of multiple fold and axial planar foliation generations. Analyses of mesoscopic textures and fabrics are crucial for determining contact relationships, structural orientations, and deformational styles of successive orogenic pulses.

Microstructures also convey valuable information about deformational sequences, transport directions and kinematics, and deformational style in high-grade metamorphic cores. Structural relationships observed in thin section generally support those recognized in outcrop and provide additional relative timing constraints to those provided by mesoscopic observations.

Foliations

Deformation-related foliations constitute the dominant planar fabrics displayed by rock units in the study area. These are differentiated from primary foliations on the basis of: lack of primary sedimentary structures; limited thickness variation; heterogeneous layer compositions; the presence of anastomosing or lensoid layering; symmetry planes parallel to layering; and similar orientations to axial surfaces of earlier fold generations (Passchier and Trouw, 1998). Although remnant compositional layering is present in the Tallulah Falls Formation and eastern IP metasedimentary lithologies, transposition, high-grade metamorphism, and migmatization have masked primary sedimentary structures.

A rare early foliation, S_1 , is preserved in intrafolial folds, boudins, and xenoliths, and is obliquely oriented to later foliations. Hopson and Hatcher (1988) identified S_1 in the Alto allochthon and western IP as F_1 axial planar gneissic layering. Davis (1993), working in the Columbus Promontory, also noted the preservation of S_1 gneissic layering in rootless F_1 folds in boudins. Moreover, Bryant and Reed (1970), working west of Lenoir, North Carolina, recognized oblique foliations truncated by later fabrics, which likely correspond to S_1 foliations observed in this study. Because of the penetrative nature of later foliations, however, it is not possible to determine the nature and extent of pre- D_2 structures.

Penetrative S_2 foliation (Fig. 3-3) constitutes the dominant foliation in the study area. It transposed all earlier fabrics except local relict F_1 folds and S_1 foliations preserved in boudins, and likely corresponds to S_2 fabrics recognized by previous

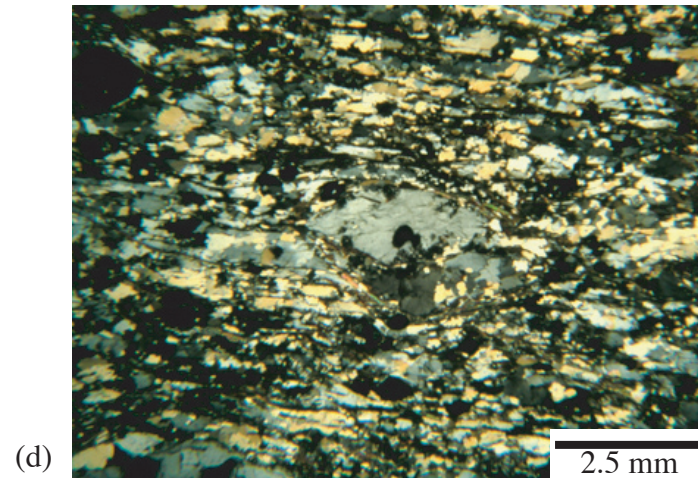


Figure 3-3. S_2 foliations in the study area. (a) Mylonitic quarry block of Walker Top Granite from Vulcan Materials 115 Quarry. Photo by R.D.Hatcher. (b) Strongly foliated Walker Top Granite near Bald Rock Mountain. (c) S_2 foliation and boudinaged migmatitic layering in metagraywacke near Brushy Mountain (MV-478). (d) Photomicrograph of ultramylonitic Walker Top Granite from the BCFZ (MV-564) showing a strong S_2 foliation defined by biotite, quartz, and K-feldspar.

investigators. Numerous IP geologists have documented the presence of a dominant S_2 foliation, noting the parallel nature of foliation, compositional layering, lithologic contacts, early fold axial surfaces, and faults (Hopson and Hatcher, 1988; Davis, 1993; Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Mersch, 2003). These studies have concluded that D_2 structures are likely the products of Neocadian penetrative deformation, high-grade metamorphism, and migmatization, citing field, petrographic, and geochronologic evidence.

In the northeastern IP, S_2 is defined by transposed compositional and migmatitic layering at the outcrop scale and a parallel alignment of quartz, biotite, muscovite, feldspar, and/or sillimanite at the microscale, depending on lithology (Fig. 3-3). All lithologies display S_2 planar fabrics on all scales. Transposed compositional layering in metasedimentary and metavolcanic lithologies is attributed to the same S_2 foliation-producing event based on the meso- and macroscale parallelism of the two surfaces; therefore, both are collectively referred to as S_2 .

S_2 foliation measurements were collected for approximately 1,700 stations in the Moravian Falls and northernmost Taylorsville quadrangles (Plate 1; Appendix B). Foliation generally strikes NE-SW, is orogen-parallel, and dips moderately SE. Contoured poles to S_2 foliation measurements have a mean orientation of 054/47SE (Fig. 3-4). Although most measurements indicate southeasterly dip, northwest-dipping foliation are present and somewhat problematic. Anomalous dip directions are best explained by late (D_5 and D_6), open, NE-trending folding events, which effectively reorient existing fabrics (discussed below).

Meso- and microscopic shear surfaces (C-planes) are common in large shear zones, but also occur in localized mesoscopic high-strain areas, especially in schistose lithologies. Where present, C-planes truncate earlier S-planes, which are oriented obliquely to shear planes, and invariably display top-to-the-SW shear sense (Fig. 3-5). C-surfaces generally parallel shear zone boundaries and trend NE-SW with steep southeasterly dips. Although very difficult to measure in outcrop, S-surfaces in shear zones generally trend NW-SE and dip steeply to the NE. C-foliation measurements recorded during this study are designated C_4 because of geometric relationships between S-C intersection lineations, F_4 folds, and F_4 crenulation axes (discussed below).

Lineations

Abundant mineral lineations in the study area are defined mostly by the alignment of feldspar, hornblende, quartz, and sillimanite grains (Fig. 3-6). Other elongate or

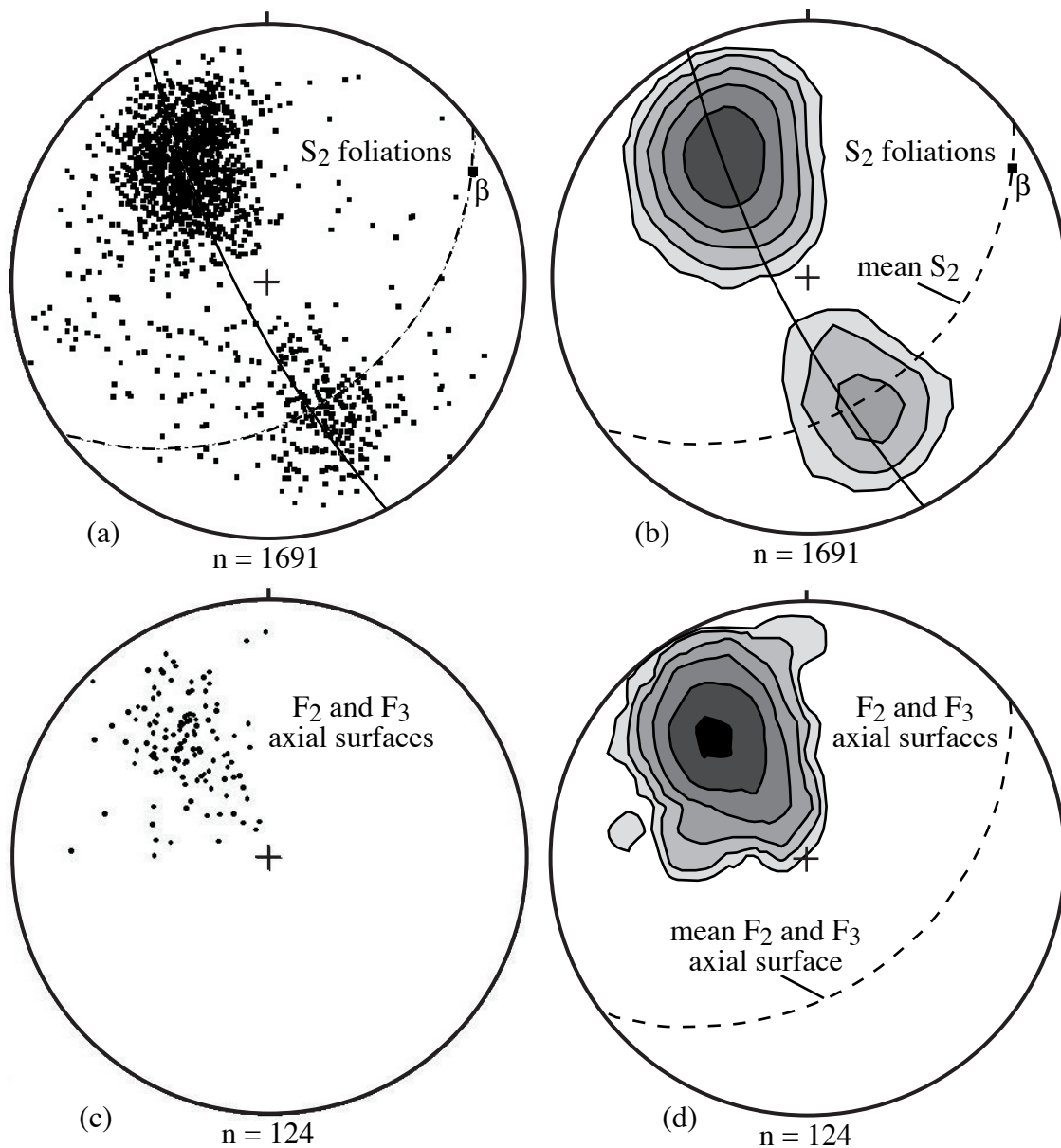


Figure 3-4. Scatter plots and fabric diagrams for all S₂, F₂, and F₃ axial surface measurements obtained in the study area. (a) Lower-hemisphere, equal-area scatter plot of 1691 poles to S₂ planes. The plunge and trend of the β -axis is 9→063. This line is parallel to F₅ fold hinges. The strike and dip of the best-fit great circle (solid line) is 333/81SW. (b) Contoured lower-hemisphere, equal-area plot of 1691 poles to S₂. Contours 1, 2, 4, 8, and 16 percent per one percent area. The plunge and trend of the mean vector is 56→319. The strike and dip of the plane to this point (dashed line = mean S₂) is 054/47SE. (c) Lower-hemisphere, equal area scatter plot of 124 poles to F₂ and F₃ axial surfaces. (d) Contoured lower-hemisphere, equal-area plot of 124 poles to F₂ and F₃ axial surfaces. Contours 1, 2, 4, 8, 16, and 32 percent per one percent area. The plunge and trend of the mean vector is 43→323. The strike and dip of the plane to this point (dashed line = mean F₂ and F₃ axial surface) is 053/49SE.

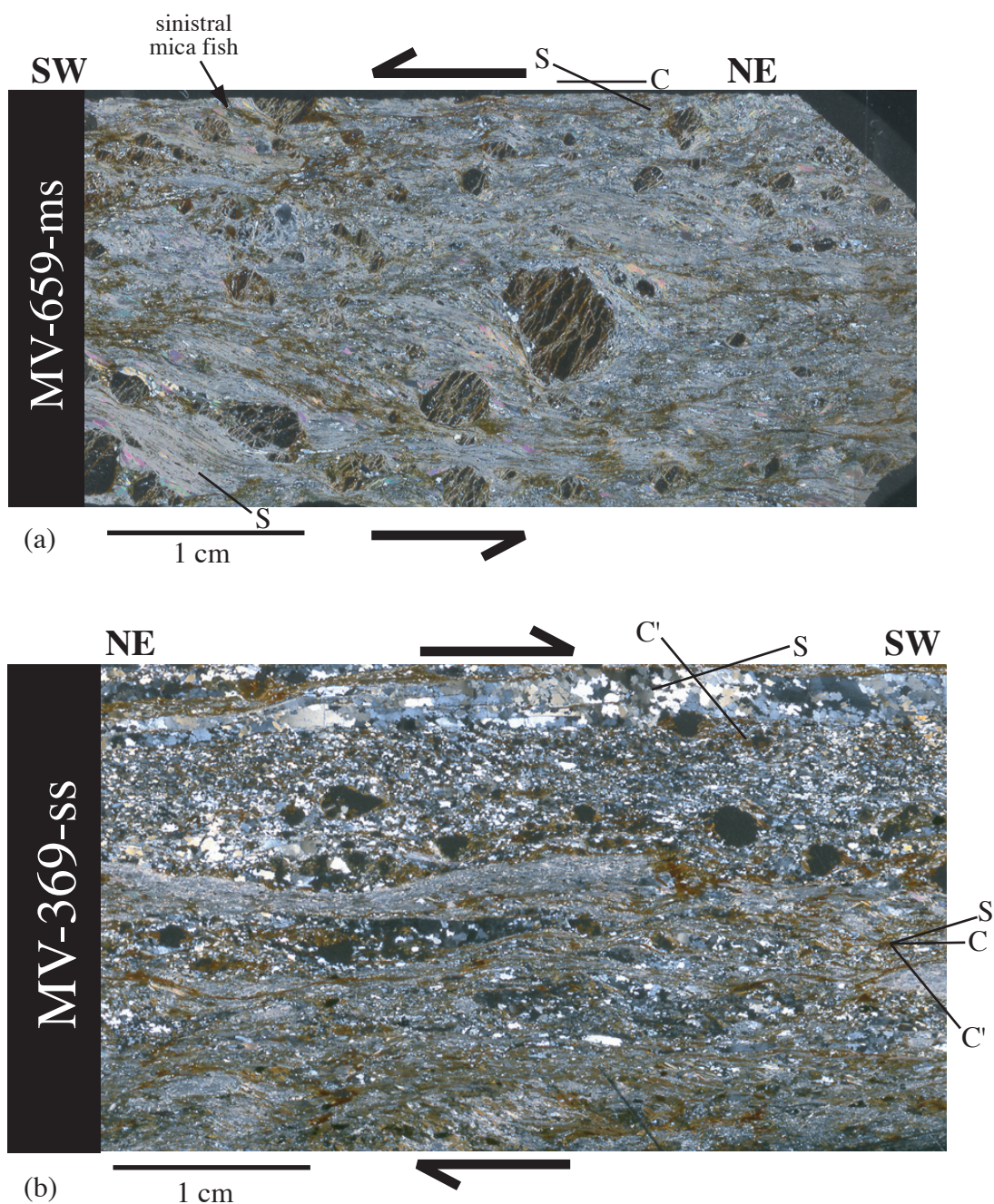
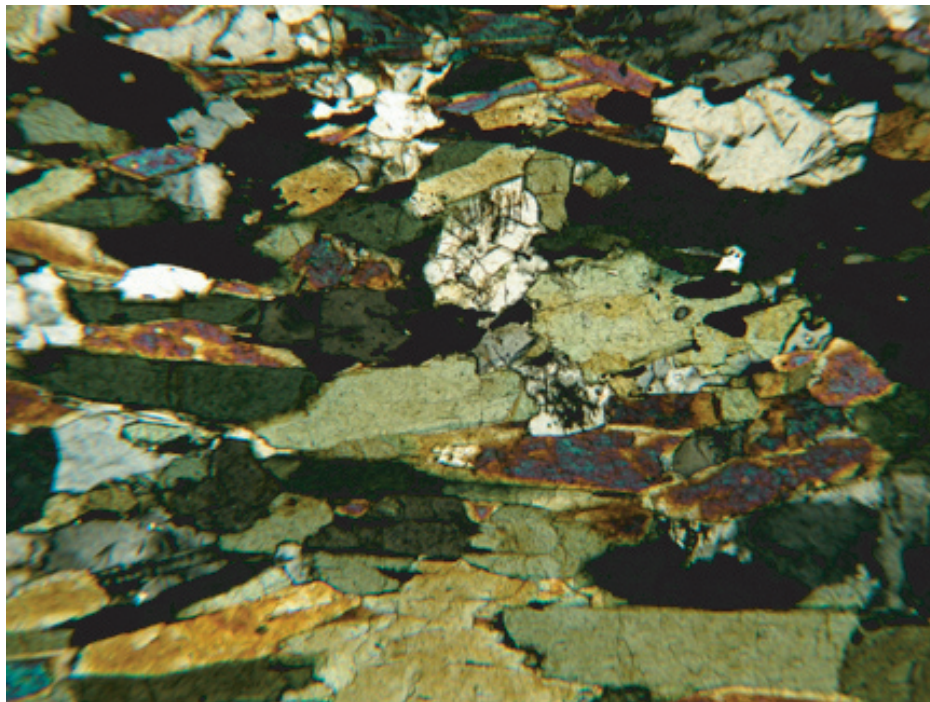


Figure 3-5. Microscopic S-C fabrics from the study area. These fabrics are typical of schistose lithologies proximal to shear zones. (a) Scanned thin section of a garnet-muscovite schist from the middle Tallulah Falls Formation near the WCFZ. Note the consistency of stair-stepping relationships between S-C fabrics, mica fish, rotated porphyroblasts, and boudinaged garnets. (b) Scanned thin section of an eastern IP sillimanite schist sample from near the PSSZ displaying a well-developed S-C-C' fabric. Sample numbers correspond to station numbers from Plate 2.



(a)



(b)

1 mm

Figure 3-6. Hand sample and photomicrograph of L_2 fabrics in the study area. (a) Strongly lineated L-S tectonite sample of ultramylonitic Walker Top Gneiss (MV-566) from the BCFZ. (b) Photomicrograph of an amphibolite L-tectonite sample (MV-665), typical of mafic amphibolite bodies occurring in the Lenoir Quarry migmatite. Note the parallel orientation of hornblende phenocrysts in the sample.

recrystallized minerals such as biotite, muscovite, and epidote also define the lineation, but to a lesser extent. Subhorizontal hornblende and megacrystic feldspar lineations can be readily observed in Lenoir Quarry migmatite, Henderson Gneiss, and Walker Top Granite, but are also present in other lithologies. Aligned fibrolitic and bladed sillimanite, along with quartz rods and epidote porphyroblasts, define linear fabrics in metasedimentary lithologies.

IP mineral lineations generally lie in S_2 foliation planes and parallel the regional trend (Hatcher, 1998). Curved regional trends of mineral lineations (Fig. 3-7) are problematic and have recently been associated with curved W- followed by SW-directed transport and map-scale sheath folding during Neocadian crustal flow and terrane accretion (Davis, 1993; Mersch et al., 2005). No such curvature of mineral lineations is indicated from linear fabric data collected in this study (Fig. 3-8). A possible explanation for this is that the study area is entirely contained in a zone of constricted alignment near the BFZ and that a curved pattern would be manifested by collection of additional data to the SE (Fig. 3-7). Field observations and structural analyses from the northeastern IP suggest that these lineations are related to SW-vergent F_2 sheath folds and NW-vergent F_3 folds, which indicate SW-directed transport during D_2 , followed by NW-directed transport during D_3 . Furthermore, these patterns are likely the result of a flow lineation developed during D_2 , which may track incremental trajectories of a flowing rock mass undergoing extreme simple shear (Figs. 3-7, 3-8, and 3-9).

Prolate mineral lineations in the study area are strongly aligned and generally have a shallow plunge, trending NE-SW, with a mean orientation of $4\rightarrow 057$ (Figs. 3-8 and 3-9). These lineations plot mostly in S_2 planes (Fig. 3-9), suggesting that linear fabric development occurred syn- to late- S_2 formation. Thus, all mineral lineations collected during this study are designated L_2 .

S-C fabrics are largely restricted to fault zones, particularly in and near the TCFZ, MSFZ, and BCFZ, but also occur in discrete shear zones throughout the study area. They, along with shear bands and fold vergence, provide the most reliable shear sense indicators in the northeastern IP. S-C intersection lineations were measured as the trend and plunge of the intersection line of S and C planes. Steeply SE-plunging orientations are constant throughout the study area, indicating a significant component of orogen-parallel strike-slip transport. Ubiquitous top to the SW shear sense also supports a strong dextral component of strike-slip movement along northeastern IP fault zones.

C-planes truncate earlier nonmylonitic S_2 fabrics, indicating that dextral strike-slip faulting occurred after D_2 . This is further supported by deformed retrograde metamorphic

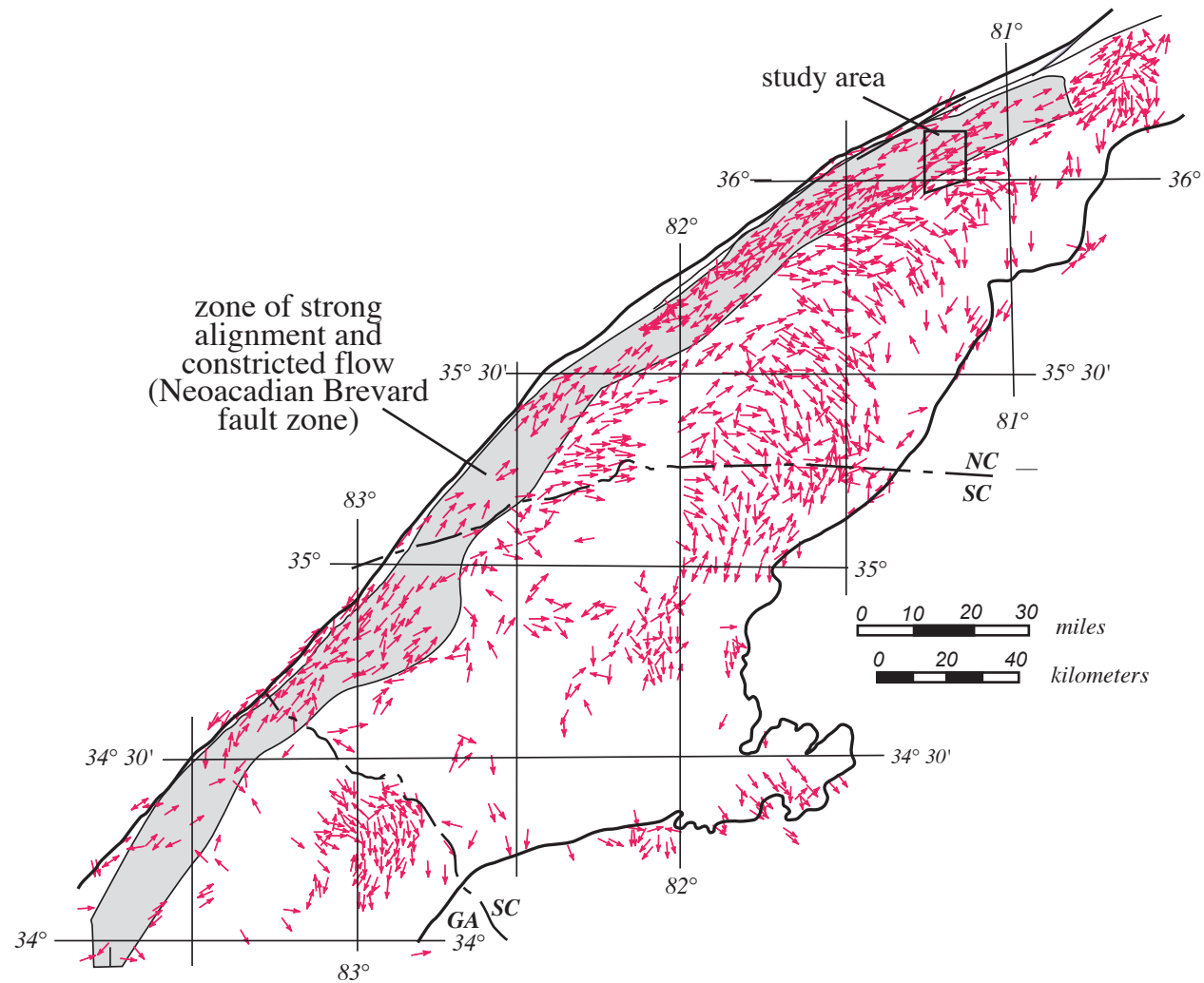


Figure 3-7. Mineral lineations for the northern part of the Inner Piedmont. Note that the study area (unfilled polygon) lies mostly within the zone of constriction. Modified from Hatcher (2001).

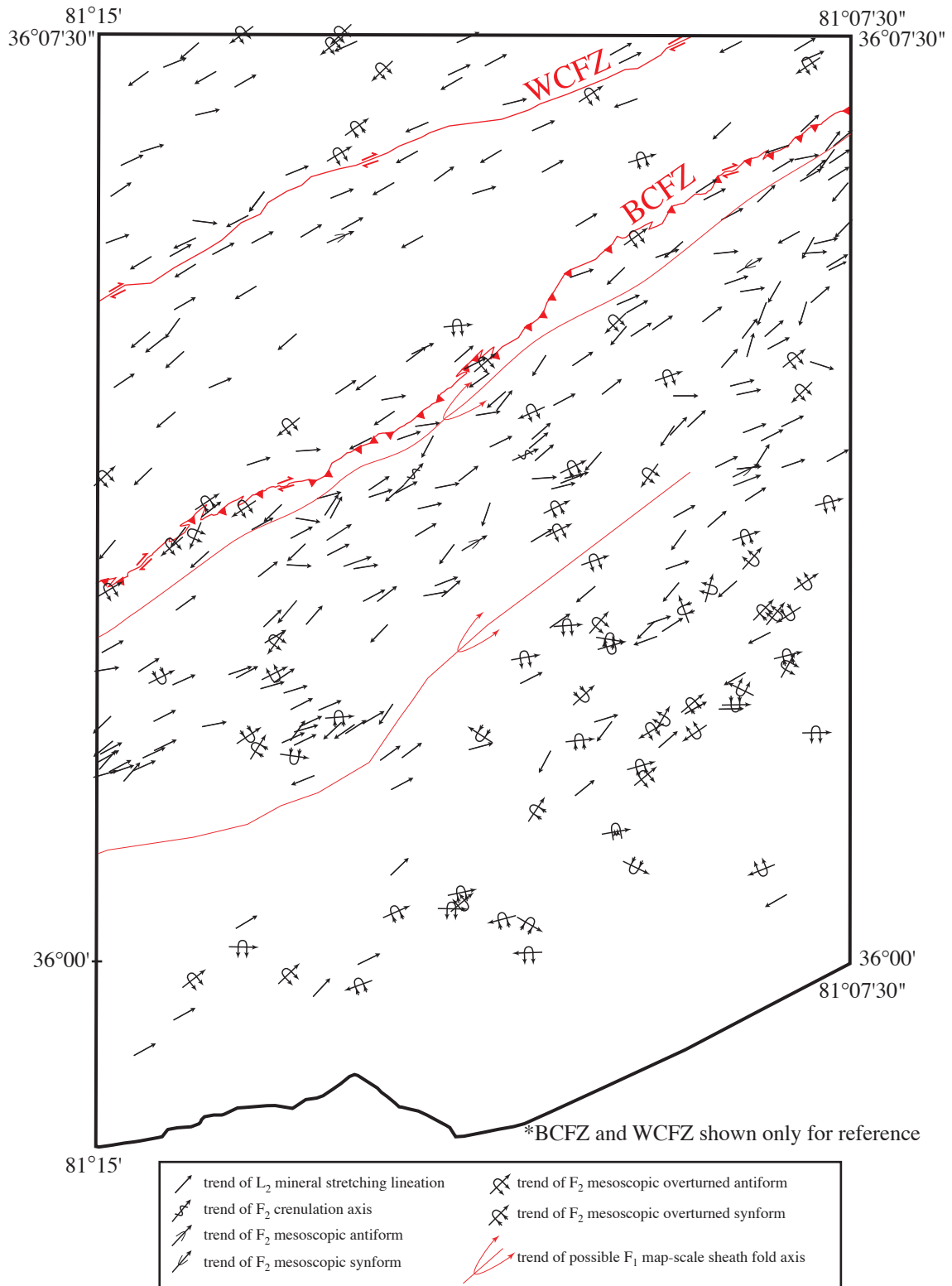


Figure 3-8. D_2 linear fabric map of the study area. Orientations of L_2 mineral stretching lineations plotted with parallel to sub-parallel F_2 and F_3 fold axes, crenulation axes, and potential map-scale sheath fold axes.

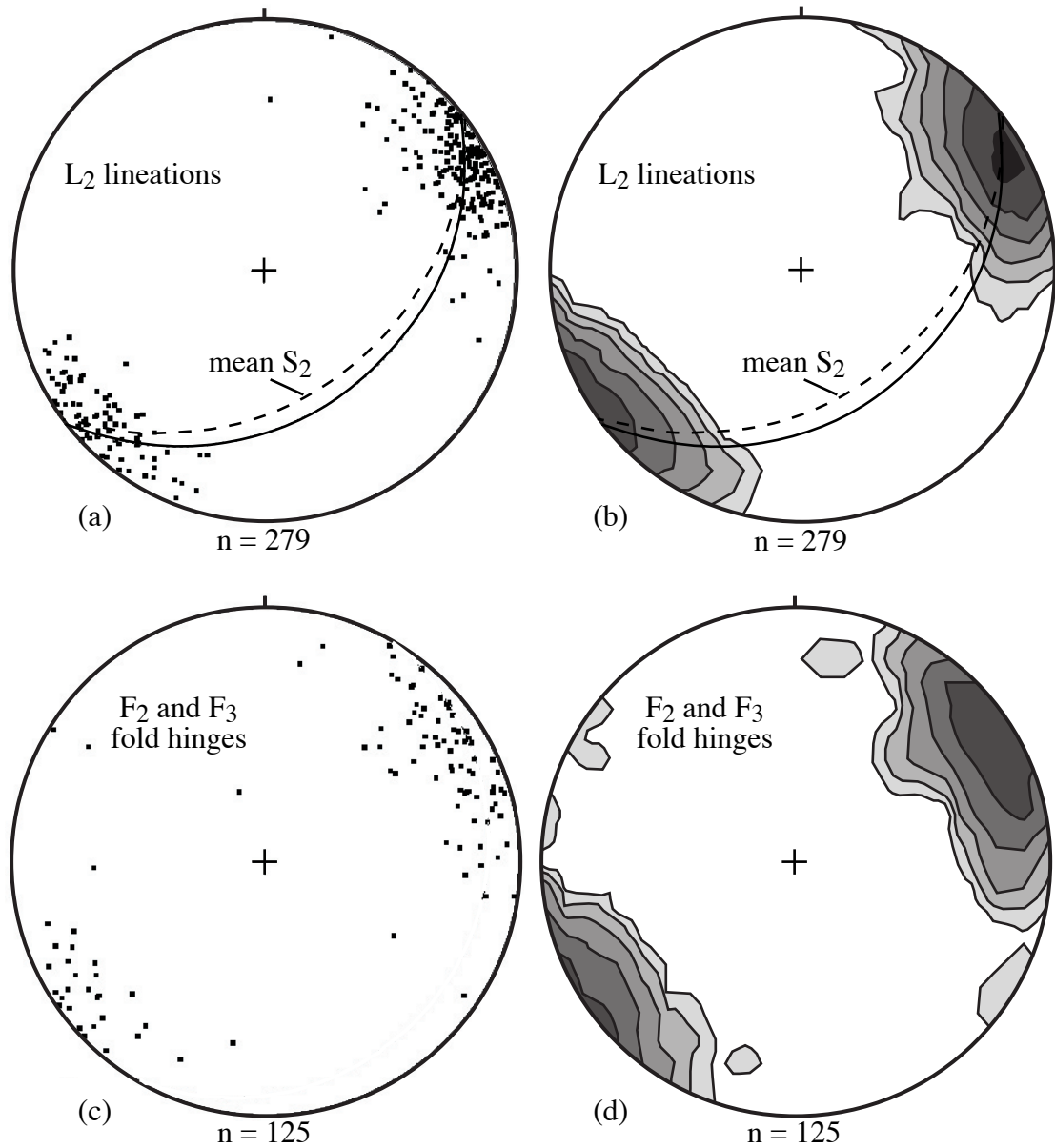


Figure 3-9. Scatter plots and fabric diagrams for all L₂ lineation with F₂ and F₃ fold-axis measurements obtained in the study area. Note that most folds designated as F₂ or F₃ are NW-vergent, tight to isoclinal, and reclined to recumbent. (a) Lower-hemisphere, equal-area scatter plot of 279 L₂ measurements. The strike and dip of the best-fit great circle (solid line) is oriented 052/41SE, and is approximately parallel to the mean S₂ foliation (dashed line), which is oriented 054/47SE. (b) Contoured lower-hemisphere, equal-area plot of 279 L₂ measurements. Contours 1, 2, 4, 8, 16, and 32 percent per one percent area. The plunge and trend of the mean vector is 4→057. (c) Lower-hemisphere, equal-area scatter plot for 125 F₂ and F₃ fold hinges. (d) Contoured lower-hemisphere, equal-area plot of 125 F₂ and F₃ fold hinge measurements. Contours 1, 2, 4, 8, and 16 percent per one percent area. The plunge and trend of the mean vector is 7→060. Note that L₂ mineral lineations are approximately parallel to SW-vergent F₂ sheath fold hinges and NW-vergent F₃ fold hinges.

textures in the shear zones, consistent with regional strike-slip faulting occurring after peak metamorphism, which is thought to coincide with D_2 and D_3 . Fabric analyses show that S-C intersection lineations have a mean orientation of $41 \rightarrow 143$, and parallel NW-SE trending F_4 fold axes (Figs. 3-10 and 3-11), which are SW-vergent (see below). Because of parallel orientations and similar shear sense to F_4 folds and crenulations, all S-C intersection lineations measured in this study were designated L_4 , and are considered to have developed coevally with D_4 structures.

Folds

Multiple generations of folding have affected the northeastern IP, typical of polydeformed terranes. Six recognizable episodes of folding (F_1 , F_2 , F_3 , F_4 , F_5 and F_6) are present in the study area. Two F_1 fold sets, F_{1WIP} and F_{1EIP} are distinguished from one another by differing fold geometries and styles across terranes. These fold generations must have formed separately before final emplacement of the BCFZ, because they are truncated by Neocadian and later structures. Successive fold generations are distinguished by differing geometries, differing orientations, and overprinting relationships observed in outcrop and thin section.

WIP F_1 Folds

Western IP rootless and intrafolial F_1 folds occurring in amphibolite boudins provide the best mesoscale evidence for deformation prior to D_2 in the western IP. Isoclinal F_1 folds in the footwall of the TCFZ provide additional macroscale evidence for western IP F_1 folds. F_1 folds a primary compositional layering in the Tallulah Falls Formation, with axial surfaces discordant to S_2 (Plate 1).

EIP F_1 Folds

Eastern IP F_1 folds occur as meso- and microscopic rootless and intrafolial folds. Additionally, isoclinal and recumbent F_1 folds are present in outcrop, but are refolded and completely transposed by D_2 structures, making their original orientations impossible to determine.

Development of F_{1EIP} folds likely predates or is coeval with eastern IP anatectic magmatism, as xenoliths in the Walker Top and Toluca Granite bodies often preserve F_1 folds (Fig. 3-12a). However, this evidence combined with the recognition of F_1 folds within eastern IP anatectic granitoid bodies suggests their genesis is coeval with F_1 .

These early fold generations in the eastern IP are likely related to subduction of the Cat

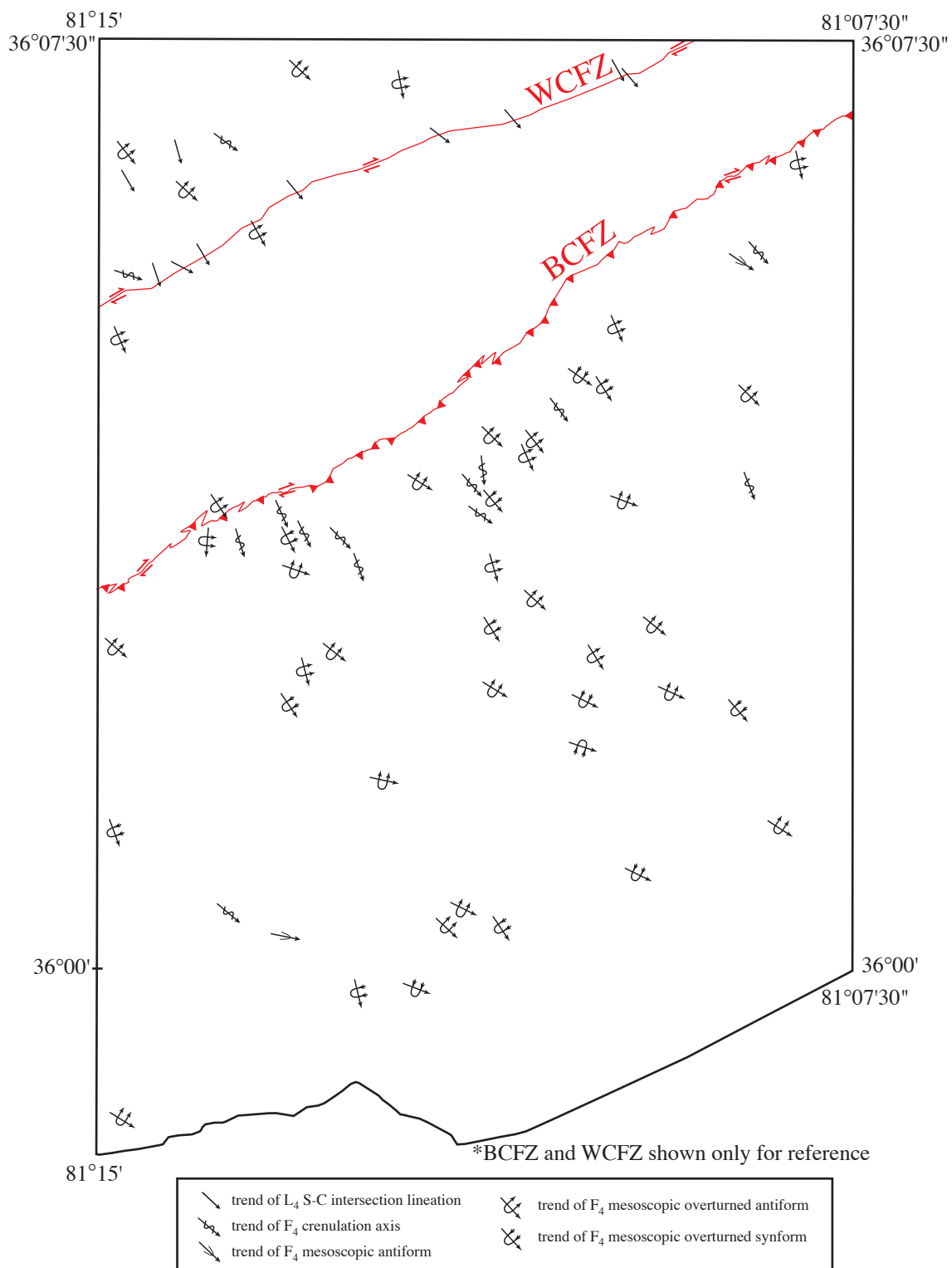


Figure 3-10. D₄ linear fabric map of the study area. Orientations of L₄ S-C intersection lineations plotted with parallel to sub-parallel F₄ fold and crenulation axes. Note that F₄ folds are mostly SW-vergent.

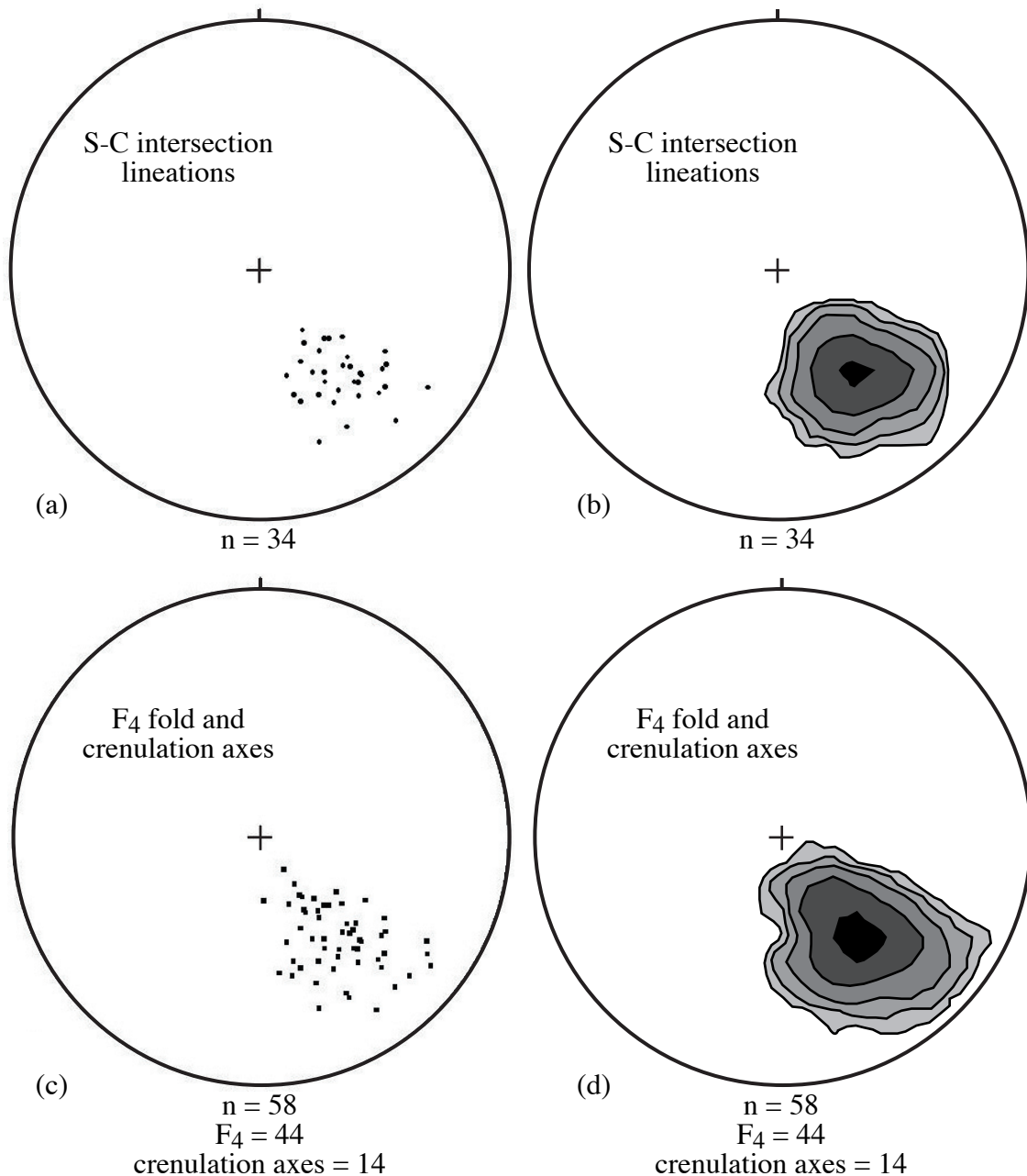


Figure 3-11. Scatter plots and fabric diagrams for S-C intersection lineations and F₄ crenulation axes and fold hinges in the study area. (a) Lower-hemisphere, equal-area scatter plot of 34 S-C intersection lineations measured in shear zones. (b) Contoured lower-hemisphere, equal-area plot of S-C intersection lineations measured in shear zones in the study area. Contours 3, 6, 12, 24, and 48 percent per one percent area. The plunge and trend of the mean vector is 45→143. (c) Lower-hemisphere, equal-area scatter plot of 58 F₄ fold hinges and crenulation axes measured in the study area (44 F₄; 14 crenulation axes). (d) Contoured lower-hemisphere, equal-area plot of 58 F₄ fold hinges and crenulation axes measured in the study area (44 F₄; 14 crenulation axes). Contours 2, 4, 8, 16, and 32 percent per one percent area. The plunge and trend of the mean vector is 41→139. Note that S-C intersection lineations are approximately parallel to F₄ fold and crenulation axes.



(a)



(b)

Figure 3-12. F_1 and F_2 folds in the study area. (a) F_1 synform folding biotite schist xenolith in Walker Top Granite near Bald Rock Mtn (photo by RDH). Note truncation of D_1 structures by S_2 fabric in Walker Top Gneiss. (b) NW-vergent isoclinal reclined to recumbent F_2 antiform-synform pair in metagraywacke (MV-596) near Moravian Creek and Walnut Grove Church.

Square terrane beneath the Carolina terrane prior to emplacement of the BCFZ (Part V, this study).

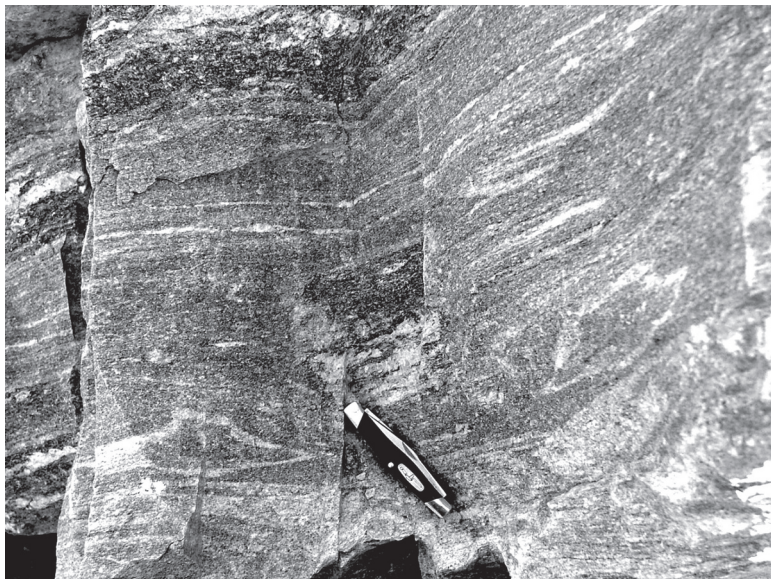
F₂ Folds

Apparent NW-vergent F_2 folds are present at all scales in the study area. The apparent vergence of this fold generation is likely caused by observation of northwest limbs of macro- and mesoscopic F_2 sheath folds. Development of F_2 is closely related to the emplacement of meso- and macroscale faults in the region. Folds are designated as F_2 , based on recognition of earlier fold generations in the eastern and western IP (discussed above), orientations, geometries, and crosscutting relationships. F_2 folds are commonly isoclinal, apparently noncylindrical, passive-flow folds, with attenuated limbs and thickened hinges (Figs. 3-13 and 3-14). Fold axes of F_2 folds trend approximately parallel to regional linear trends with a mean orientation of $7\rightarrow 060$ (Figs. 3-7 and 3-8), and have inclined to recumbent SE-dipping axial surfaces with an average orientation of $053/49SE$ (Figs. 3-4 and 3-13). An apparent genetic relationship exists between F_2 fold hinges and L_2 mineral lineations (Figs. 3-8 and 3-9). F_2 and L_2 linear fabrics are consistently parallel throughout the study area, inferring simultaneous development. Additionally, F_2 axial surfaces are approximately parallel to S_2 foliation surfaces, suggesting that F_2 developed pre- to syn- S_2 , and that S_2 is an axial planar foliation throughout the study area (Fig. 3-4).

Sillimanite needles and fibers, likely representing peak metamorphic conditions, are folded by F_2 and F_3 folds, but also truncate these folds, indicating that these deformation events occurred before and during peak metamorphism. Parallel F_2 folds in eastern and western IP terranes, and F_2 folding of the BCFZ and TCFZ suggest that these folds developed during and after BCFZ emplacement. Hence, generation of F_2 folds is likely related to Neoacadian thrust sheet emplacement.

F₃ Folds

F_3 folds are distinguished from F_2 folds on the basis of fold geometries and interlimb angles, although similar orientations suggest they belong to the same fold generation. However, outcrop relationships show that F_3 folds often refold F_2 folds into type-3 fold interference patterns with hinges nearly parallel to F_3 (Fig. 3-14). NW-vergent F_3 folds typically have more open geometries and are moderately to steeply inclined. S_2 surfaces are folded by F_3 folds in the study area. Where F_3 folds are observable, hinges and limbs are slightly thickened, suggesting that these may be



(a)



(b)

Figure 3-13. Mesoscopic F_1 sheath folds in the study area. (a) Sheath fold in quarry block of Walker Top Granite from Vulcan Materials 115 quarry (Gilreath quadrangle). Note that the knife is resting between two near-orthogonal joints (a sub-horizontal to the left and a vertical to the right) and the flattened cylindrical eye-shape geometry of the fold. Photo by A. J. Mersch. (b) Sheath fold in metagraywacke (MV-561) near Cove Gap. Note that the pencil is resting on a raised surface and the closure of the felsic layer on either end.



Figure 3-14. Field photographs showing F_3 refolds of F_2 folds. Note the parallel orientations of F_2 and F_3 fold hinges and that both F_3 folds are NW-vergent. (a) Type-3 "hook" fold interference pattern in sillimanite schist outcrop (MV-215) off Price Rd. (b) Type-3 fold interference pattern in metagraywacke (MV-532) northeast of Pores Knob.

flexural-slip folds, with buckling as a possible folding mechanism (Fig. 3-14). As noted by Yanagihara (1994), differing styles of folding may indicate rheologic contrasts between F_2 and F_3 , corresponding to cooling after peak metamorphism. This folding event produced the majority of the map-scale fold patterns between adjacent thrust sheets and lithologies (Plate 1).

F₄ Folds

This folding event produced asymmetric, SW-vergent, open to tight folds with SE-plunging hinge lines and crenulations, approximately perpendicular to F_2 and F_3 folds, with a mean orientation of 46→143 (Figs. 3-10, 3-11, and 3-15). F_4 axial planes are steeply to moderately inclined, and NE-dipping. Layer thicknesses are sometimes preserved between hinge zones and limbs, suggesting that these are flexural-slip folds resulting from buckling mechanisms under semi-brittle conditions (Fig. 3-15). Evidence for F_4 passive-slip folding is also present in SW-vergent F_4 folds with slightly thickened hinges (Fig. 3-15). Variation in fold style may reflect a transition from ductile to brittle conditions during the course of D_4 . SW-vergent F_4 folds and crenulations fold all earlier fabrics, with axes oriented parallel to S-C intersection lineations throughout the study area, indicating simultaneous development during regional SW-directed dextral strike-slip movement along large IP fault zones (Figs. 3-10 and 3-11). Although F_4 folds are present at macro-, meso-, and microscales, no S_4 axial planar foliation is present.

F₅ Folds

F_5 produced regional and outcrop-scale symmetric open upright flexural-slip folds that trend NE-SW. Map-scale F_5 folds are likely responsible for producing the slight fold girdle pattern, present in foliation fabric diagrams (Fig. 3-4). A foliation β -plot approximates the hinge orientation for this folding event as 9→063 (Fig. 3-4). Observation of this fold generation provides a possible explanation for anomalous northwest dips of S_2 foliation (Fig. 3-4). Layer thickness is maintained from limbs to hinge zones, indicating that these are flexural-slip folds, developed under low P-T conditions. F_5 folds are likely related to regional fracture development during Alleghanian and Mesozoic uplift and rifting.

F₆ Folds

F_6 folds occur only at the macroscale. Although similar to F_5 folds in geometry, F_6 folds trend NW-SE, roughly perpendicular to F_5 orientations. Perpendicular orientations

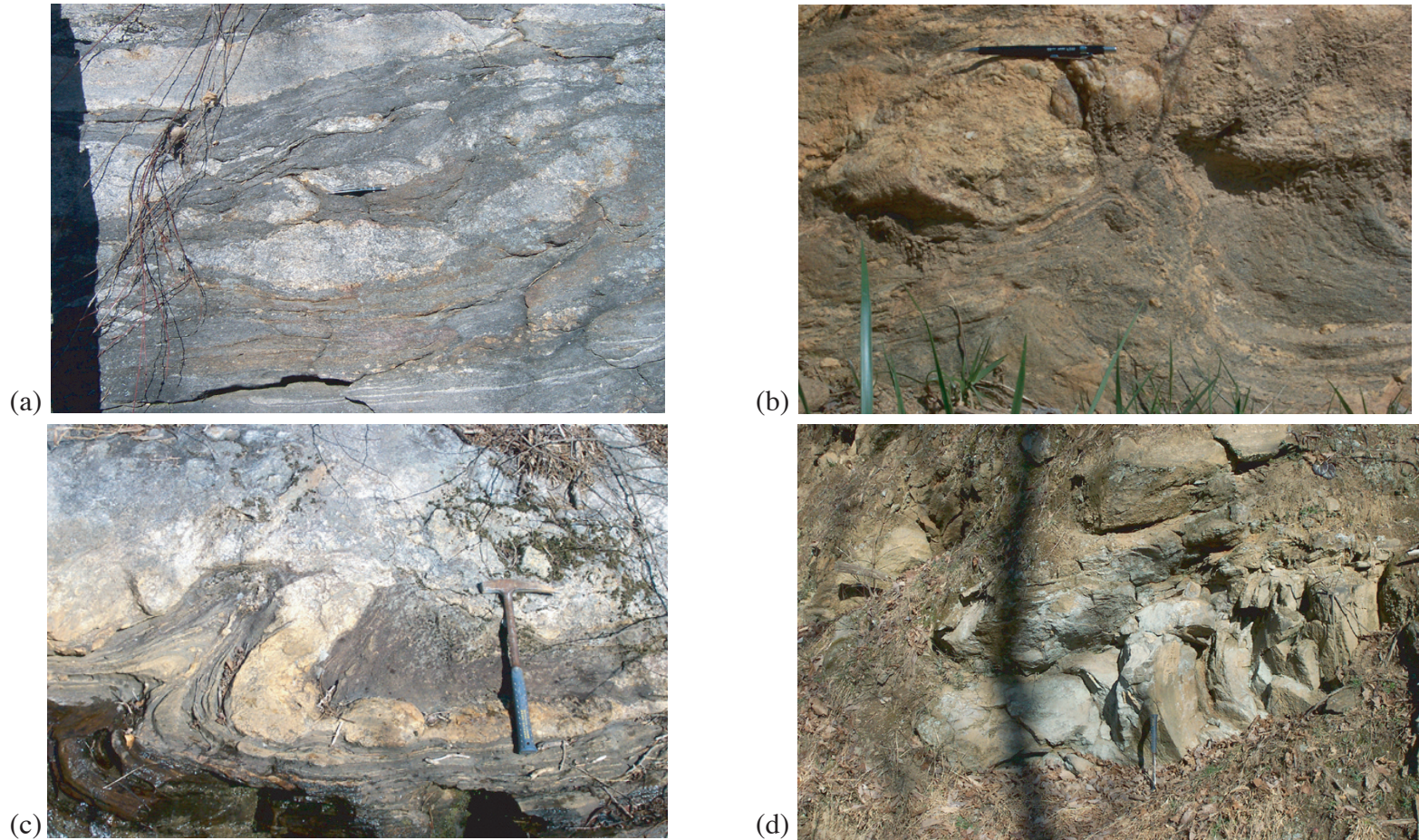


Figure 3-15. SW-vergent mesoscopic F₄ folds in the study area. (a) SW-vergent F₄ folds and imbricates in leucocratic boudins from lower Tallulah Falls Formation metagraywacke (MV-1538) near Whites Creek. (b) F₄ antiform in eastern IP metagraywacke (MV-601) near Rocky Creek. (c) Mesoscopic F₄ antiform-synform pair folding eastern IP migmatitic metagraywacke (MV-405) along the South Yadkin River. (d) SW-vergent F₄ synform-antiform pair in Brooks Crossroads Granite (MV-309) off Pores Knob Rd.

for F_5 and F_6 produce type-1 fold interference patterns with very broad domes and basins. Alternating NE-SW plunge orientations for adjacent L_2 mineral lineations (Fig. 3-8) may be the product of NW-SE oriented regional open folding. Alternatively, this characteristic could be related to the shallow plunge of these mineral lineations and may be unrelated to F_6 .

Joints

Eight hundred sixty-three fracture orientations reveal two dominant joint sets (Fig. 3-16). Set 1 trends 332° with an orthogonal conjugate surface striking 062° and corresponds to the dominant fracture orientation in the study area. Set 2 strikes 016° and 286° and is less common than set 1. Most joints in the study area dip steeply (70° - 90°) and have small apertures. Fracture sets in the study area probably formed during three deformation events (D_4 , D_5 and D_6 ; Table 3-1). The first likely accompanied brittle deformation during late D_4 corresponding to brittle deformation in the Alleghanian BFZ. Subsequent D_5 and D_6 joint sets developed in response to Alleghanian and post-Alleghanian exhumation of composite crystalline thrust sheets in the eastern Blue Ridge and IP, Mesozoic and Cenozoic deformation (e.g. Garihan et al., 1993; Knapp, 2001), and contemporary stress fields (Engelder, 1982).

STRUCTURAL TRENDS

Many studies of IP geology have recognized structures parallel, oblique, and normal to the orogen (e.g., Reed and Bryant, 1964; Griffin, 1971; Hatcher, 1972; Roper and Dunn, 1973). Davis (1993) interpreted these observations as a product of early oblique convergence in the southern Appalachians. Observations from this study also reveal a variety of structural orientations; each can be explained, however, by recognition of differing structural domains in the study area and successive deformation pulses affecting this area. Regional patterns represent a finite strain path resulting from a multi-phase deformational history.

The two lithotectonic crystalline thrust packages that comprise the geologic make-up of the study area correspond to those recognized by Kalbas (2003) and Merschat (2003) in the southwestern Brushy Mountains (Plate 3). A portion of the Marion thrust sheet occurs in the northwesternmost portion of the study area, while the southeastern part of the area contains lithologies of the Brindle Creek thrust sheet. These thrust sheets are partitioned across the Brindle Creek fault zone and correspond to the eastern and western IP, respectively. Observations of deformational fabrics on all scales reveal that

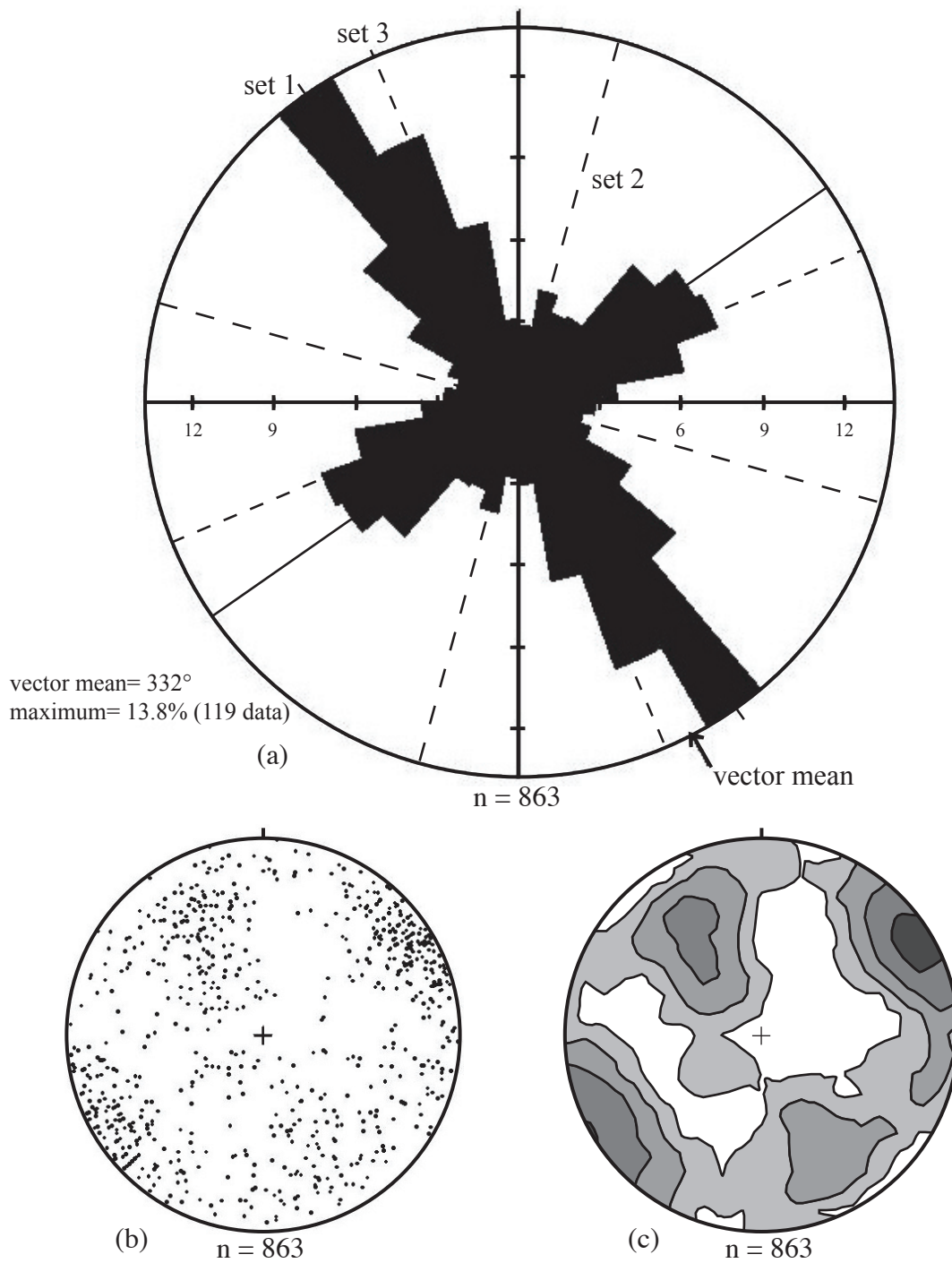


Figure 3-16. Distribution of systematic joint orientations in the study area. (a) Rose diagram illustrating the strike of joint planes. Major and conjugate ($\sim 90^\circ$ from the dominant) joint pairs are shown as individual sets. (b) Lower-hemisphere equal-area scatter plot of 863 poles to joint surfaces. (c) Contoured lower-hemisphere equal-area fabric plot of 863 poles to joint surfaces. Contours 1, 2, 4, and 8 percent per one percent area.

all lithotectonic assemblages are penetratively deformed, with similar characteristics from micro- to macroscale.

Foliation trends throughout the study area allow for subdivision into three distinct homogeneous domains (Fig. 3-17) on which fabric analyses can be grouped. Form-line fabric analyses mimic map patterns; however, foliation form lines truncate lithologic contacts and map-scale structural features such as faults and shear zones. Structural domains recognized in this study mostly correspond to those documented by Merschat and Kalbas (2002) in the southwestern Brushy Mountains, who noted that each domain exhibits an approximate triclinic symmetry.

Domain I

Domain I constitutes the majority of the study area, encompassing the area between the Neoacadian BFZ and the southeastern boundary of the PSSZ (Fig. 3-17), and marks the structural boundary of the zone of constricted alignment (Fig. 3-7). The entire Marion and northwesternmost portion of the Brindle Creek thrust sheet are contained within domain I. Structurally, domain I is homogeneous containing consistent NE-SW striking fabrics with moderately SE-dipping structures (Figs. 3-17 and 3-18). The mean foliation is orogen parallel and oriented 055/49SE (Fig. 3-18). Planar fabrics in domain I consist of foliations, schistosity, compositional, and migmatitic layering, fault zones, F_2 and F_3 axial surfaces, and lithologic contacts, all of which have been transposed into parallelism with each other. The mean vector of mineral lineations in domain I is oriented 3→058, and is defined by the alignment of feldspar, quartz, hornblende, and sillimanite (Fig. 3-19). Macroscale structures, fault zones, and overturned folds verge NW and SW. Fold axes of overturned and reclined F_2 and F_3 folds plunge gently to the NE and SW, with a mean orientation of 7→060 (Fig. 3-19).

Four macroscale ductile fault zones are located in domain I (Plate 1; Fig. 3-2). All are parallel to the regional structural grain, trending NE-SW through the study area. Structurally the lowest, the TCFZ is discontinuous and located in the northwest corner of the Moravian Falls quadrangle. The MSFZ, a late strike-slip fault also located in the northwestern part of the study area, truncates the TCFZ. Collectively, these fault zones comprise the Alleghanian BFZ in the northwestern IP. To the southeast, the BCFZ partitions eastern and western IP lithologies and is structurally above the Neoacadian BFZ. Although structurally higher than the BCFZ, the PSSZ, an internal shear zone in the Cat Square terrane, is truncated by the BCFZ (Plate 1; Fig. 3-2).

Domain I corresponds to the zone of strong alignment or zone of constricted flow

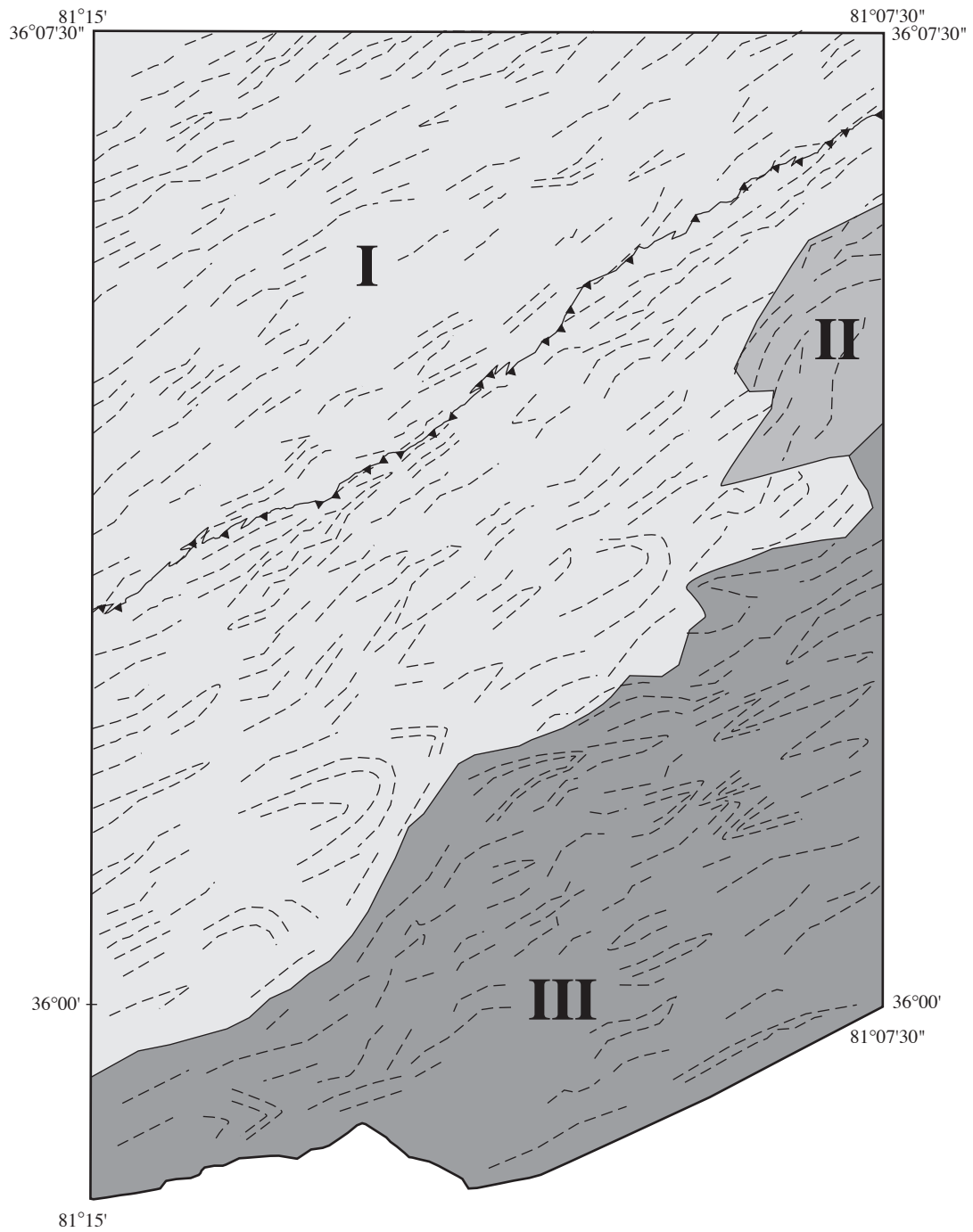


Figure 3-17. S₂ foliation form line and domain map of the Moravian Falls and Taylorsville quadrangles. The Brindle Creek fault zone is shown for reference.

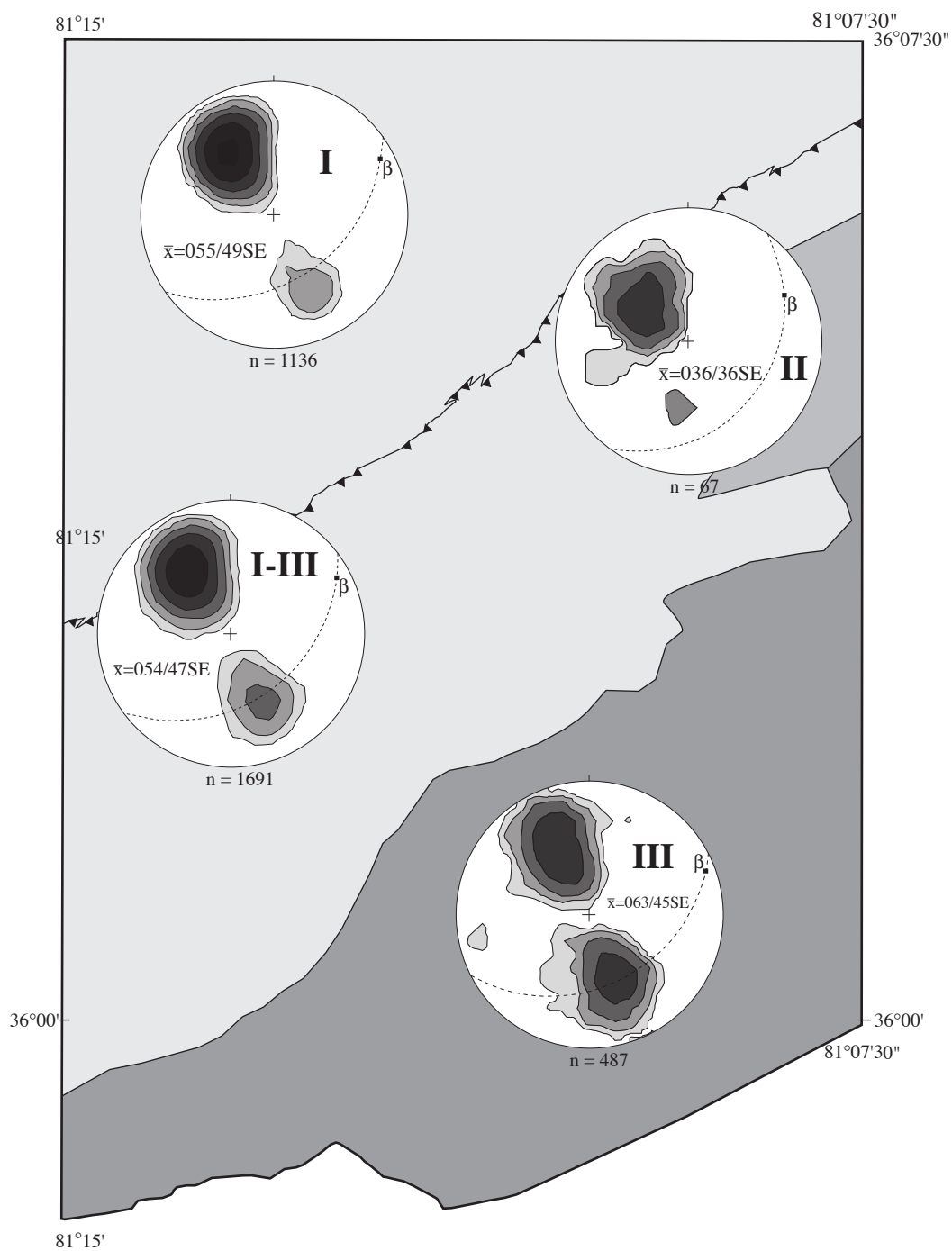


Figure 3-18. Contoured, lower-hemisphere equal-area projections of poles to foliation. Data from 1691 measurements are shown together as "I-III" and separated into three structural domains. Contours 1, 2, 4, 8, 16, and 32 percent per one percent area, except for domain II corresponding to 2, 4, 8, and 16 percent per one percent area.

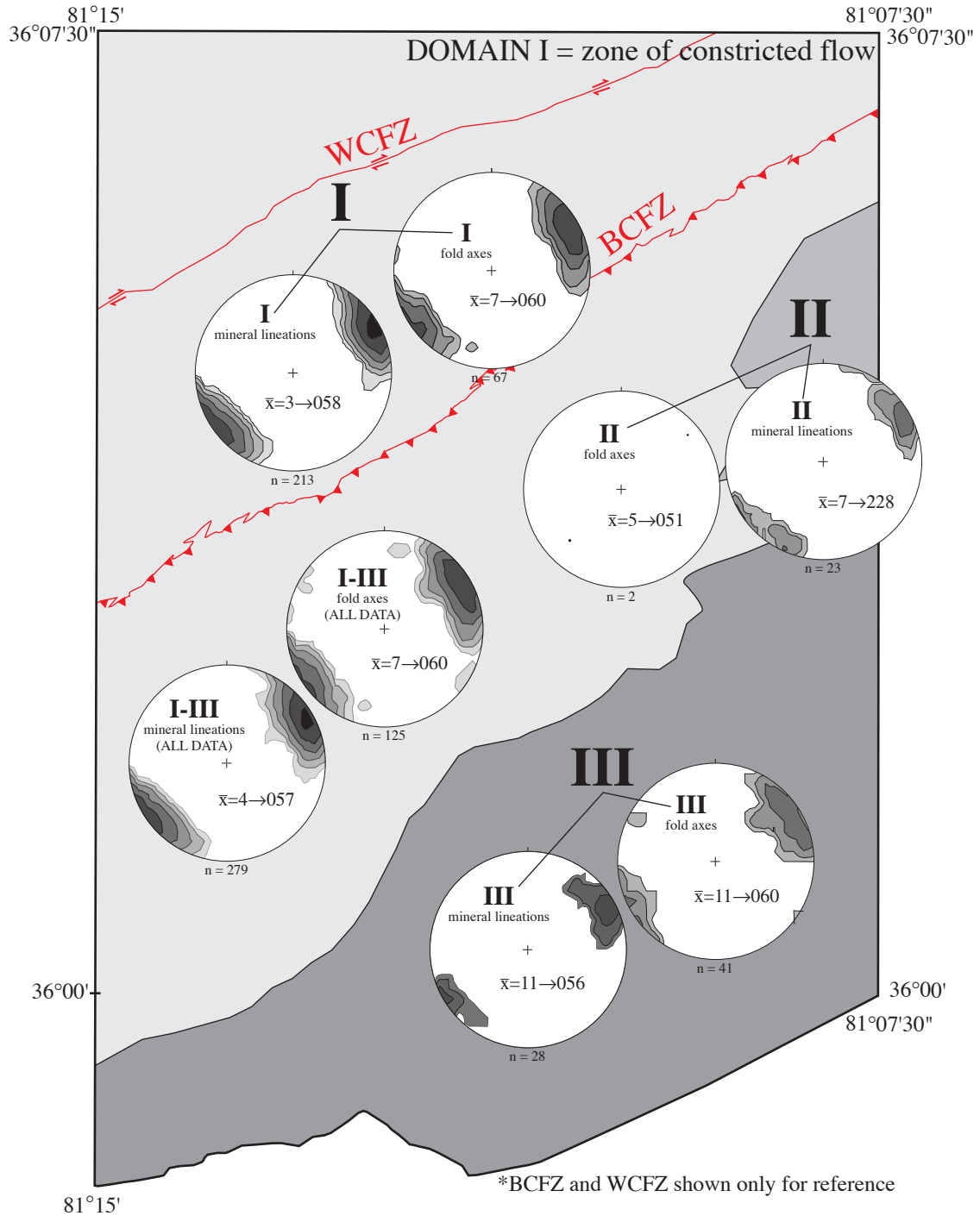


Figure 3-19. Contoured, lower-hemisphere equal-area projections of mineral lineation and fold axis orientations. Data from 279 mineral lineation and 125 fold axis measurements are shown together as "I-III" and separated into three structural domains. Contours 1, 2, 4, 8, 16, and 32 percent per one percent area.

in the study area (Fig. 3-7), as recognized by Hatcher (2001). Consistent orientations of planar and linear fabrics in this domain suggest that it is unique relative to the other domains. The proximity of the Neocadian BFZ to this domain presents a possible explanation for the strongly aligned planar and linear fabrics here (discussed below).

Domain II

Domain II occurs near the eastern boundary of the study area and corresponds to a reentrant in the Brindle Creek thrust sheet. A form-line map shows a significant deflection of planar fabrics occurs near the boundary between domains I and II (Fig. 3-17). Domain II is more heterogeneous than domain I, with northerly trends and shallower dips. The mean foliation is oriented 036/36SE and mineral lineations trend NE-SW with an average of 7→228 (Fig. 3-18). Early folds verge NW with NE- and SW-plunging axes (Fig. 3-19), similar to other domains. Map patterns are controlled by macroscale antiform-synform pairs (Plate 1). Folding of the Brindle Creek thrust sheet along with western IP lithologies has produced these structures. Truncation of the BCFZ by foliation form lines suggests that the deflection of foliations in this region is likely caused by late movement along the BCFZ, possibly related to dextral strike-slip motion between the BFZ and the BCFZ.

Domain III

Domain III exists in the southeastern portion of the study area, and is separated from domain I based on differences in dip direction and magnitude (Figs. 3-17 and 3-18). These differences are best illustrated in domain-specific foliation fabric diagrams (Fig. 3-18). Although similar to domain I, domain III likely represents transition from a zone of constriction (domain I) to a less homogeneous structural domain farther away from the BFZ. Domain III is heterogeneous with the average foliation oriented 063/45SE, and a much more pronounced fold girdle effect than domain I (Fig. 3-18). This pattern is most likely the effect of late open F_5 folds that trend NE-SW (discussed above), and is best illustrated by map patterns of dismembered Toluca Granite bodies in the southern portion of the Moravian Falls quadrangle (Plate 1). Axial planar foliations to late folds do occur sporadically here and likely account for deflections apparent in the form-line map (Fig. 3-17). The mean orientation of mineral lineations in domain III trends 11→056 (Fig. 3-19). Fold axes show similar patterns to other domains. NW-vergent F_2 and F_3 mesoscopic folds have axes parallel to L_2 mineral lineations and trend 11→060 (Fig. 3-19), while F_4 folds and crenulations are SW-vergent, with SE-plunging axes.

TRANSPORT AND FLOW KINEMATICS

As previously noted, regionally curved mineral lineation patterns (Fig. 3-7) are somewhat problematic for interpreting transport kinematics. Davis (1993), Hatcher (2001), and Merschat et al. (2005) have used these regional patterns to reconstruct flow paths for IP thrust sheets. Davis (1993) suggested that buttressing of IP thrust sheets against a NE-SW trending, SE-dipping structure (potentially the BFZ) could have deflected W-advancing thrust sheets to the SW. Hatcher (2001) proposed that the initial localization of the early BFZ corresponds to a stratigraphically controlled crustal anisotropy. A zone of constricted flow, as identified by Hatcher (2001), refers to the area immediately southeast of the BFZ that is characterized by strongly aligned NE-SW oriented structures, produced by SW-directed transpressional flow (Fig. 3-7). This zone extends from the Georgia into the North Carolina IP, encompasses most of the present study area, and ultimately ends near the Sauratown Mountains window (Hatcher, 2001).

Davis (1993) and Merschat et al. (2005) used regional curved mineral lineation patterns to reconstruct and delineate patterns of Neoacadian mid-crustal flow and ductile faulting in the IP. IP mineral-shape lineations are thought to track ductile flow of plastic type-F thrust sheets. Using these patterns and orogen-parallel map-scale sheath fold axes, a model has been developed for the trajectories of IP tectonic transport, in which NW- and W-directed transport and flow were deflected to the SW by a footwall buttress beneath the Neoacadian BFZ during thrust emplacement (Hatcher, 2001; Merschat et al., 2005; Hatcher and Merschat, in press). A gradual change in the orientation of structures in a 15-20 km wide belt immediately above the BFZ is thought to result from a gradual change in displacement direction from NW to W as the BFZ is approached and to SW proximal to the BFZ. Davis (1993) suggested that this area above the BFZ, the zone of constricted alignment (Fig. 3-7), had deformed by a combination of pure and orogen-parallel simple shear, resulting from extension, ductile thrusting, and horizontal shearing. These factors combined with the environmental conditions required for high-grade metamorphism and migmatization, ultimately produced SW-directed net displacements and lateral extrusion of ductile rock masses near the base of the IP.

No curved lineation pattern can be surmised from linear fabric patterns in this study (Fig. 3-8). The apparent lack of curved lineation patterns for the present study area may simply be a result of lying within the Neoacadian BFZ and the zone of constriction, and does not necessarily imply that these patterns are not present in the northeastern IP.

Evidence for the SW-directed ductile extrusion of IP schists and gneisses does exist in the form of SW-vergent D_2 sheath folds in both eastern and western IP terranes. Eastern IP F_2 sheath folds must have developed after eastern IP anatectic magmatism (~407 Ma), but before BCFZ emplacement (~360 Ma), as they are cored by anatectic melts restricted to the eastern IP and truncated by the BCFZ (Fig. 3-2; Plates 1 and 3). These folds were likely developed shortly after intrusion and transposition of eastern IP anatectic melts by regional inhomogeneous simple shear generated by a combination of subduction by the Carolina superterrane and SW-directed extrusion or “escape flow” by the eastern IP. These structures are the product of long-term subduction of eastern IP lithologies by the Carolina superterrane, and are successively overprinted and transposed by late Neocadian, Alleghanian, and later fabrics.

Strongly aligned NE-SW trending mineral lineations present in the study area are parallel to SW-vergent F_2 sheath folds and NW-vergent F_3 fold hinges (Figs. 3-8 and 3-9). This evidence suggests that D_2 linear fabrics are oriented parallel to SW-vergent transport. Parallel orientations of L_2 mineral lineations and D_2 sheath fold hinges can be explained by their simultaneous development during D_2 and SW-directed crustal flow. D_4 S-C fabric intersection lineations, SE-plunging crenulation axes, and axes of SW-vergent F_4 folds are parallel and overprint earlier D_2 SW-vergent and D_3 NW-vergent folds, NE-SW oriented mineral lineations, and NE-SW trending planar fabrics.

The above suggests that transport during D_2 was SW-directed, followed by NW-directed transport during D_3 , and SW-directed transport during D_4 . However, material transport during D_1 , D_2 and D_3 may have been orthogonal to tectonic transport due to melt weakening and ductile extrusion of material to the SW. If so, this explains the strong constriction of linear fabrics proximal to the BFZ and BCFZ as a flow lineation. Intense migmatization and thermobarometric data support the conclusion that northeastern IP rocks were above minimum melt conditions during the Neocadian. Therefore, it is plausible that strongly aligned L_2 mineral lineations in the study area represent a syn-post-Neocadian flow lines.

Kinematic indicators display consistent shear sense throughout the study area. Rotated porphyroblasts, S-C fabrics, asymmetric folds, shear bands, mica fish, rotated porphyroclasts, quartz ribbons, and deflected foliations show dominantly top-to-the-SW transport for the northeastern IP (Figs. 3-5, 3-10 and 3-20). Strongly NE-SW oriented L_2 mineral lineations are parallel to the overall shear sense of the region, suggesting a genetic relationship between linear fabrics and transport. Some NW-verging D_2 folds in domain I record initial dip-slip convergence. D_2 linear fabrics and top-to-the-SW shear

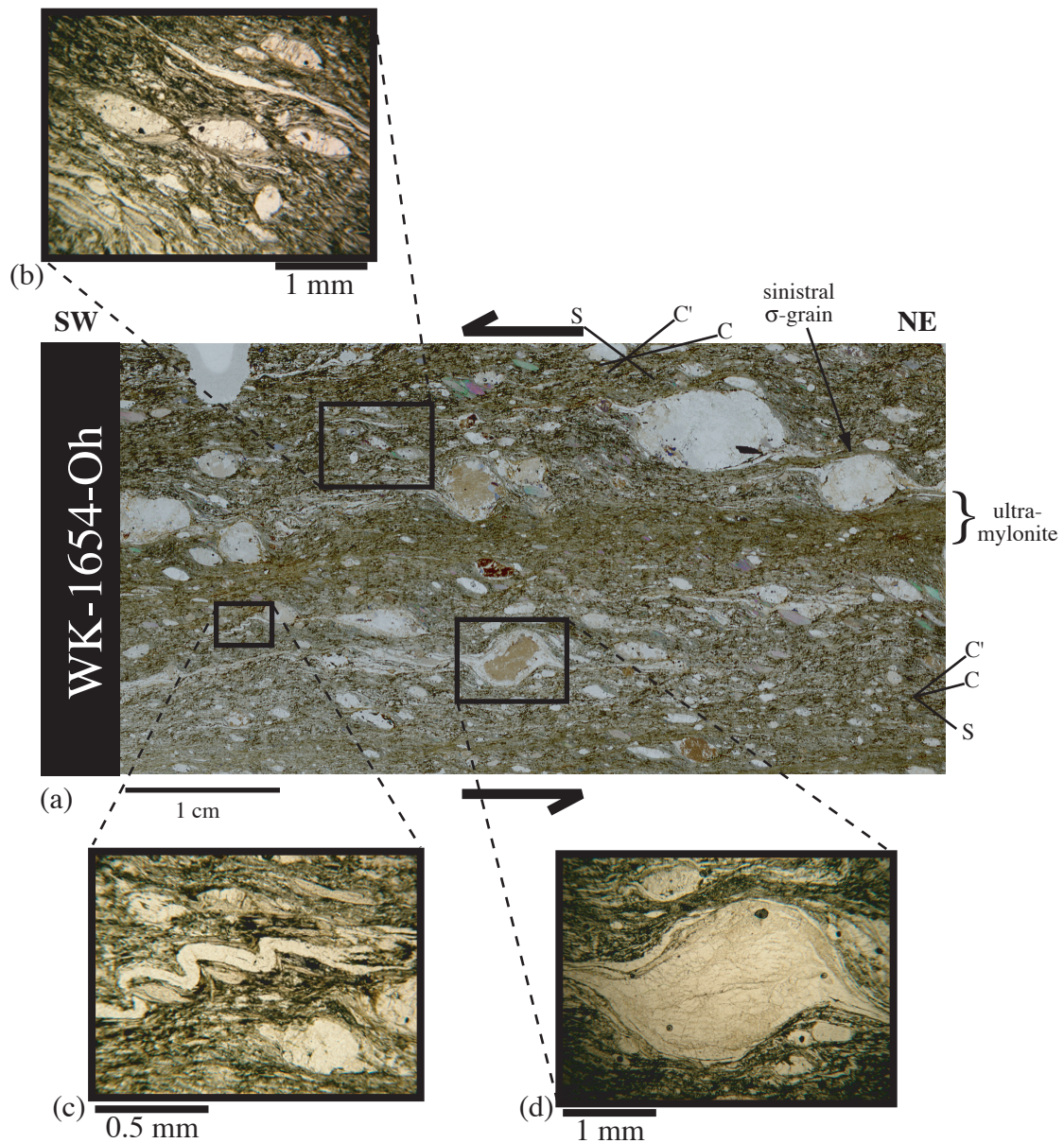


Figure 3-20. Microstructural kinematic indicators from the study area. Note the consistency of shear sense indicators consisting of mica fish, S-C fabrics, σ - and δ -grains, asymmetric microfolds, and stair-stepping geometries of microboudinage. (a) Scanned thin section of mylonitic Henderson Gneiss near Whites Creek in plane-polarized light. (b) Enlarged image showing deformed microboudinage of quartzofeldspathic material. Note the top-to-the-SW stair stepping geometries. (c) Enlarged image of SW-vergent F4 microfolds with σ -grains indicating top-to-the-SW shear sense. (d) Enlarged image of a sheared δ -clast indicating top-to-the-SW shear sense.

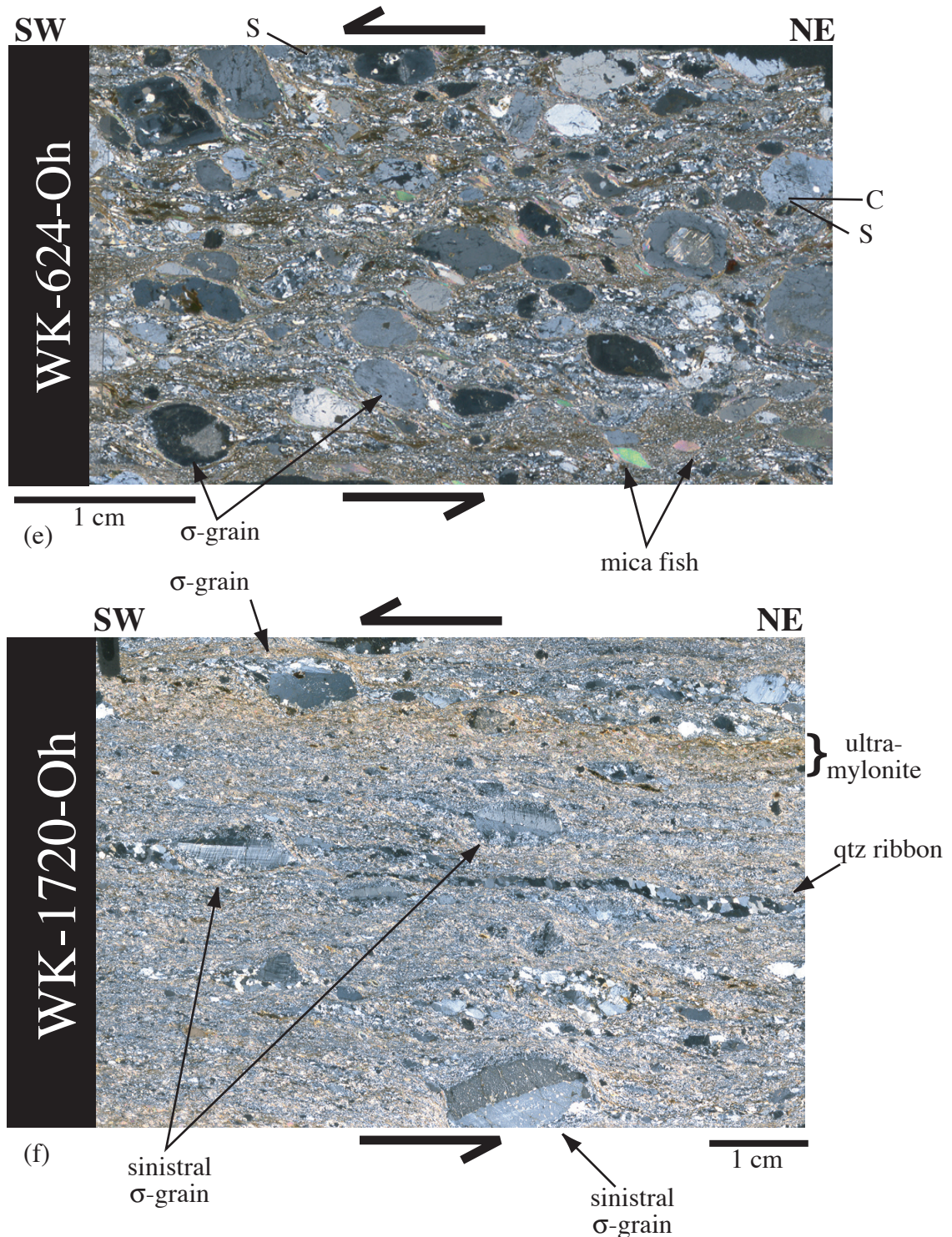


Figure 3-20 continued. (e) Scanned thin section of mylonitic Henderson Gneiss (cross polarized light). The sample locality is near the W Kerr Scott reservoir. Note the top-to-the-SW shear sense from mica fish, S-C fabrics, and rotated porphyroclasts. (f) Scanned thin section of mylonitic Henderson Gneiss from near Poplar Grove Church (crossed polarized light). Note the consistency of shear sense from σ -clasts.

sense indicators, however, reveal the transpressive nature of D_2 , in which synkinematic mineral lineations track incremental flow paths (Worley and Wilson, 1996) and deflection of northeastern IP thrust sheets to the SW after buttressing. SW-directed crustal flow can be attributed to constricted, internal, dextral plastic flow caused by buttressing of crystalline thrust sheets against the Neoacadian BFZ (Hatcher, 2001; Davis, 1993; Merschhat et al., 2005). Data from this study support the conclusions of Davis (1993) and subsequent workers; the dominant transpositional deformation event likely occurred during the Neoacadian orogeny and had a significant dextral flow component. The consistent nature of shear sense indicators qualitatively infer a dominance of simple shear in the IP during D_2 ductile deformation. During D_4 , transport was likely again SW-directed, but under lower P-T conditions. A predominance of oblate planar D_2 and D_3 fabrics suggests that the main foliation is due to pervasive flattening rather than simple shearing. However, it is also possible that previously developed D_1 S-surfaces acted as slip planes during simple shear dominated D_2 and D_4 events, producing the SW-vergent overprinting fabrics observed in the study area.

Structural relationships in the Brushy Mountains provide evidence for a developmental model of the northeastern IP similar to those envisaged by previous investigators, with modifications to incorporate new data from this study. Modifications are designed to also incorporate new geochronologic data, which provide additional timing constraints, and are summarized in Table 3-1. Initially, eastern and western IP terranes underwent separate D_1 events, as evidenced by differing early deformational styles and the partitioning of anatectic melts across the BCFZ. Western IP D_1 structures indicate that some map-scale folds in Tallulah Falls Formation metasedimentary assemblages were developed prior to TCFZ emplacement, likely during a pre- to early Neoacadian orogenic event. Eastern IP D_1 structures were developed before BCFZ emplacement, but after eastern IP anatectic magmatism. This is likely related to a pre- to early-Neoacadian subduction of the eastern IP beneath the Carolina superterrane outboard of the western IP. Subduction led to high-grade metamorphism and anatectic magmatism ~407 Ma and successive SW-directed extrusion of ductile rock masses, resulting from regional inhomogeneous simple shear, and producing macroscale sheath folds cored by anatectic melts in the eastern IP. Emplacement of the BCFZ occurred during the Neoacadian orogeny, producing ductile D_2 and D_3 structures during continued migmatization and high-grade metamorphism, which transposed and masked earlier fabrics. Parallel top-to-the-SW shear sense indicators and NE-SW oriented mineral lineations suggest that initial NW-convergence was followed by SW-directed transport

and crustal flow during D_2 transpression. Continued thrust emplacement causing uplift and cooling occurred over the course of D_3 , but was NW-vergent as evidenced by fold asymmetry. Alleghanian D_4 deformation brought about differing deformational styles and structures as cooler lithotectonic assemblages underwent dextral strike-slip transport along preexisting fault and shear zones. This orogenic pulse took place over the transition from ductile to brittle deformational styles, overprints all previously developed fabrics, and is responsible for additional SW-vergent kinematic indicators in the study area. D_5 and D_6 produced brittle extensional structures that overprint all earlier structures and are likely related to Alleghanian and post-Paleozoic orogenic pulses.

CROSS SECTION INTERPRETATION

Subsurface relationships in the study area are illustrated in four cross sections oriented roughly perpendicular to the strike of dominant planar fabrics (Fig. 3-2; Plate 1). Although Ramsay (1967) demonstrated the inefficiency of cross sections for interpreting fabric data from polydeformed terranes, clearly the constricted NE-SW alignment of structures here permits their use. Parallel cross sections A-A', B-B', and C-C' were constructed primarily to depict the relationships of macroscale fault zones in the northeastern IP. Relative steep dips depicted for thrust faults are interpreted to be the result of later folding and transposing events.

Section A-A'

Section A-A' (Fig. 3-2; Plate 1) illustrates the subsurface geometries of the BCFZ and PSSZ in the southwestern part of the study area (Fig. 3-21). The BCFZ juxtaposes eastern and western IP lithologies. New mapping from this study has shown that F_1 sheath folds in the Brindle Creek thrust sheet (PSSZ) are truncated at depth by the BCFZ as depicted in this section. F_2 and F_3 tight to isoclinal folds fold hanging wall and footwall lithologies together along the BCFZ. Metagraywacke and schist units are thought to be conformable, and may be genetically related. Contact relationships between metasedimentary and metaigneous lithologies are depicted as concordant. Toluca Granite lithologies are folded with boudinaged limbs. Walker Top Granite bodies are shown as layer-parallel sills folded into F_1 map-scale sheath folds and exhumed in shear zones. Macroscale sheath folds are refolded and transposed by later F_2 and F_3 structures. Strike-slip motion is indicated but cannot be illustrated due to the orientation of the section.

Section B-B'

Section B-B' (Fig. 3-2; Plate 1) traverses the Neoacadian BFZ and the BCFZ. Four major fault zones, the TCFZ, MSFZ, BCFZ, and PSSZ, are depicted in this section (Fig. 3-21). Differences in F_1 fold style between eastern and western IP terranes are best illustrated in this section. Western IP F_1 folds exist as map-scale anticline-syncline pairs in the footwall of the discontinuous TCFZ, while eastern IP F_1 folds occur as map-scale sheath folds. Macroscale folds in the western IP are recognized by the repetition of stratigraphic units in the Tallulah Falls Formation. The TCFZ is recognized by strong mylonitic fabrics in the Henderson Gneiss near contacts. Dismembered bodies of Henderson Gneiss are characteristic of the western IP in the area and are likely the products of a boudinaged early Neoacadian thrust sheet containing the Henderson Gneiss. Neoacadian A-type subduction and deformation likely folded and dismembered the TCFZ. Shear sense indicators also show a large component of dextral strike-slip movement between the Henderson Gneiss and underlying lithologies, suggesting that further detachment of the Henderson Gneiss bodies could have occurred during a later orogen-parallel deformational event. The MSFZ is primarily a strike-slip fault and truncates all earlier western IP structures. Folding of the MSFZ likely occurred post D_4 and after fault development.

The folded BCFZ is shown to the southeast and truncates F_1 structures in the PSSZ. The PSSZ is shown to have a shallower dip than in section A-A', which can be attributed to late folding events. F_2 and F_3 folds refold F_1 fabrics. Evidence for late strike-slip motion exists along all fault zones. Foliation form lines and intrusive contacts between the Toluca Granite and metasedimentary lithologies illustrate map-scale F_5 refolds of earlier (F_2 and F_3) fold generations.

Section C-C'

Section C-C' also includes a segment of the Neoacadian BFZ and the BCFZ. This section best illustrates the juxtaposition of eastern and western IP lithologies along the folded BCFZ. As in section B-B', macroscale folds in the Tallulah Falls Formation are truncated by the Henderson Gneiss in the tightly folded TCFZ. Map relationships infer truncation of the TCFZ by the MSFZ near the western boundary of the study area. Therefore, the MSFZ here is shown to truncate the TCFZ and associated lithologies.

Map patterns clearly indicate the isoclinally folded nature of the BCFZ and its truncation of the PSSZ. Map-scale folds plunge to the southwest and expose the Silurian Brooks Crossroads Pluton in an embayment on the BCFZ. An additional body of Walker

Top Granite is exposed near the eastern boundary of the Moravian Falls quadrangle and is interpreted in this section to be fault bounded based on mylonitic textures near contacts. However, insufficient exposure and outcrop area do not permit a more detailed structural interpretation. Late (F_5) open folds can be seen to refold earlier fold generations, and NE-plunging folds in Toluca Granite bodies are inferred to be present in the subsurface here.

CONCLUSIONS

1. Four map-scale shear zones, the TCFZ, the MSFZ, the BCFZ, and the PSSZ, are present in the study area and are orogen parallel, striking northeast-southwest across the Moravian Falls quadrangle.
2. Six successive deformation events can be recognized in the northeastern IP, roughly corresponding to those outlined by previous investigators.
3. Eastern and western IP terranes experienced separate D_1 events, as indicated by deformational style and geochronologic constraints, before being deformed and metamorphosed together during D_2 .
4. Truncated macroscale F_1 folds in the TCFZ footwall must have formed earlier than the crystallization age of the Henderson Gneiss (~490 Ma).
5. Development of the TCFZ must postdate the age of the Henderson Gneiss, and is likely related late Taconian to early Neoacadian thrust emplacement.
6. The Walker Top and Toluca Granites occur exclusively southeast of the BCFZ and must have intruded eastern IP lithologies before BCFZ emplacement.
7. Map patterns show laterally continuous tabular bodies of Walker Top Granite occurring in map-scale shear zones throughout the study area, suggesting that these bodies are present in the lowermost portions of the Brindle Creek thrust sheet and are exhumed along fault zones as the thrust sheet is successively imbricated to the SE.
8. Developments of both the PSSZ and the BCFZ must postdate the crystallization age of the Walker Top Granite (~407 Ma).
9. Truncation of PSSZ by the BCFZ further constrains the timing of PSSZ development to 407-360 Ma.
10. Penetrative D_2 structures in the Moravian Falls quadrangle were developed during the Neoacadian tectonothermal event and are orogen-parallel.
11. As evidenced from F_2 and F_3 fold interference patterns D_2 and D_3 structures represent an initial and continued emplacement of the BCFZ.

12. L_2 mineral lineations parallel hinge lines of SW-directed F_2 sheath folds and NW-vergent F_3 folds in eastern and western IP terranes, suggesting their simultaneous development during initial NW- followed by SW-, and finally NW-directed thrust sheet emplacement during the Neoacadian. These fabrics define a flow lineation developed in response to high-grade metamorphism and migmatization during the Neoacadian, causing SW-directed crustal flow and extrusion of material. Ubiquitous top-to-the-SW shear sense indicators further support this hypothesis.
13. Persistent D_4 folds and shear fabrics indicate SW-directed transport and overprint earlier NW-vergent structures.
14. The MSFZ is a dextral strike-slip fault, which truncates NW-vergent D_2 and D_3 fabrics, and likely coincides with SW-directed transport during D_4 .
15. Dismemberment of the Henderson Gneiss body in the northeastern IP could have occurred either during Neoacadian thrust emplacement (D_2 and D_3) or early dextral reactivation of the Neoacadian BFZ (early D_4), but must have occurred before the development of the MSFZ.
16. The transition from ductile to brittle deformation in the northeastern IP likely took place over the course of D_4 as indicated from the transition from passive to flexural fold styles.
17. Foliation patterns permit subdivision of the study area into three distinct domains.
18. The zone of constricted flow corresponds to domain I and encompasses most of the study area. Domain II is recognized by a deflection of foliations near the BCFZ. Domain III shows similar patterns to domain I, but is separated by differences in dip direction and magnitude.
19. Mineral lineations are consistently oriented throughout the study area and no curvature or deflection of linear fabrics is apparent. The proximity of the BFZ to the study area may account for this apparent constriction of fabrics.
20. Kinematic indicators show a dominance top-to-the-SW shear sense most likely resulting from dextral strike-slip movement during D_2 and D_4 . A significant component of orogen-parallel simple shear would be required to overprint NW-vergent fabrics developed during earlier deformational events. However, overprinted F_2 and F_3 folds are asymmetric and indicate initial NW-directed transport.
21. Structures in the study area are overprinted by two younger generations of open folds and joint sets.
22. Structural observations and analyses provide evidence for a qualitative model in

which initial NW-directed convergence and subduction of eastern IP lithologies evolved to NW-directed terrane accretion and orogenesis and were ultimately followed by SW-directed orogen parallel transport between thrust sheets. Structures produced during these events are successively overprinted by later brittle fabrics developed during extension and uplift.

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PART IV

High-Temperature Mylonite Formation and Petrogenesis of Northeastern Inner Piedmont Orthogneisses: Structural and Geochemical Analyses of Ductile Shear Zones

ABSTRACT

Granitic mylonites from two northeastern Inner Piedmont (IP) high-temperature retrograde shear zones, the Tumblebug Creek fault zone (TCFZ) and Brindle Creek fault zone (BCFZ), were studied to investigate the relationship between mineral reactions, deformation mechanisms, fluid flow, volume loss, and mylonitization. Regional SW-trending linear fabrics developed in a zone of strong transpression and track fluid flow paths through the shear zones. In general, shear zone formation is characterized by the breakdown of feldspar and possibly quartz with the formation of white mica, myrmekite, and ferromagnesian phyllosilicate phases. Deformation in the shear zones occurred by crystal-plastic mechanisms at temperatures $>400^{\circ}\text{C}$. Silica and alkalis were mobile and lost from the system, while Al_2O_3 , ΣFe , MnO , MgO , Na_2O , TiO_2 , and P_2O_5 , immobile trace elements, and REE remained relatively immobile during deformation and metamorphism. Gains and losses of these components are consistent with feldspar dissolution and recrystallization, and are interpreted to result from moderate volume losses. Isocon analyses suggest that volume loss of 41 and 48% occurred for the TCFZ and BCFZ, respectively.

INTRODUCTION

During the development of orogenic belts, accretionary events are often recorded by the development of shear zones, which are marked by the presence of mylonite in deeply eroded and exhumed metamorphic cores. Although textural characteristics of these fabrics are easily recognizable and likely develop from well-documented processes (Higgins, 1971; Sibson, 1977; White et al., 1980; Tullis et al., 1982; Wise et al., 1984; Simpson, 1985; Passchier and Trouw, 1996), their chemical and isotopic evolution is considerably more complex. Ubiquitous features of exhumed metamorphic terranes, retrograde shear zones are sites of enhanced metamorphic reactions (White and Knipe, 1978), and conduits through which large volumes of crustal fluids circulate. Thus, large ductile shear zones can be considered a fundamental feature of metamorphic flow patterns (Etheridge, 1983), and are invaluable for the study of coupled deformation and metamorphism.

In areas undergoing dynamic metamorphism, the presence of a fluid phase is perhaps the most controlling factor in large-scale physical, chemical, and isotopic changes in rocks. The flux of fluids through midcrustal shear zones affects the rates of chemical and mechanical processes occurring during progressive deformation by

enhancing solution transport, microfracturing, and recrystallization (Sinha et al., 1986). By altering the compositions and rheologies of mineral assemblages present, fluid flux can produce drastic changes in deformational style within ductile shear zones. Doubtless, shear zones also develop in fluid-poor environments (Passchier, 1985) where physically dominated processes (heat, grain size reduction and recrystallization) control mineral paragenesis. These processes are consequently isochemical, however, and unlikely to cause any significant alteration of the chemical properties of the system. Conversely, analyses of shear zones in which addition of fluids has commonly occurred reveal important differences between the protolith and mylonitic rocks derived from it. Studies of chemical variation and mineral paragenesis in shear zones that have undergone localized strain and fluid-enhanced recrystallization are crucial for resolving the extent of metamorphic equilibration and its effect on the physical attributes of the rocks.

The northeastern Appalachian IP is ideal for study of Paleozoic retrograde shear zones. Long-term exhumation of midcrustal shear zones provides for an opportunity to explore the internal portions of a Paleozoic mountain chain. The presence of several large ductile fault zones close to one another provides a unique opportunity to study the characteristics and interaction of these crustal-scale structures. This study investigates the structural makeup and the behavior of chemical constituents in a fluid-rich high-strain zone to gain better insight into the relationships between midcrustal deformation and metamorphism. To document these characteristics, portions of two large northeastern IP retrograde shear zones, the Brindle Creek fault zone (BCFZ) and the Tumblebug Creek fault zone (TCFZ), were selected. Recent detailed geologic mapping and structural analyses (Parts II and III) have delineated their geometries and structural developments and revealed large strain gradients across the shear zones with deformational rock types ranging from protomylonite to ultramylonite. Accessibility of shear zones possessing such a range of fault rocks provides an opportunity for comparison of petrographic, textural, structural, and chemical characteristics of rocks in two high temperature shear zones that have undergone varying degrees of deformation. These different analyses are employed here to derive a physical model for the development of northeastern IP retrograde high temperature shear zones.

GEOLOGIC SETTING

The IP comprises a large portion of the metamorphic core of the southern Appalachians (Fig. 4-1). Three orogenic events occurred during the Paleozoic to produce several successive episodes of deformation and metamorphism in the IP. Northeastern IP

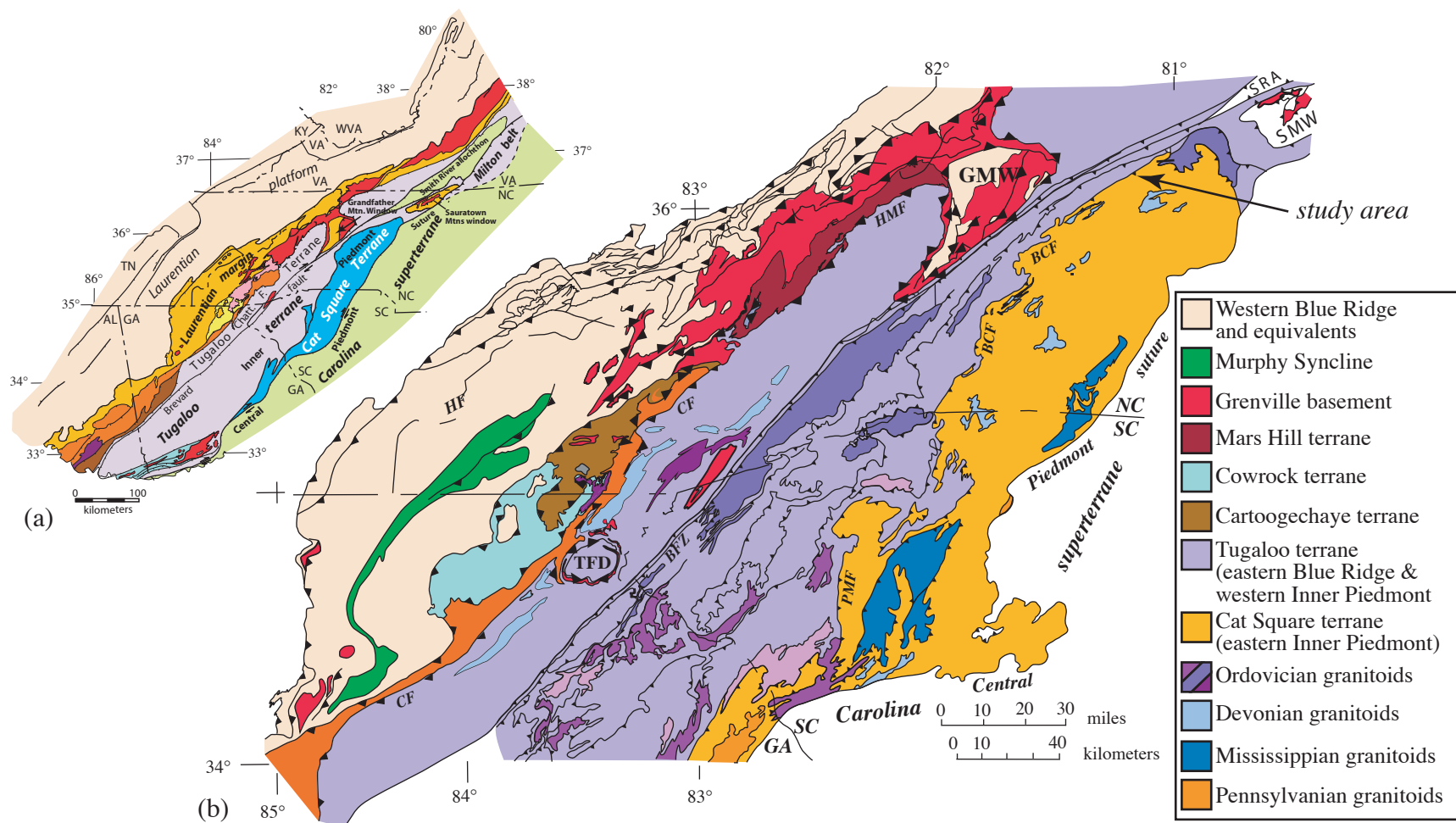


Figure 4-1. Southern Appalachian index maps, modified from Hatcher (2002). (a) Southern Appalachian tectonostratigraphic terranes. (b) Tectonic map of a portion of the southern Appalachians with sample locations. AF-Allatoona fault; BCF-Brindle Creek fault; BFZ-Brevard fault zone; CF-Chattahoochee fault; CPS-Central Piedmont suture; GMW-Grandfather Mountain window; HF-Hayesville fault; HMF-Holland Mountain fault; GLF-Gossan Lead fault; SMW-Sauratown Mountains window; SRA-Smith River allochthon; TFD-Tallulah Falls dome.

shear zones addressed here were likely developed during the Neoacadian (360-340 Ma) orogeny and reactivated during the Alleghanian (325-265 Ma) orogeny. Both involve ductile deformation of megacrystic granitoids reveal multiple episodes of deformation under ductile conditions that were later overprinted by brittle structures (Part III). These shear zones were likely developed and reactivated simultaneously in similar settings. Megacrystic granitic gneisses present in both shear zones contain excellent strain markers and present a unique opportunity to study two complete suites of mylonitized rock ranging from protomylonite to ultramylonite. Megacrystic lithologies chosen for analysis include the ~490 Ma Henderson Gneiss and the ~407 Ma Walker Top Granite.

Numerous recent studies have documented the nature and characteristics of IP metamorphism. These studies have yielded peak estimates of kyanite- to sillimanite I- and locally sillimanite II grade conditions to granulite facies and documented peak metamorphism as occurring between 360 and 340 Ma (e.g. Dennis and Wright, 1997a; 1997b; Hill, 1999; Bream et al., 2000; Mirante and Patino-Douce, 2000; Williams, 2000; Bier, 2001; Carrigan et al., 2001; Mirante, 2001; Kohn, 2001; Kalbas et al., 2002; Mersch, 2003). Textural evidence indicates that northeastern IP lithologies have experienced sillimanite-grade conditions during two separate metamorphic pulses (Part II). For the northeastern IP, mineralogical characteristics and P-T estimates suggest that peak sillimanite I grade conditions followed kyanite-grade conditions and a clockwise P-T path can be inferred from these results (Part II). These results indicate that northeastern IP shear zones were developed under initial upper amphibolite conditions and later reactivated under retrograde amphibolite then greenschist conditions.

ANALYTICAL PROCEDURES

Structural Analysis

A detailed geologic map of the Moravian Falls quadrangle and the northwestern portion of Taylorsville quadrangle were constructed during the 2003 and 2004 field seasons (January-July). Additional field excursions were conducted as necessary for sample collection and field reviews during 2004 and 2005. Structural analyses of all data were conducted on completion of all fieldwork. Coeval structures were initially grouped by their relative timing based on field observations, crosscutting relationships, and orientations. Oriented samples were collected from selected outcrops for microstructural analyses. Microstructures and petrofabrics were examined and interpreted for oriented standard (2.4 x 4.6 cm) and oversized (5.08 x 7.62 cm) thin sections.

Whole-rock Geochemistry

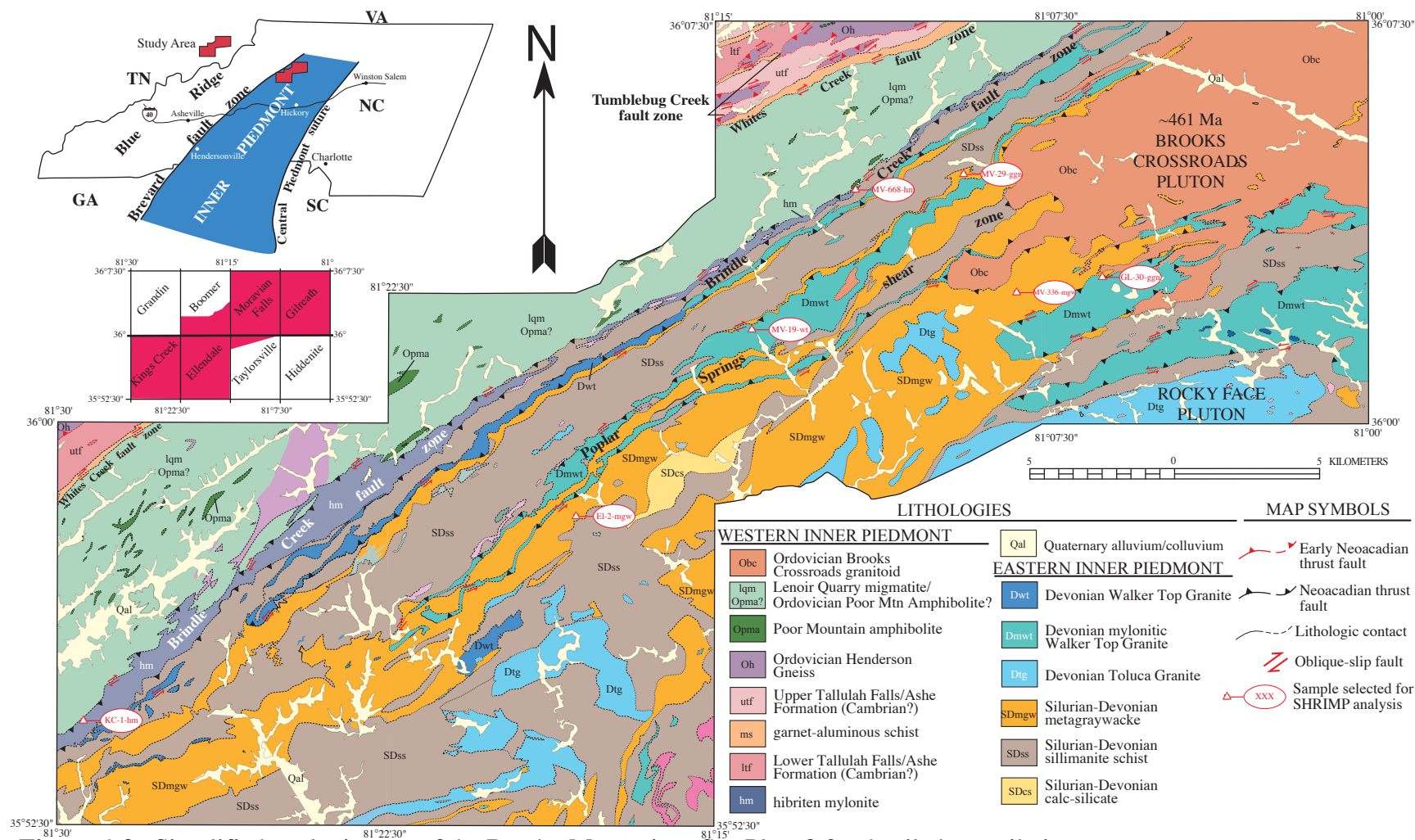
Fresh material was collected from the TCFZ and BCFZ for geochemical analyses. Weathering rinds were removed and representative thin slabs were cut with a diamond bit trim saw. Slabs were then washed with tap and distilled water, rinsed with isopropyl alcohol, overnight dried at ~85° C, and powdered in a shatterbox with an alumina ceramic mill. Multielement whole-rock analyses of the sample splits were then performed by Activation Laboratories (Ancaster, Ontario) using lithium metaborate/tetraborate fusion inductively coupled plasma optical emission spectroscopy (ICP-OES), inductively coupled plasma mass spectrometry (ICP-MS), near-total digestion ICP-MS, and instrumental neutron activation analysis (INAA). Analytical precision was validated by comparisons with 20 natural calibration standards.

NORTHEASTERN IP DUCTILE FAULT ZONES

Tumblebug Creek Fault Zone

The TCFZ has been recently delineated in the northwesternmost portions of the Moravian Falls and Kings Creek 7.5-minute quadrangles (Fig. 4-2). It is located within the Neoacadian Brevard fault zone (BFZ), and is recognized by the juxtaposition of mylonitic Henderson Gneiss with mylonitic metasediments of the Tallulah Falls Formation (Fig. 4-2). Degrees of mylonitization vary with proximity to the shear zone, in that more strain is accommodated near fault contacts and is manifested by the presence of ultramylonitic Henderson Gneiss (Fig. 4-3). Numerous separable bodies of Henderson Gneiss occur in the northeastern IP, each enveloped by the discontinuous TCFZ (Fig. 4-2). Previous detailed work closer to the main body of the Henderson Gneiss to the SW initially recognized the faulted nature of the contact between the Henderson Gneiss and footwall lithologies (e.g. Davis, 1993; Bream, 1999; Hill, 1999; Kalbas, 2003). Although mylonitic rocks are also present in the footwall of the TCFZ, they do not contain good strain markers and the megacrystic gneiss in the hanging wall is preferred for study.

The discontinuous nature of the TCFZ in the northeastern IP contrasts with the main body of Henderson Gneiss to the SW. To the northeast, a series of disconnected lenticular bodies of mylonitic Henderson Gneiss compose the hanging wall of the TCFZ (Fig. 4-2). Map patterns recognized here correspond well with those of previous studies in the northeastern IP (e.g. Bryant and Reed, 1970). Truncation of F_1 (Taconic?) map-scale folds in the TCFZ footwall may suggest that the Henderson Gneiss was intruded



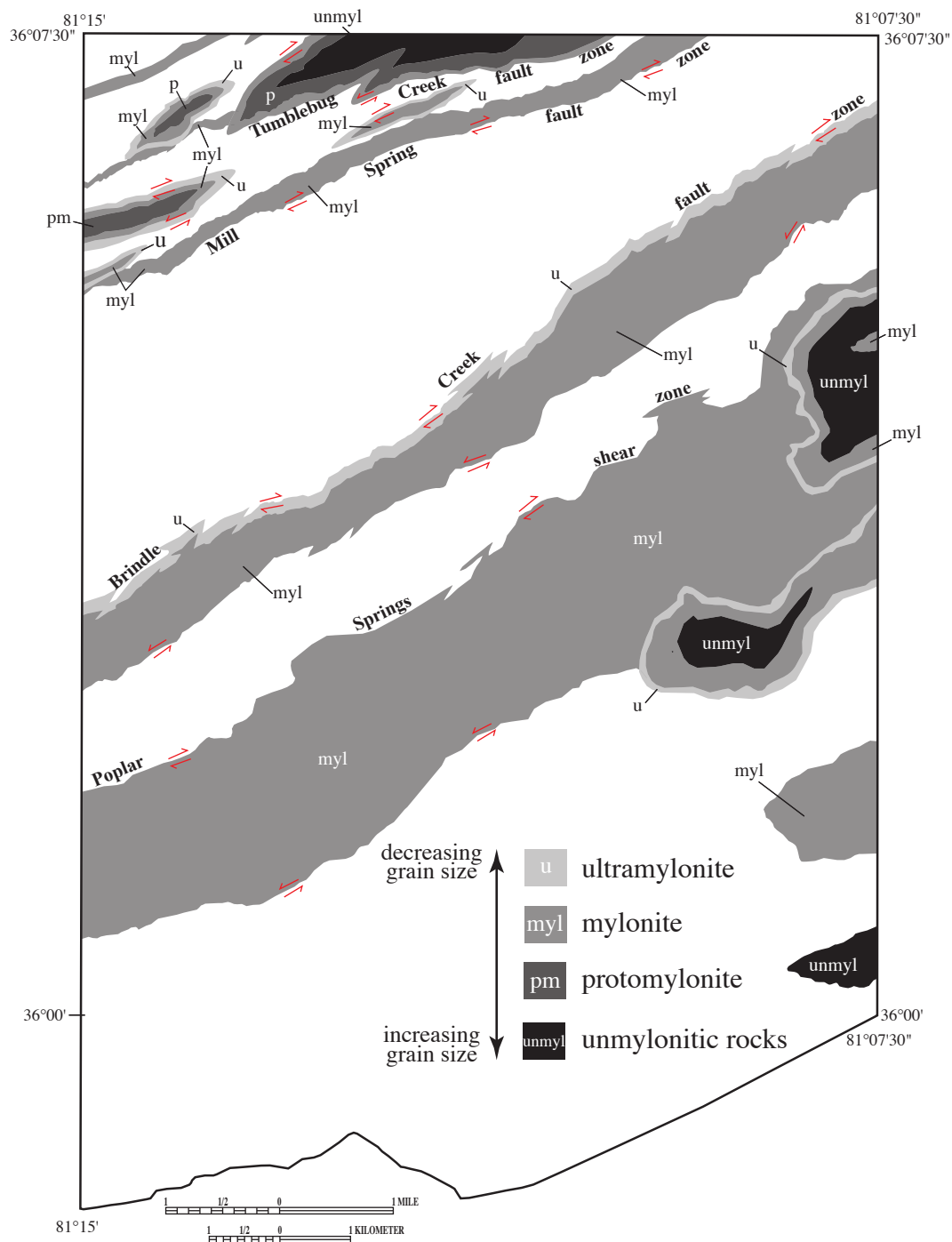


Figure 4-3. Distribution of mylonitic rocks and deformation gradients within the study area. Mylonitic textures are recognized by a reduction in grain size and the presence of S-C fabrics, shear bands, mica fish, assymetric folds, rotated porphyroclasts, and L-S tectonite fabrics.

elsewhere and then thrust over western IP lithologies during a later, possibly unrelated thrusting event (Hatcher, 2002; Merschat et al., 2005). Thus the Neoacadian would be a likely possibility for initial TCFZ development. Furthermore, folded fault contacts, petrofabrics, and outcrop patterns imply that after TCFZ emplacement, hanging wall and footwall lithologies were deformed together, developing the observed map-scale boudinage patterns due to strain partitioning between these units. Neoacadian thrust emplacement of the Brindle Creek sheet is a likely candidate for causing this style of deformation. If initial Neoacadian thrusting was northwest-directed, then A-type subduction of western IP lithologies beneath the eastern IP and Carolina terrane could have produced structures such as these by causing extensive pure shear and northeast-southwest extension. Additionally, dextral strike-slip movement between northeastern IP thrust sheets during late D_2 and D_4 could have further dismembered these bodies by reactivating earlier fault zones. Evidence for strike-parallel transport under moderate P-T conditions can be seen in meso- and microscale structures along the TCFZ (discussed below).

Map-scale lenses and boudins of the Tumblebug Creek thrust sheet resulting from northeast-southwest extension are successively pulled apart along the Neoacadian BFZ. Dextral strike-slip movement between the Neoacadian BFZ and BCFZ could have produced this style and pattern of deformation. Mylonitic fabrics observed in the Tallulah Falls Formation and all occurrences of Henderson Gneiss invariably display top-to-the-SW shear sense, indicating dextral strike-slip motion along the mid-Paleozoic BFZ. Also, ubiquitous top-to-the-SW kinematic indicators throughout the study area suggest a strike-slip component of dextral shear for all thrust sheets of the BFZ and BCFZ.

Brindle Creek Fault Zone

The BCFZ, first recognized by Giorgis (1999), is a Neoacadian terrane boundary juxtaposing eastern and western IP lithologies of different affinities (Bream, 2003). The BCFZ is continuous throughout most of the central and eastern IP of the Carolinas and northeastern Georgia, and may be the most significant fault in the IP, behind the Brevard fault and the central Piedmont suture. Recognition of the BCFZ in the study area is based on the presence of a variably wide shear zone composed heterogeneous lithology informally named the Hibriten gneiss by Kalbas (2003). Recent recognition of mixed eastern and western IP lithologies occurring within the fault zone has resolved the nature of this fault zone as a crustal-scale lithologic blending zone in which igneous and metasedimentary rocks of different affinities are juxtaposed against one another during

terrane accretion processes.

The restriction of the megacrystic Walker Top Granite to the eastern IP has been well documented by numerous investigators (e.g. Giorgis, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Mersch, 2003; Wilson, 2006). This lithology is easily recognizable and continuous throughout the South and Brushy Mountains, finally truncating near the northeasternmost portion of the study area (Fig. 4-2). The occurrence of tabular-shaped bodies within the BCFZ recognized during this study suggests a mechanical stratigraphy for the eastern IP, in which the Walker Top Granite is present along the lowermost portions of the Brindle Creek thrust sheet and brought to the surface along large shear zones and potential map-scale sheath folds (e.g., Mersch et al., 2005) occurring successively to the SE of the main BCFZ (Fig. 4-2; Parts II and III). High-strain zones near contacts contain mylonitic and ultramylonitic modifications of the protolith Walker Top Granite (Fig. 4-3), and provide an additional suite of mylonites from northeastern IP shear zones for study.

FAULT ZONE STRUCTURE AND KINEMATICS

Prominent structures within the mylonites are penetrative foliation and schistosity associated with a mineral lineation and isoclinal to tight shear zone-related folds. The foliation is marked by metamorphic and migmatitic banding. All foliations within the shear zones have anastomosing patterns at meso- and microscales. The mineral lineations are either characterized by the preferred alignment of sillimanite and hornblende or by ductilely stretched quartz-feldspar aggregates. The orientations of these structures vary somewhat because of postmylonitic folding.

Based on numerous occurrences of mylonitic fabrics throughout the IP, Davis et al. (1991) characterized the IP as a crustal shear zone. Regionally curved mineral lineation patterns are problematic for interpreting transport kinematics. Regional patterns indicate a systematic change in the orientation of subhorizontal mineral lineations and early fold hinges from strongly aligned northeast-southwest in the northwestern IP to east-west in the central IP to northwest-southeast in the southeastern IP (Fig. 4-4; Goldsmith, 1981; Bream, 1999; Hill, 1999; Giorgis, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Mersch, 2003; Wilson, 2006). Davis (1993) determined that regional IP lineations were developed during a high-temperature deformation, and proposed that the systematic change in linear fabric orientations track material flow and tectonic transport. More recently, these patterns have been used to reconstruct flow paths for IP thrust sheets (Davis, 1993; Mersch et al., 2005). These studies have concluded that a buttressing

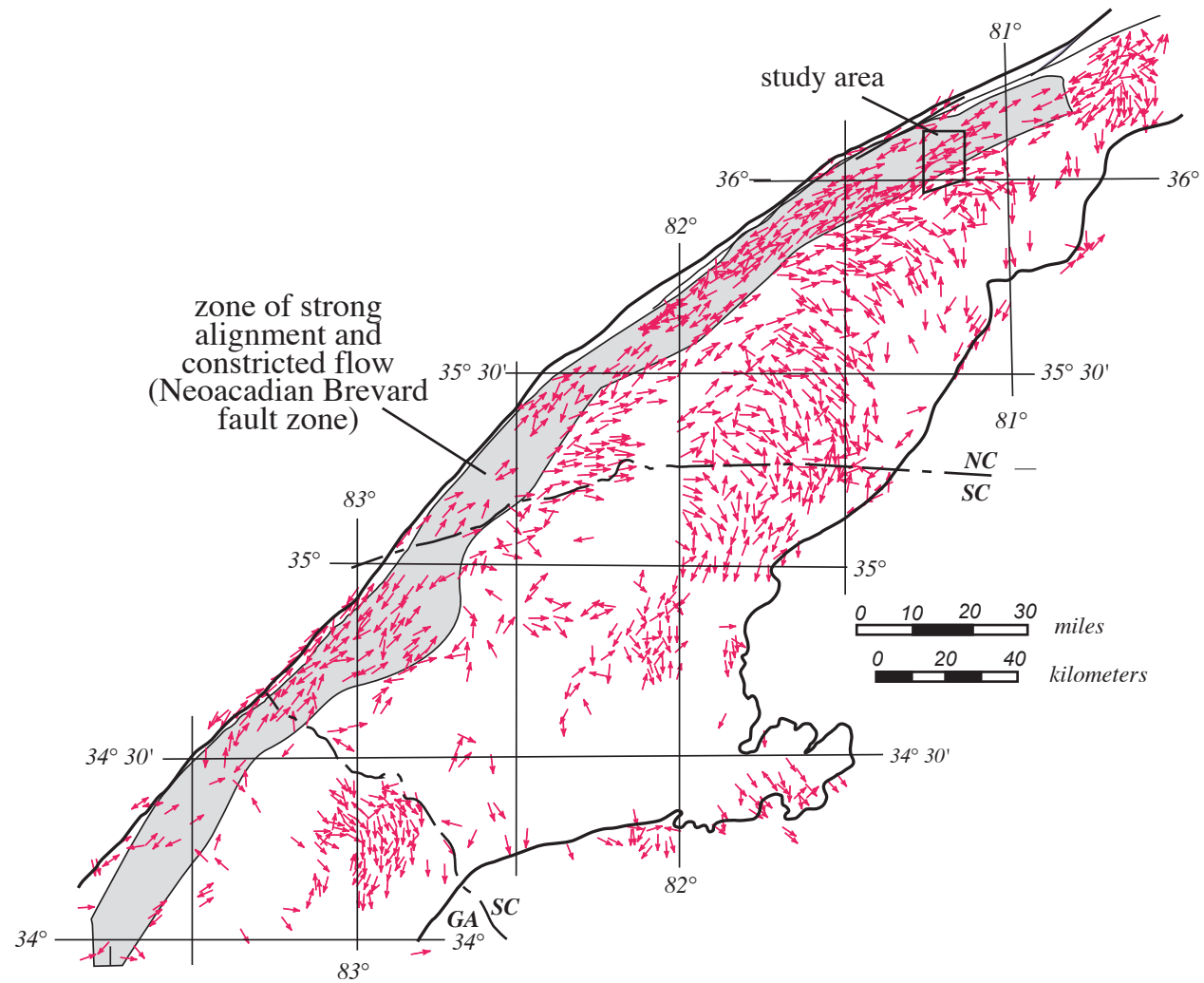


Figure 4-4. Mineral lineations for the northern part of the Inner Piedmont. Note that the study area (unfilled polygon) lies mostly within the zone of constriction. Modified from Hatcher (2001).

of initially northwest vergent IP thrust sheets against a NE-SW trending, SE-dipping structure (the early BFZ) could have deflected these thrusts to the SW in a strike-parallel transpression zone, and that the kinematics of these thrusts are manifested in regional lineation patterns (Fig. 4-4). Hatcher (2001) proposed that the initial localization of the early BFZ corresponds to a stratigraphically controlled zone of crustal anisotropy, and identified a zone of constricted flow (Fig. 4-4) immediately SE of the BFZ, containing strongly aligned NE-SW trending structures produced by SW-directed transpressional flow. This zone encompasses most of the present study area and includes the BCFZ and TCFZ included in this study.

The portion of the northeastern IP examined here lies completely within the zone of constricted flow and no deflection of linear fabrics is evident from map patterns (Part III). However, mineral lineations within the shear zones are invariably parallel to ubiquitous top-to-the-SW shear sense indicators throughout both shear zones. This indicates that late and possibly early motion along these was SW-directed (Part III), supporting the conclusions of Davis (1993) and Merschat et al. (2005). If these are flow paths, then this has important consequences for fluid flux vectors within the shear zones. Mesoscopic sheath fold hinges parallel these flow paths, indicating SW-directed ductile extrusion of material near the base of the IP (i.e. the zone of constricted flow). SW-directed net displacement of thrusts and material transport should correspond to focused fluid flow paths within the shear zones, and loss of material (volume) from components within the shear zones should escape to the SW.

MYLONITES

As noted above, mylonites from two similar thrust settings were studied; Henderson Gneiss lithologies from the western IP TCFZ and Walker Top Granite lithologies from the BCFZ. Both shear zones contain wide expanses of mylonitized granitic gneiss ranging from protomylonite to ultramylonite (Fig. 4-5). Because of petrographic similarities of the lithologies studied here (i.e. both are derived from porphyritic granitoids), with both showing similar mineralogical variations across textural variations (Table 4-1), their petrographic characteristics will be discussed together (see below).

Petrography

Protomylonitic rocks from both mylonite suites are porphyritic, medium- to coarse-grained, granitic to granodioritic in composition, and typically contain quartz,

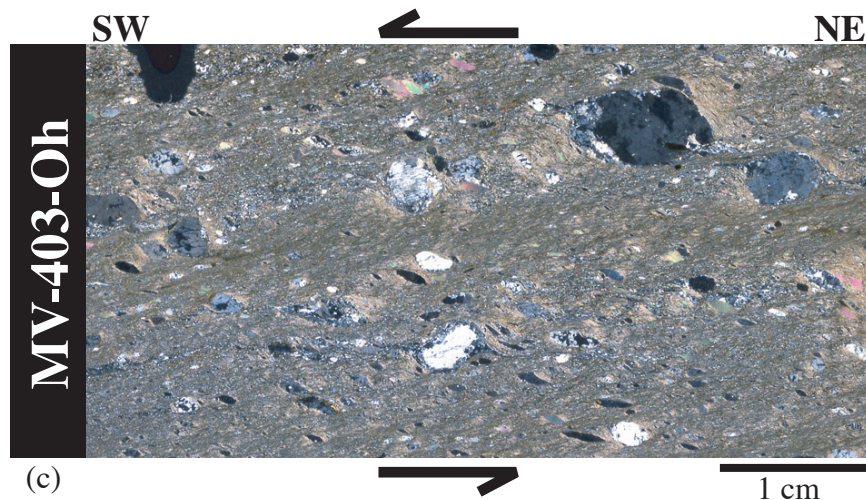
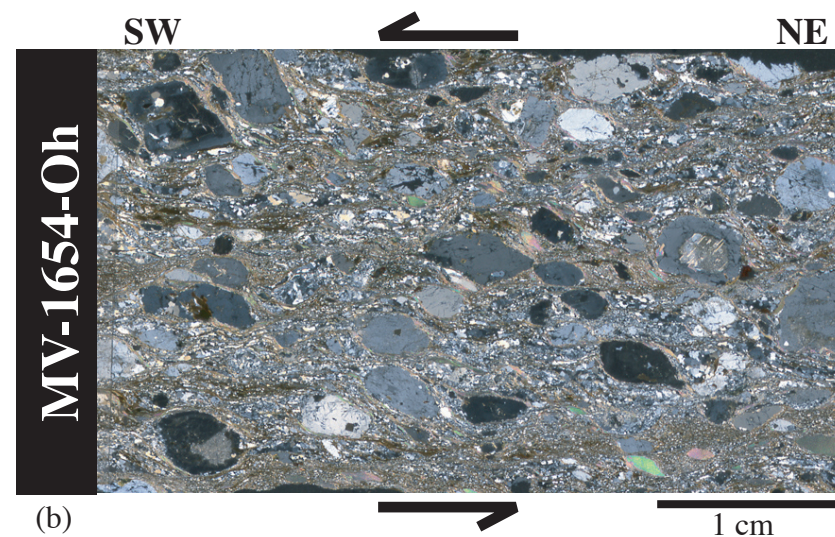
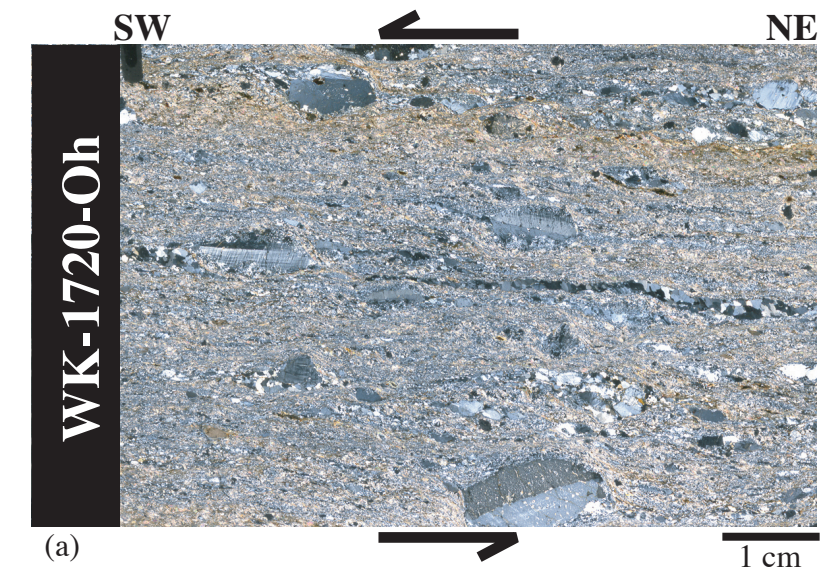


Figure 4-5. Microtextural variation of northeastern IP mylonites. Note the consistency of top-to-the-SW shear-sense indicators and grain-size reduction between differing degrees of deformation. Also, note the different scales of the photo-micrographs between textural variations. Mylonitic suite collected from the TCFZ. (a) Protomylonitic Henderson augen gneiss from near Poplar Grove Church. (b) Mylonitic Henderson Gneiss from off of HWY 268. (c) Ultramylonitic Henderson Gneiss from off of Germantown Rd. See Plate 2 for specific station locations.

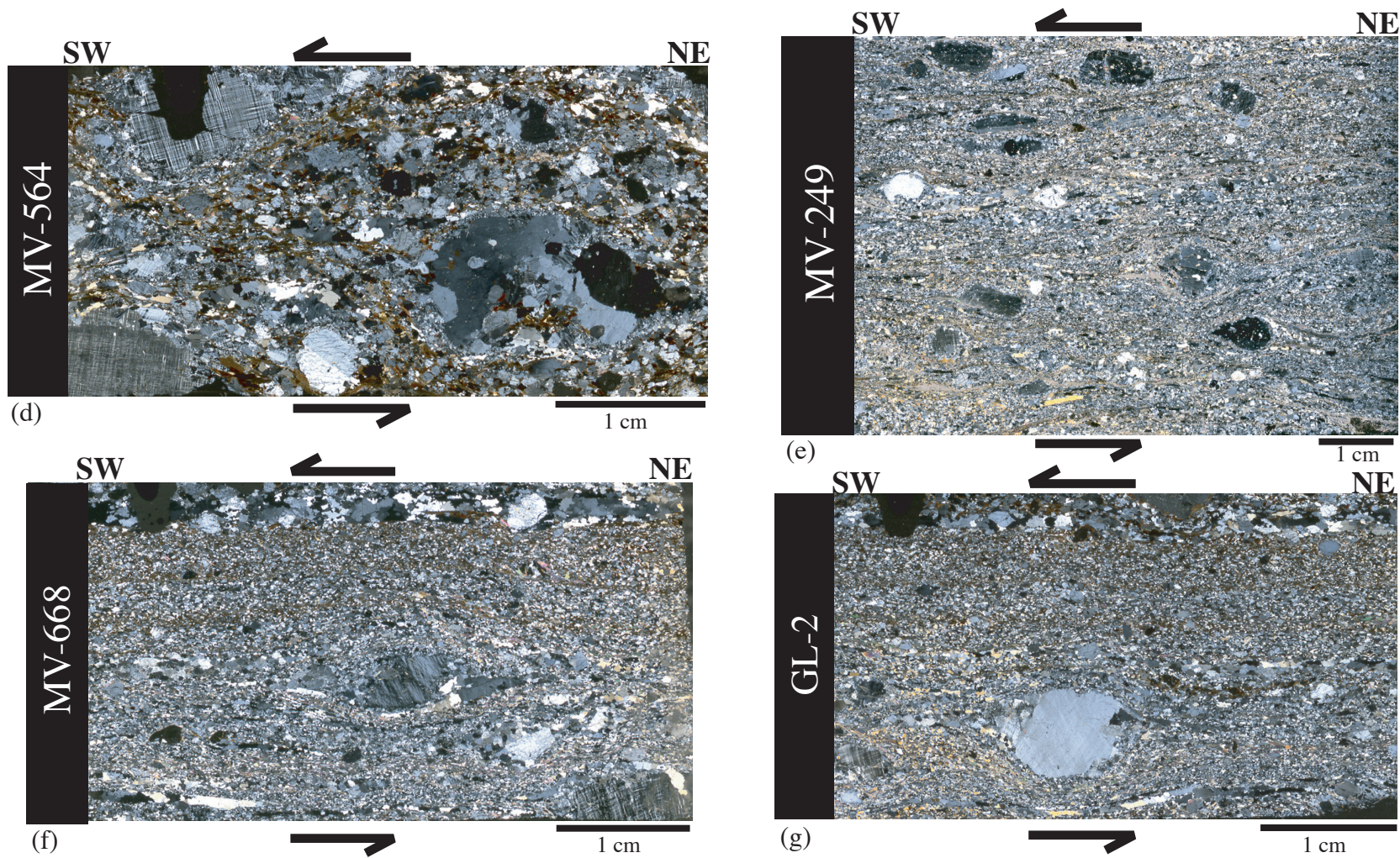


Figure 4-5 continued. (d) Protomylonitic megacrystic Walker Top Granite from Bald rock Mtn. (e) Mylonitic Walker Top Granite from Moravian Creek. (f and g) Ultramylonitic Walker Top Granite from the BCFZ off of Brocktown Rd.

Table 4-1. Modal analyses of mylonitic gneisses (%).

	TCFZ Henderson Gneiss*			BCFZ Walker Top Granite*		
	protomylonite	mylonite	ultramylonite	protomylonite	mylonite	ultramylonite
	n=2	n=3	n=2	n=5	n=4	n=3
Quartz	24.4	22.6	24.2	20.4	23.5	26.1
Plagioclase	32.1	20.6	5.3	31.7	17.8	7.7
K-feldspar	12.3	7.9	5.0	21.0	14.2	9.0
Hornblende	1.8	tr	-	-	tr	-
Biotite	12.4	14.7	19.5	18.4	21.4	24.7
Muscovite	4.9	7.3	11.5	3.4	9.8	12.9
Chlorite	tr	3.3	4.3	-	-	tr
Sericite	7.5	16.4	24.8	2.9	12.1	15.3
Myrmekite	2.4	3.6	4.4	1.5	2.7	2.2
Epidote	tr	tr	tr	-	-	tr
Garnet	-	-	-	0.7	tr	0.6
Sillimanite	-	-	-	-	tr	tr
Sphene	0.6	2.4	0.7	tr	tr	tr
Apatite	tr	tr	tr	tr	tr	tr
Zircon	tr	tr	tr	0.1	tr	tr
Monazite	tr	tr	tr	tr	tr	tr
Rutile	tr	tr	tr	tr	tr	tr
Allanite	tr	tr	tr	tr	tr	tr
Calcite	-	-	tr	-	-	-
Opakes	2.3	1.4	0.7	0.5	0.2	1.8
totals	100.7	100.2	100.4	100.6	101.7	100.3
density (g/cm ³)†	2.6	2.6	2.7	2.7	2.8	2.8

* 1000 points per sample.

† Bulk density based on modal composition using representative mineral densities.

tr = present but not counted.

alkali feldspar (perthitic microcline), plagioclase, biotite, muscovite, chlorite, and accessory garnet, zircon, epidote, sillimanite, sphene, apatite, monazite, rutile, allanite, calcite, and opaques (Table 4-1). Protomylonitic TCFZ Henderson Gneiss samples consist of augen gneiss mylonite, while protomylonitic BCFZ Walker Top Granite samples are megacrystic with blocky K-feldspar megacrysts (Fig. 4-5). A mesoscopic regional foliation is subparallel to the mylonitic foliation and is defined by elongated recrystallized quartz ribbons, biotite, and feldspar grains (Fig. 4-5). Large megacrysts of alkali feldspar and plagioclase are rimmed with recrystallized quartz, feldspar, and myrmekite (Fig. 4-5).

In the mylonite samples quartz usually occurs as elongate polycrystalline ribbons with large aspect ratios parallel to a well-developed lineation (Fig. 4-5). In sections parallel to lineation and perpendicular to foliation, feldspar clasts commonly have subrounded to rounded and elliptical shapes (Fig. 4-5). Although rounded feldspar grains reveal considerable grain-size reduction between the protomylonites and mylonites, they do not display brittle deformation by brittle processes. Alkali feldspars are invariably rimmed by myrmekite and quartz. Plagioclase in all mylonites is partially altered to sericitic muscovite, suggesting retrograding of the shear zones after a high temperature event. In general, feldspars display a monoclinic symmetry with respect to the foliation. The foliation that wraps the clasts commonly contains laths of muscovite fish, which provide excellent top-to-the-SW shear sense (Fig. 4-5).

Ultramylonite samples show almost completely recrystallized quartzofeldspathic material and the best-developed shear sense indicators of the mylonite suites (Fig. 4-5). Few K-feldspar clasts remain in the ultramylonites and all are rimmed by myrmekite. Samples display drastic grain-size reduction between mylonitic and ultramylonitic textures. Quartz is present in ultramylonites as small recrystallized matrix phases or polycrystalline ribbons and shows appreciable undulatory extinction, indicative of incomplete annealing. Alkali feldspar exists as flattened isolated clasts, while all plagioclase has been recrystallized (Fig. 4-5).

Comparison of the mylonites with the protolith gneisses indicates that the major modal mineralogical changes involved during deformation are a decrease in feldspar (from 40-50% in the protomylonites to 10-15% in the ultramylonites) and an increase in white mica (from 5-10% in protomylonites to 20-30% in the ultramylonites). Other major phyllosilicate phases present in greater abundance in the mylonites are chlorite and biotite (Table 4-1). Textural evidence suggests that the greater modal abundance of chlorite and sericite in the mylonites is due to late retrograde events affecting the shear

zones. Chlorite laths replace biotite and are oriented at a high angle to the mylonitic foliation. Sericite is present as an alteration product of feldspar and is oriented obliquely to primary micas that define the foliation.

Deformation Mechanisms

Quartz was deformed by crystal-plastic mechanisms in all rocks examined. It displays evidence for syntectonic recrystallization in mosaics of smaller grains and elongate monocrystalline and polycrystalline ribbons that show appreciable undulose extinction (Fig. 4-5). These microstructures provide a minimum estimate for temperature during deformation since crystal-plastic mechanisms operate above 300°C (Hirth and Tullis, 1992). Alternatively, strained quartz lattices could have developed during late movement along the shear zones under retrograde conditions, following the high-temperature deformation, which produced the mono- and polycrystalline ribbons.

Deformed feldspar clasts in the mylonites provide a much better estimate of the conditions of deformation than do quartz textures. The presence of ubiquitous recrystallized feldspar suggests that it attained its rounded shape during deformation by crystal-plastic processes. The oval shapes of all feldspars in the mylonite and ultramylonite (Figs. 4-5) samples reveal that cataclasis is not solely responsible for their geometries. This indicates that during and/or after deformation, ambient temperatures were >450°C where crystal-plastic mechanisms become important in feldspar deformation (Tullis, 1983).

GEOCHEMICAL TRENDS AND VOLUME LOSS

Theoretical Considerations

In the context of fluid-rock interaction, the relationship between trace element enrichment and finite strain is presented below. As derived by O'Hara (1990) from the Gresens (1967) original mass balance equations, the amount of any element in a fluid-rock system is given by:

$$C_i M_i = C_w (M_i - M_f) + C_f M_f \quad (1)$$

where C_i and C_f correspond to initial and final concentrations, M_i and M_f refer to initial and final masses of the rock, and C_w is the concentration of the element in the fluid. If the element in question is immobile, C_w will be near zero. Also assuming that density changes between the protolith and mylonite are small (Table 4-1), the above equation reduces to:

$$C_i V_i = C_f V_f \quad (2)$$

where V refers to initial and final volume. In the context of dilation (Δ) which is defined as:

$$\Delta = (V_f - V_i)/V_i \quad (3)$$

equation (2) can be written as:

$$C_f/C_i = 1/(1 + \Delta) \quad (4)$$

where C_f/C_i is an enrichment factor, which graphically represents the slope of the best-fit line to immobile trace element data (isocon) on a plot of the concentration in the protolith versus the concentration in the mylonites (O'Hara, 1990).

The general idea is that certain components (i.e. high field-strength cations) are likely to have been immobile during alteration processes and therefore should be enriched in mylonite that underwent volume loss (O'Hara and Blackburn, 1989). Concentrations of these elements can be compared across textural classifications (between protoliths and mylonites) to establish any volume loss that has taken place (Grensens, 1967; Grant, 1986). Gains or losses of other components can then be calculated assuming that volume change is a factor common to all components.

The isocon technique simplifies mass balance equations for metasomatism by comparing initial and final concentrations graphically (Grant, 1986). Use of this method implicitly assumes that an originally chemically homogeneous rock was altered. In the case of metaigneous lithologies, this is likely the case. To overcome potential problems of heterogeneity, large samples were collected and results of multiple analyses were averaged (Tables 4-2 and 4-3). Small deviations between the averaged samples suggest initial homogeneity (Tables 4-2 and 4-3). Nevertheless, uncertainties arising from heterogeneous protolith composition and the analytical procedures limits derivation of absolute values for volume loss during deformation.

Chemical Analyses

Whole-rock major and trace element analyses of mylonite samples from the TCFZ and BCFZ are summarized in Tables 4-2 and 4-3. Distinct chemical variation is present across both mylonite suites (Fig. 4-6). Major element chemical data reveal that Al_2O_3 , ΣFe , MnO , MgO , Na_2O , TiO_2 , and P_2O_5 , concentrations increase systematically from protomylonite to ultramylonite (Fig. 4-6). Systematic decreases in SiO_2 , K_2O , and LOI across the mylonite suites are also indicated by the data (Fig. 4-6). Trace and REE variation patterns generally show significant enrichment in ultramylonitic lithologies (Fig. 4-6).

Table 4-2. Whole-rock chemical analyses* of mylonitic Henderson Gneiss.

			Protomylonite					Mylonite					Ultramylonite				
Sample #			WK-1720	WK-1720B	WK-1719	Mean	1 σ	MV-1654	MV-1654B	MV-1653	Mean	1 σ	MV-403	MV-403B	MV-654	Mean	1 σ
Det.																	
SiO ₂	0.01	wt%	69.60	69.07	68.67	69.11	0.47	67.40	66.86	66.55	66.94	0.43	60.79	60.30	60.57	60.55	0.25
Al ₂ O ₃	0.01	wt%	15.24	14.67	15.08	15.00	0.29	15.38	15.19	15.17	15.25	0.12	18.54	18.08	17.92	18.18	0.32
Σ Fe	0.01	wt%	3.34	3.29	3.33	3.32	0.03	5.79	5.85	5.83	5.82	0.03	5.99	5.87	5.71	5.86	0.14
MnO	0.001	wt%	0.055	0.057	0.057	0.056	0.001	0.079	0.082	0.080	0.080	0.002	0.089	0.090	0.086	0.088	0.002
MgO	0.01	wt%	0.78	0.79	0.80	0.79	0.01	1.58	1.58	1.58	1.58	0.00	1.35	1.35	1.32	1.34	0.02
CaO	0.01	wt%	1.67	1.65	1.66	1.66	0.01	1.84	1.77	1.78	1.80	0.04	3.73	3.66	3.58	3.66	0.08
Na ₂ O	0.01	wt%	2.75	2.77	2.82	2.78	0.04	2.40	2.44	2.44	2.43	0.02	3.86	4.06	3.91	3.94	0.10
K ₂ O	0.01	wt%	4.40	4.50	4.56	4.49	0.08	3.19	3.34	3.32	3.28	0.08	3.52	3.56	3.75	3.61	0.12
TiO ₂	0.001	wt%	0.563	0.564	0.555	0.561	0.005	0.991	0.980	0.985	0.985	0.006	0.963	0.966	0.940	0.956	0.014
P ₂ O ₅	0.01	wt%	0.19	0.18	0.19	0.19	0.01	0.17	0.14	0.16	0.16	0.02	0.35	0.34	0.35	0.35	0.01
LOI	0.01	wt%	2.13	2.05	2.23	2.14	0.09	1.93	1.96	1.91	1.93	0.03	1.57	1.55	1.41	1.51	0.09
TOTAL		wt%	100.72	99.59	99.95	100.09	0.58	100.75	100.19	99.81	100.25	0.48	100.75	99.83	99.55	100.04	0.63
V	5	ppm	36	34	36	35	1	86	86	86	86	0	63	63	64	63	1
Cr	0.5	ppm	9.8	6.7	5.3	7.3	2.3	60	46.2	41.2	49.1	9.7	15.9	13.7	10.4	13.3	2.8
Co	0.1	ppm	7.4	7.6	6.0	7.0	0.9	9.7	8.1	8.6	8.8	0.8	8.4	6.6	6.5	7.2	1.1
Ni	1	ppm	4	3	3	3	1	20	18	18	19	1	5	5	6	5	1
Cu	1	ppm	6	6	6	6	0	44	37	41	41	4	9	9	8	9	1
Zn	1	ppm	66	55	55	59	6	98	85	86	90	7	117	97	97	104	12
Ga	1	ppm	17	20	20	19	2	18	23	22	21	3	22	28	26	25	3
Ge	0.5	ppm	1.3	1.1	1.2	1.2	0.1	1.5	1.5	1.3	1.4	0.1	1.5	1.6	1.4	1.5	0.1
As	1	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	nd	2	2	2	0
Rb	2	ppm	103	108	109	107	3	112	123	122	119	6	104	114	111	110	5
Sr	2	ppm	240	234	241	238	4	195	192	192	193	2	417	410	409	412	4
Y	1	ppm	21	21	21	21	0	33	32	42	36	6	61	61	58	60	2
Zr	1	ppm	388	445	374	402	38	370	525	439	445	78	727	852	682	754	88
Nb	0.2	ppm	20.9	22.2	20.9	21.3	0.8	17.8	20.3	19.9	19.3	1.3	21.5	23.7	23	22.7	1.1
Mo	2	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	nd	nd	nd	-	-
Ag	0.5	ppm	1.2	nd	nd	1.2	-	nd	nd	nd	-	-	nd	nd	nd	-	-
In	0.1	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	nd	nd	nd	-	-
Sn	1	ppm	4	3	2	3	1	4	3	3	3	1	4	3	2	3.0	1.0
Sb	0.1	ppm	nd	0.1	nd	0.1	-	nd	0.2	nd	0.2	-	0.3	nd	nd	0.3	-
Cs	0.1	ppm	1.9	1.6	1.9	1.8	0.2	3.1	2.9	2.8	2.9	0.2	3.3	2.6	2.7	2.9	0.4
Ba	1	ppm	1358	1280	1326	1321	39	778	752	763	764	13	1964	1854	2026	1948	87
La	0.1	ppm	31.8	26.3	32.6	30.2	3.4	38	34.9	37.5	36.8	1.7	150.6	160.2	145.7	152.2	7.4
Ce	0.1	ppm	59.5	49.3	59.7	56.2	5.9	45.2	41.5	42.8	43.2	1.9	236.0	254.0	244.0	244.7	9.0
Pr	0.02	ppm	8.51	7.11	8.50	8.04	0.81	8.55	7.79	8.13	8.16	0.38	32.70	34.10	31.00	32.60	1.55
Nd	0.1	ppm	31.7	25.6	29.9	29.1	3.1	30.8	26.7	28.1	28.5	2.1	121.0	121.0	111.0	117.7	5.8

Table 4-2 continued.

			Wall Rock					Mylonite I					Mylonite II				
Sample #			WK-1720	WK-1720B	WK-1719	Mean	1 σ	MV-1654	MV-1654B	MV-1653	Mean	1 σ	MV-403	MV-403B	MV-654	Mean	1 σ
Sm	0.01	ppm	5.89	5.11	5.58	5.53	0.39	6.69	5.98	6.22	6.30	0.36	18.90	18.90	17.70	18.50	0.69
Eu	0.005	ppm	1.450	1.280	1.340	1.357	0.086	1.530	1.390	1.480	1.467	0.071	5.680	5.460	5.250	5.463	0.215
Gd	0.02	ppm	5.3	4.94	5.20	5.15	0.19	6.51	6.06	6.69	6.42	0.32	15.30	16.10	15.10	15.50	0.53
Tb	0.01	ppm	0.82	0.75	0.76	0.78	0.04	1.08	0.96	1.17	1.07	0.11	2.24	2.35	2.22	2.27	0.07
Dy	0.02	ppm	4.48	4.15	4.20	4.28	0.18	6.4	5.68	7.33	6.47	0.83	12.60	12.30	11.70	12.20	0.46
Ho	0.01	ppm	0.86	0.80	0.80	0.82	0.03	1.25	1.17	1.56	1.33	0.21	2.28	2.24	2.19	2.24	0.05
Er	0.01	ppm	2.53	2.33	2.29	2.38	0.13	3.75	3.52	4.73	4.00	0.64	6.09	5.89	5.69	5.89	0.20
Tm	0.005	ppm	0.38	0.36	0.36	0.37	0.01	0.62	0.57	0.77	0.65	0.10	0.80	0.79	0.75	0.78	0.03
Yb	0.01	ppm	2.43	2.31	2.35	2.36	0.06	4.02	3.77	4.99	4.26	0.64	4.69	4.61	4.40	4.57	0.15
Lu	0.002	ppm	0.359	0.339	0.325	0.341	0.017	0.598	0.576	0.733	0.636	0.085	0.652	0.633	0.597	0.627	0.028
Hf	0.1	ppm	10.6	10.6	9.3	10.2	0.8	10.3	12.6	11.0	11.3	1.2	17.8	18.6	15.1	17.2	1.8
Ta	0.1	ppm	1.5	1.6	1.4	1.5	0.1	1.26	1.3	1.4	1.3	0.1	0.99	1	1.1	1.0	0.1
W	1	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	nd	nd	nd	-	-
Tl	0.05	ppm	0.91	0.63	0.79	0.78	0.14	1.06	0.83	0.83	0.91	0.13	0.95	0.72	0.71	0.79	0.14
Pb	5	ppm	21	16	18	18	3	23	16	15	18	4	18	12	13	14	3
Bi	0.1	ppm	nd	nd	0.4	0.4	-	0.9	0.6	0.6	0.7	0.2	1.1	1.5	1.1	1.2	0.2
Th	0.1	ppm	16.2	14.7	15.8	15.6	0.8	10.3	10.0	10.4	10.2	0.2	8.5	9.5	8.8	8.9	0.5
U	0.05	ppm	2.72	2.74	2.84	2.77	0.06	3.87	3.58	4.31	3.92	0.37	1.29	1.36	1.29	1.31	0.04

ΣFe = total Fe

*Analyses performed by Actlabs, Ancaster, Ontario. Major element chemistry determined by FUS-ICP; Minor and trace element analyses determined by FUS-ICP, INAA, and TD-ICP.

Table 4-3. Whole-rock chemical analyses* of mylonitic Walker Top Granite.

			Protomylonite					Mylonite					Ultramylonite				
Sample #			MV-566	MV-566B	MV-564	Mean	1 σ	MV-19	MV-19B	MV-249	Mean	1 σ	GL-1	GL-1B	GL-2	Mean	1 σ
Det.																	
SiO ₂	0.01	wt%	73.13	71.79	71.48	72.13	0.88	67.96	68.37	68.05	68.13	0.22	66.36	65.03	64.66	65.35	0.89
Al ₂ O ₃	0.01	wt%	14.64	15.01	15.09	14.91	0.24	15.18	15.35	15.38	15.30	0.11	15.74	15.77	15.85	15.79	0.06
Σ Fe	0.01	wt%	2.22	2.29	2.30	2.27	0.04	3.48	3.45	3.38	3.44	0.05	4.54	4.56	4.67	4.59	0.07
MnO	0.001	wt%	0.042	0.049	0.052	0.048	0.005	0.062	0.064	0.063	0.063	0.001	0.085	0.086	0.090	0.087	0.003
MgO	0.01	wt%	0.50	0.50	0.51	0.50	0.01	1.33	1.34	1.30	1.32	0.02	1.99	2.03	2.09	2.04	0.05
CaO	0.01	wt%	1.16	1.17	1.17	1.17	0.01	2.55	2.57	2.55	2.56	0.01	3.47	3.57	3.59	3.54	0.06
Na ₂ O	0.01	wt%	2.76	2.91	2.89	2.85	0.08	3.10	3.28	3.26	3.21	0.10	2.69	2.96	2.98	2.88	0.16
K ₂ O	0.01	wt%	4.37	4.84	4.86	4.69	0.28	3.96	4.26	4.38	4.20	0.22	4.16	4.16	4.17	4.16	0.01
TiO ₂	0.001	wt%	0.321	0.319	0.318	0.319	0.002	0.576	0.561	0.538	0.558	0.019	0.76	0.75	0.77	0.76	0.01
P ₂ O ₅	0.01	wt%	0.24	0.24	0.24	0.24	0.00	0.22	0.21	0.22	0.22	0.01	0.26	0.26	0.26	0.26	0.00
LOI	0.01	wt%	1.28	1.06	0.87	1.07	0.21	0.82	0.76	0.80	0.79	0.03	0.82	0.70	0.74	0.75	0.06
TOTAL		wt%	100.66	100.18	99.78	100.21	0.44	99.24	100.22	99.92	99.79	0.50	100.87	99.88	99.87	100.21	0.57
V	5	ppm	22	19	19	20	2	64	62	61	62	2	94	96	97	96	2
Cr	0.5	ppm	8.6	6.2	3.9	6.2	2.4	50.1	42.3	32.2	41.5	9.0	73.6	58.3	61.3	64.4	8.1
Co	0.1	ppm	3.5	3.0	2.7	3.1	0.4	8.8	7.0	6.5	7.4	1.2	12.9	9.9	11.0	11.3	1.5
Ni	1	ppm	2	2	2	2	0	12	11	9	11	2	19	16	17	17	2
Cu	1	ppm	1	2	1	1	1	2	4	4	3	1	10	10	9	10	1
Zn	1	ppm	65	58	56	60	5	61	51	49	54	6	71	63	64	66	4
Ga	1	ppm	18	21	22	20	2	16	19	18	18	2	20	20	20	20	0
Ge	0.5	ppm	1.8	1.6	1.6	1.7	0.1	1.7	1.5	1.3	1.5	0.2	2.2	1.3	1.3	1.6	0.5
As	1	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	2	nd	nd	2	-
Rb	2	ppm	209	234	244	229	18	167	176	170	171	5	200	195	195	197	3
Sr	2	ppm	155	163	162	160	4	195	202	204	200	5	297	304	305	302	4
Y	1	ppm	18	19	19	19	1	22	27	28	26	3	23	24	24	24	1
Zr	1	ppm	136	148	156	147	10	157	203	235	198	39	247	235	253	245	9
Nb	0.2	ppm	15.1	15.7	15.6	15.5	0.3	13.5	13.6	12.7	13.3	0.5	14.7	14.1	14.3	14.4	0.3
Mo	2	ppm	4	nd	nd	4	-	nd	nd	nd	-	-	4	nd	nd	4	-
Ag	0.5	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	nd	nd	nd	-	-
In	0.1	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	nd	nd	nd	-	-
Sn	1	ppm	2	2	2	2	0	2	nd	nd	2	-	2	nd	nd	2	-
Sb	0.1	ppm	0.3	nd	nd	0.30	-	nd	nd	nd	-	-	nd	nd	nd	-	-
Cs	0.1	ppm	2.3	2.4	4.8	3.2	1.4	3.8	3.6	3.3	3.6	0.3	5.4	5.7	5.8	5.6	0.2
Ba	1	ppm	389	416	429	411	20	572	603	628	601	28	719	676	664	686	29
La	0.1	ppm	37.1	36.8	35.7	36.5	0.7	44.2	43.3	44.9	44.1	0.8	38.6	54.3	35.7	42.9	10.0
Ce	0.1	ppm	83.8	81.3	77.0	80.7	3.4	93.1	88.9	91.4	91.1	2.1	81.5	109.0	73.4	88.0	18.7
Pr	0.02	ppm	9.49	9.21	8.78	9.16	0.36	10.30	9.92	10.10	10.11	0.19	9.48	12.20	8.31	10.00	2.00
Nd	0.05	ppm	36.00	34.70	33.20	34.63	1.40	38.60	35.60	36.40	36.87	1.55	34.60	43.40	31.50	36.50	6.17

Table 4-3 continued.

Sample #			Wall Rock					Mylonite I					Mylonite II				
			MV-566	MV-566B	MV-564	Mean	1 σ	MV-19	MV-19B	MV-249	Mean	1 σ	GL-1	GL-1B	GL-2	Mean	1 σ
Sm	0.01	ppm	8.16	7.82	7.51	7.83	0.33	7.71	7.36	7.54	7.54	0.18	6.99	8.24	6.75	7.33	0.80
Eu	0.005	ppm	0.800	0.822	0.824	0.815	0.013	1.280	1.270	1.260	1.270	0.010	1.640	1.680	1.610	1.643	0.035
Gd	0.02	ppm	6.23	6.31	6.11	6.22	0.10	6.24	6.26	6.36	6.29	0.06	6.07	7.01	6.18	6.42	0.51
Tb	0.01	ppm	0.87	0.84	0.84	0.85	0.02	0.90	0.92	0.94	0.92	0.02	0.86	0.96	0.90	0.91	0.05
Dy	0.02	ppm	4.06	3.97	3.89	3.97	0.09	4.74	5.03	5.03	4.93	0.17	4.65	4.91	4.71	4.76	0.14
Ho	0.01	ppm	0.64	0.65	0.69	0.66	0.03	0.82	0.93	0.91	0.89	0.06	0.82	0.90	0.87	0.86	0.04
Er	0.01	ppm	1.59	1.70	1.84	1.71	0.13	2.11	2.49	2.34	2.31	0.19	2.27	2.38	2.42	2.36	0.08
Tm	0.005	ppm	0.22	0.25	0.28	0.25	0.03	0.28	0.34	0.33	0.32	0.03	0.32	0.33	0.34	0.33	0.01
Yb	0.01	ppm	1.36	1.56	1.76	1.56	0.20	1.62	2.00	1.93	1.85	0.20	1.92	2.02	2.06	2.00	0.07
Lu	0.002	ppm	0.182	0.211	0.241	0.211	0.030	0.216	0.284	0.251	0.250	0.034	0.265	0.278	0.285	0.276	0.010
Hf	0.1	ppm	4.1	4.0	4.2	4.1	0.1	4.4	5.1	6	5.2	0.8	6.0	5.9	6.4	6.1	0.3
Ta	0.1	ppm	0.9	1.2	0.9	1.0	0.2	0.89	0.9	0.8	0.9	0.1	0.9	1.0	1.0	1.0	0.1
W	1	ppm	nd	nd	nd	-	-	nd	nd	nd	-	-	nd	nd	nd	-	-
Tl	0.05	ppm	1.99	1.76	1.72	1.82	0.15	1.39	1.08	1.04	1.17	0.19	1.65	1.16	1.26	1.36	0.26
Pb	5	ppm	27	24	25	25	2	39	32	32	34	4	28	26	20	25	4
Bi	0.1	ppm	0.7	1.0	1.4	1.0	0.4	0.4	0.5	0.2	0.4	0.2	0.7	0.2	0.4	0.4	0.3
Th	0.1	ppm	17.7	18.3	17.4	17.8	0.5	23.6	21.9	22.8	22.8	0.9	9.3	15.6	8.1	11.0	4.0
U	0.05	ppm	4.35	4.61	4.26	4.41	0.18	2.13	2.41	3.21	2.58	0.56	1.82	2.21	1.82	1.95	0.23

ΣFe = total Fe

*Analyses performed by Actlabs, Ancaster, Ontario. Major element chemistry determined by FUS-ICP; Minor and trace element analyses determined by FUS-ICP, INAA, and TD-ICP.

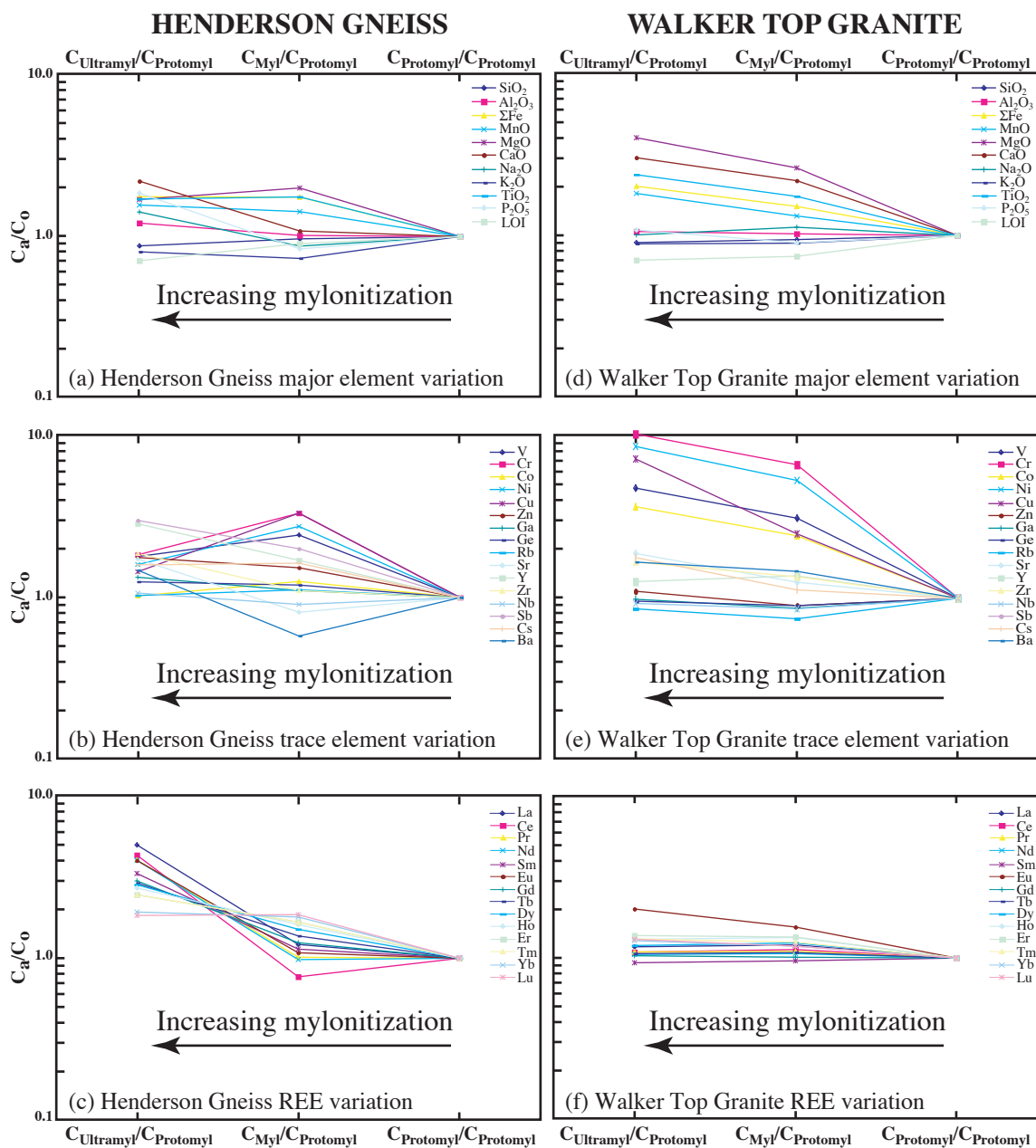


Figure 4-6. Element variation in northeastern IP mylonite suites relative to protomylonites. Each point represents an average of three analyses (see Table 4-2). Note the large increases of immobile elements in the ultramylonites. (a) Major element variation in Henderson Gneiss mylonites. (b) Trace element variation in Henderson Gneiss mylonites. (c) REE variation in Henderson Gneiss mylonites. (d) Major element variation in Walker Top Granite mylonites. (e) Trace element variation in Walker Top Granite mylonites. (f) REE variation in Walker Top Granite mylonites. C_a/C_o represents the ratio of element concentrations in the altered (mylonite) to that in the original (unmylonitic protolith).

Trace element enrichment can be attributed to refractory phases such as zircon, apatite, ilmenite, and epidote, which are present in all mylonites. During deformation and metasomatism, these phases may fracture, recrystallize, or dissolve, depending on the composition of the fluid phase and the conditions of deformation (e.g., Wayne and Sinha, 1988). However, due to the low solubility of the high valence cations (e.g., P^{5+} , Ti^{4+} , Y^{3+}), their release upon breakdown of the host phase will likely result in local redistribution into new overgrowths, and on the whole-rock scale they can be assumed to be largely immobile (Wayne and Sinha, 1988). Frequent utilization of Ti, Y, and Zr concentrations to identify primary magmatic signatures in hydrothermally altered rocks supports this conclusion (e.g., Pearce and Cann, 1973). Therefore, immobile trace element enrichments are interpreted here to result from large volume losses rather than mobility of these elements (O'Hara and Blackburn, 1989).

Further supporting the above conclusion, the trivalent rare earth elements (REE), generally regarded as immobile (Hanson, 1980), are progressively enriched in the ultramylonites compared to the protomylonites (Figs. 4-6 and 4-7). Chondrite-normalized REE patterns display similar trends in both the TCFZ and BCFZ profiles, and contain LREE enrichment with significant Eu anomalies, and depletion of HREE (Fig. 4-7). Although REE increase in abundance with increasing deformation, their patterns are nearly parallel, with the exception of ultramylonitic Henderson Gneiss (Fig. 4-7). This implies that these rocks are petrogenetically related (i.e., the protomylonite is the protolith of the ultramylonite) and that either fractionation of the REE did not take place during mylonitization or that both the HREE and LREE fractionated by the same amount during mylonitization. The latter possibility can be largely discounted based on large and systematic variations in the partitioning between the HREE and LREE (Fig. 4-7).

Ultramylonitic Henderson Gneiss samples from the TCFZ contain drastic increases in REE concentrations relative to protomylonite and mylonite samples (Fig. 4-7). The presence of carbonate in this sample presents a possible explanation of late hydrothermal alteration by carbonate-rich fluids circulating through the late Paleozoic BFZ. Although speculative, a potential source for these fluids may exist in carbonate lithologies present within the BFZ (Hatcher et al., 1973; Clark, 1974; Hatcher, 1978). For mylonitic Henderson Gneiss samples from near Rosman, NC, Sinha et al. (1986) also speculated on fluid sources from sedimentary lithologies underlying the BFZ.

Isocon analyses comparing differing degrees of mylonitization reveal substantial enrichment of ΣFe , MnO , TiO_2 , P_2O_5 , Y, V, and Zr, as more strain is accommodated (Fig. 4-8). The argument that SiO_2 remained constant could be made, since it plots near

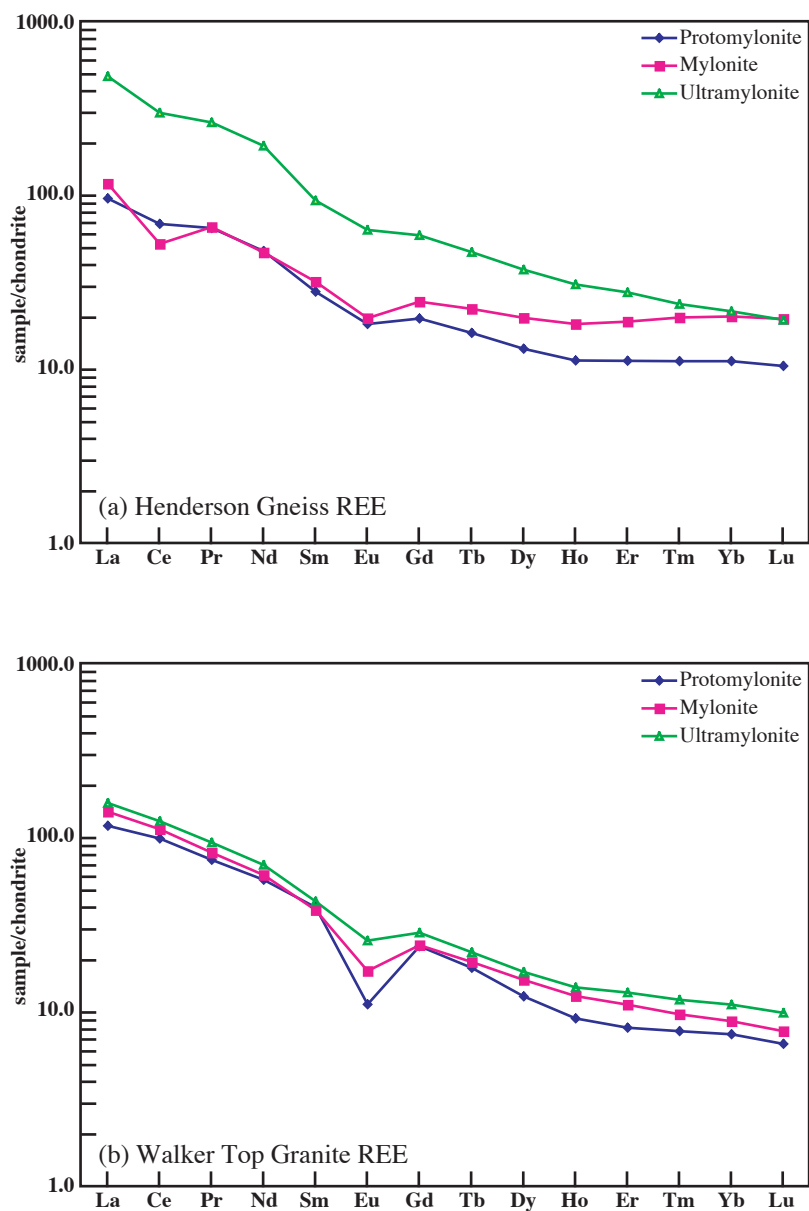


Figure 4-7. Chondrite-normalized rare earth element concentrations for northeastern IP mylonite variations. Note the subparallelism of patterns and the enrichment in progressively more mylonitized material. Chondrite values are from Boynton (1984). (a) REE variation in Henderson Gneiss mylonites. (b) REE variation in Walker Top Granite mylonites.

constant-volume isocons (Fig. 4-8), and that most other elements have been enriched during mylonitization. However, immobile elements define strong linear trends with steeper slopes than constant volume isocons, suggesting that significant volume loss has occurred in both shear zones (Fig. 4-8). Therefore, it seems more reasonable to assume that elements plotting near an isocon fit to ΣFe , MnO , TiO_2 , P_2O_5 , Y , V , and Zr remained relatively immobile during metasomatism and deformation, and that elements falling below this isocon were lost (Fig. 4-8).

Using the slopes of immobile element isocons and the equations of Grens (1967) and O'Hara (1990) (equations 1-4), total volume losses of 41% and 48% were calculated for TCFZ Henderson Gneiss and BCFZ Walker Top Granite samples, respectively (Fig. 4-8). For TCFZ Henderson Gneiss samples, the development of mylonite from protomylonite led to a calculated 33% volume loss. The transition from mylonite to ultramylonite caused another 7% volume decrease, resulting in a net volume loss of 41% (Fig. 4-8). Walker Top Granite samples from the BCFZ also suggest an initial 33% loss during the development of mylonite from protomylonite. An additional volume loss of 17% occurred during the transition from mylonite to ultramylonite, causing an overall volume loss of 48% (Fig. 4-8). REE enrichment patterns in the mylonites and ultramylonites relative to protomylonites support these values.

Although relatively good correlation coefficient (r^2) values were obtained for fitting isocons to immobile elements (Fig. 4-8), variable scatter of data points about these lines may be due to a combination of analytical uncertainty, protolith heterogeneities, variable volume losses, and selective mobility of some elements. The above evidence suggests that a significant amount of material was removed from the system as fluids passed through the mylonite zones. It should be noted, however, that such volume losses may not be representative of the shear zones as a whole, as Bailey et al. (1994) have shown that the amount of volume loss can vary significantly along the same shear zone.

DISCUSSION

Shear zones have traditionally been divided into three groups based on volume changes during deformation (e.g., Ramsay, 1980; O'Hara, 1988; O'Hara and Blackburn, 1989; Selverstone et al., 1991; Bailey et al., 1994; Ring, 1999): volume-gain, isovolume, and volume-loss. In reality, volume-loss and volume-gain are two end members in a broad spectrum, and some shear zones may even appear to have volume gains and losses in different parts of the same shear zone (Bailey et al., 1994). The TCFZ and the BCFZ appear to be examples of volume-loss shear zones having lost 41 and 48% by volume,

respectively (Fig. 4-8c).

Major elements, such as SiO_2 , Na_2O , and K_2O , which plot below immobile element regression lines (Fig. 4-8) indicate that these elements were probably lost from the system (Grant, 1986). Textural, modal mineralogical, and microstructural observations (Table 4-1; Fig. 4-5) suggest that extensive quartz and feldspar dissolution and recrystallization occurred during a high-temperature deformation, which likely corresponds to the release of silica and alkalis to the fluid phase. Additionally, increases in the modal abundance of myrmekite in the ultramylonites, while modal K-feldspar decreases, favors a decrease in volume as K_2O is lost from the system (Simpson and Wintsch, 1989). Subsequent alteration of feldspar and micas during a retrograde (Alleghanian?) event facilitated the replacement of biotite by chlorite and the alteration of plagioclase to sericite. Fluid changes (determined as loss on ignition) show systematic decreases across the mylonite suites, suggesting that dehydration reactions were occurring during mylonitization. This is consistent with progressive metamorphism and the systematic increase in modal abundance of sillimanite. Higher ΣFe and MgO concentrations in the ultramylonite probably reflects the higher increasing abundance of biotite with more increasing strain (Table 4-1).

Overall, volume-loss estimates for northeastern IP shear zones studied here seem reasonable when compared to other volume-loss shear zones with similar compositions (e.g. Sinha et al., 1986; O'Hara, 1990; Newman and Mitra, 1993; Bailey et al., 1994; Condie and Sinha, 1996; Ring, 1999; Yonkee et al., 2003). They range from 20-75%, with most estimates between 45-60%. Although these estimates may be representative for local volume changes, they are in no way representative of these shear zones as a whole. Additional detailed structural and geochemical studies addressing the nature of large shear zones in the northeastern IP are required to more adequately characterize volume changes during deformation.

CONCLUSIONS

1. Two retrograde shear zones in the northeastern IP each contain an entire suite of mylonitic granitic gneisses ranging from protomylonite to ultramylonite, and were initially developed under amphibolite facies conditions.
2. Regional linear fabric patterns reflect the SW-directed transport of material and constricted fluid flow through ductile shear zones in the northeastern IP.
3. Deformation in the mylonites occurred by crystal plastic mechanisms operating at temperatures $>400^\circ\text{C}$.

4. Increase of Al_2O_3 , ΣFe , MnO , MgO , Na_2O , TiO_2 , and P_2O_5 , immobile trace elements, and REE in the ultramylonites relative to the protomylonites likely result from significant volume loss.
5. Depletion of SiO_2 , K_2O , Na_2O , and LOI in the ultramylonites relative to the protomylonites is consistent with dissolution and recrystallization of alkali feldspar and the formation of myrmekite. Enrichment of ΣFe and MgO in the ultramylonites may be attributed to a higher modal abundance of ferromagnesian phyllosilicate phases than in the protomylonites.
6. Isocon analyses suggest volume losses of 41 and 48% during mylonitization in the TCFZ and the BCFZ, respectively. Steep slopes and good fits to regression lines for the immobile elements ΣFe , MnO , TiO_2 , P_2O_5 , Y, V, and Zr indicate their increased relative concentrations in the mylonites, which imply significant negative volume changes. These values seem reasonable when compared to other shear zones of similar width and protolith composition.

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PART V

Inner Piedmont Orogenic Timing Relationships From Zircon Geochronology Delimits the Timing of Orogenesis in the southern Appalachians

ABSTRACT

Northeastern Inner Piedmont (IP) rocks retain a polydeformational and polymetamorphic history that is the final product of long-lived convergence along the Paleozoic eastern Laurentian margin. New data and observations provide information about the nature and timing of these Paleozoic orogenic events and their roles in the development of the southern Appalachian orogenic core. Ordovician granitoids in the western IP signify the development of a volcanic arc complex outboard of the Laurentian margin ~490 Ma. Arc- and continental-related eastern Blue Ridge and western IP magmatic belts record Taconic (480-460 Ma) arc accretion and subsequent metamorphism, magmatism, and volcanism from 460-440 Ma. Eastern IP metasedimentary assemblages contain detrital zircon age populations of 1500, 1100, 1000, 600, 500, 465, and 430 Ma. Magmatic and metamorphic ages for eastern IP lithologies indicate that they were being subducted by the Carolina superterrane by ~415 Ma. These ages constrain the deposition of eastern IP sediments in the Cat Square ocean basin to 430-415 Ma. The Neoacadian orogeny occurred 360-340 Ma during the accretion of the Cat Square terrane and Carolina superterrane, resulting in the first shared thermal event between the eastern and western IP. It is responsible for sillimanite I and II facies peak metamorphism and penetrative deformation fabrics throughout the IP. Alleghanian deformation and metamorphism produced dextral strike-slip reactivation of existing IP fault zones, producing S-C and related shear fabrics in the IP and once again brought about sillimanite-grade conditions.

INTRODUCTION

The tectonic evolution of the southern Appalachian crystalline core is largely obscure due to extended, complex orogenesis that apparently resulted from multiple orogenic pulses occurring during the Paleozoic. These tectonothermal episodes are the direct results of a series of collisional tectonic events, which closed small and large ocean basins off of the eastern Laurentian margin. This protracted history effectively shaped the Appalachian orogen from Laurentia and exotic terranes.

The IP along with the Blue Ridge and portions of the Carolina terrane comprise the composite orogenic core of the southern Appalachians. The grouping of the IP with the adjacent eastern Blue Ridge is based on interpretations that correlate stratigraphies across the Brevard fault zone (BFZ) (e.g. Hatcher, 1989). Correlation of units and lithologies across the BFZ has been a recent topic of much debate as several investigators

argue that the BFZ is a major crustal boundary and that the eastern Blue Ridge and IP are not related (e.g., Butler, 1971; Horton et al., 1989; Dennis and Wright, 1997a, 1997b). IP rocks retain evidence of all three contractional deformation events (Part III, this study), which are the products of a long-lived convergence off of the eastern Laurentian margin (present day coordinates). Due to its spatial position and geologic evolution, the IP exists as the principle locality for tectonic study in the southern Appalachians. Modern conceptions of the IP stem from a number of pioneering investigations, specifically Griffin (1967; 1969a; 1969b; 1971a; 1971b; 1974a; 1974b), Hatcher (1969; 1970; 1978; 1993), Bentley and Neatherly (1970), along with more recent studies (e.g., Davis 1993a; Yanagihara 1993; Hibbard, 1993; Grimes et al., 1993; Goldberg and Fullagar, 1993; Garihan, 2002; Giorgis et al., 2002; Bream, 2002; Bier et al., 2002; Merschat and Kalbas, 2002). Many of the conclusions from these studies, and slight modifications of them, provide the groundwork upon which all subsequent IP studies are based (e.g. Davis, 1993b; Yanagihara, 1994; Bream, 1999, Giorgis, 1999; Hill, 1999, Williams, 2000; Bier, 2001; Kalbas, 2003; Merschat, 2003).

The IP is composed primarily of high-grade metamorphic and plutonic rocks, for which knowledge of provenance and crystallization ages are crucial for constructing tectonic interpretations. However, most existing age data for the IP is outdated and unreliable. This is likely due to a combination of complex, polyphase plutonic-metamorphic episodes in the IP, and outdated technologies employed for analyses.

Modern advances in geochronologic techniques provide the most reliable and absolute temporal constraints on IP sedimentation, magmatic, metamorphic, deformational, and tectonic pulses. Recent utilization of these methods has led to the progressive construction of increasingly appealing models for the Paleozoic tectonic development of the southern Appalachians, in which tectonostratigraphic terranes are identified based on their crustal affinities and terrane boundaries separating them are variably defined and interpreted (e.g., Brown, 1970; Harper and Fullagar, 1981; Williams and Hatcher, 1983; Hatcher, 1987, 1989; Horton et al., 1989; Sinha et al., 1989; Dalla Salda, 1992a, 1992b; Davis, 1993; Hibbard and Samson, 1995; Hibbard, 2000; Hibbard et al., 2002; Bream, 2003). These studies have mostly favored Ordovician (Taconic) accretion, deformation, and metamorphism of IP suspect terranes northwest of the Carolina terrane (e.g., Williams and Hatcher, 1982; Horton et al., 1989). Ordovician accretion of the Carolina superterrane is also depicted in these models (e.g., Vick et al., 1997; Hibbard, 2000). More recent studies, however, have incorporated monazite and zircon rim metamorphic age data (e. g., Dallmeyer, 1988; Dennis and Wright, 1997a,

1997b; Mirante and Patino-Douce, 2000) with new magmatic ages (e.g., Vinson, 1999; Mapes, 2002), which document the effects of a major thermal-magmatic event ~360-340 Ma in the IP, and support Devonian (Acadian) accretion of the Carolina superterrene (e.g., Hatcher et al., 1999; Kohn, 2001), as proposed in earlier models (e.g., Hatcher, 1987, 1989). Alternative tectonic models for the development of the IP include: accretionary wedge (Abbot and Raymond, 1984), mélange complex (Goldsmith et al., 1988; Horton et al., 1989), and a possible accreted exotic terrane (Rankin et al., 1989; Dennis, 1991; Rankin, 1994; Dennis and Wright, 1997a, 1997b). Gaps between areas of detailed study along with limited reliable geochemical and geochronological data undoubtedly preclude attempts to construct a comprehensive tectonic reconstruction incorporating data from northern and southern Appalachian terranes.

The purpose of this study is to: (1) present new igneous geochronologic data, which reveal crystallization ages for northeastern IP igneous and metaigneous lithologies to help constrain the timing of tectonothermal and magmatic events; (2) present new detrital geochronology data for comparison with previously determined eastern IP provenance ages, (3) provide additional data for the timing of metamorphism in the IP; (4) incorporate all geochronologic data with detailed mapping, structural observations and analyses, and metamorphic P-T estimates from the northeastern IP (Part II and III, this study) to produce a pressure-temperature-time-deformation (P-T-t-D) path; and (5) to present an updated model for the Paleozoic tectonic evolution of the northeastern IP, including modifications of existing models based on new structural and geochronologic data.

GEOLOGIC SETTING

The southern Appalachian mountain chain is the net result of long-lived convergence along the eastern Laurentian margin during the Paleozoic. Laurentian-derived rifted margin and platform rocks have been deformed, metamorphosed, and juxtaposed with suspect and exotic terranes of various crustal affinities during a series of Paleozoic accretionary tectonic pulses: the Taconic (Middle-Late Ordovician), Acadian (Devonian), Neoacadian (Devonian-Mississippian), and Alleghanian (Pennsylvanian-Permian) orogenies. The IP and eastern Blue Ridge (Tugaloo terrane of Hatcher, et al., 1999) constitute most of the southern Appalachian igneous and metamorphic core (Davis, 1993a; Hatcher, 1993, 2002). The IP consists of a distinct assemblage of para- and orthogneisses continuous for approximately 700 km along strike southwestward from the Sauratown Mountains window in North Carolina to the Coastal Plain overlap in Alabama

(Fig. 5-1). Across strike, its width reaches approximately 100 km from the BFZ to the northwest to the Central Piedmont suture (CPS) to the southeast. Long recognized as a stack of westward-verging, crystalline thrust sheets containing predominantly high-grade metamorphic rocks (Griffin, 1969b; Hatcher, 1969), the IP can be characterized as a shallowly-dipping, polydeformed series of distal slope-and-rise facies metasedimentary and igneous rocks of various crustal affinities, containing macroscale structures, high-grade metamorphism, migmatization, and plutonism (Osberg et al., 1989; Davis, 1993b; Hatcher, 1993). Hatcher and Hooper (1992) concluded that the macroscale structure of the IP consists of consists of passive or flexural-flow antiform-synform pairs, which shear off the common limb, producing low-angle Type-F thrusts and reclined to recumbent folds. Davis (1993b) resolved a series of five deformational events affecting IP rocks, of which D₂ and D₃ coincided with peak metamorphism and are responsible for the major penetrative deformation and regional foliation in the IP.

Bream et al. (2001) and Bream and Hatcher (2002) have redefined IP terrane assemblages, based on recent structural and geochronologic studies, by partitioning eastern and western IP terranes (or eastern Tugaloo and Cat Square terrane, respectively) across the Brindle Creek fault zone (BCFZ; Figs. 5-1 and 5-2). Subdivision of eastern and western IP terranes is based on the recognition of temporally, isotopically, and chemically distinct plutonic suites (Mapes, 2002) and differing sedimentary provenances (Bream, 2003) occurring across the BCFZ. The BCFZ, first recognized by Giorgis (1999) near Morganton, North Carolina, separates Laurentian-affinity paragneisses and primarily Ordovician and older orthogneisses of the western IP from eastern IP Siluro-Devonian metasedimentary lithologies of mixed crustal affinities intruded primarily by Devonian and Mississippian granitoids. Citing the mixed Laurentian (1.1, 1.4, 1.8, 2.8 Ga) and peri-Gondwanan (500, 600 Ma) affinities of eastern IP metasedimentary lithologies, Hatcher and Mersch (in review) have proposed that Cat Square terrane metasedimentary assemblages comprise a Siluro-Devonian remnant ocean basin that existed between the Laurentian margin and approaching Carolina terrane, and hypothesized that interlayering of metapsammitic and pelitic lithologies could result from turbidite deposits shed from adjacent highlands bounding the basins eastern and western extents.

The IP constitutes the largest area of sillimanite-grade metamorphism in the Appalachians (Fig. 5-3). Metamorphic grade ranges from garnet-staurolite (in South Carolina) and staurolite-kyanite (in North Carolina) near the northwestern flank of the IP (Chauga belt), to sillimanite and higher grade near the IP core, and back to localized

Cartoogechaye terrane—Tallulah Falls/Coweeta Group(?) metasandstone and schist deposited on oceanic crust (?) and 1.1 Ga continental basement fragments. Abundant mafic-ultramafic complexes (e.g., Buck Creek, Kimsey Bald [arc], Carroll Knob). No Paleozoic granitic plutons.

Cowrock terrane—Coweeta Group metasandstone and schist intruded by Middle Ordovician Persimmon Creek Tonalite. Sandstone contains 1.2, 1.3, 1.4, 1.6, 2.7 Ga detrital zircons.

Dahlonega gold belt—Cambrian (?) meta-sedimentary and Ordovician (460 & 480 Ma) arc volcanic rocks (mostly basalt) deposited on 1.1 Ga granitic basement fragments and oceanic(?) crust. Intruded by Ordovician granites. Detrital zircons from meta-sandstone contain 1.1, 1.2, 1.3, 1.4, 1.8, 1.9, 2.0, 2.1, 2.7, and 2.9 Ga ages.

Exotic Neoproterozoic to early Paleozoic volcanic arc formed close to Gondwana (bimodal volcanic rocks and related sedimentary rocks intruded by Neoproterozoic to Cambrian granitic plutons; contains European-African Cambrian trilobites, and possibly Ordovician fossils. Deformation Ordovician and older, then Alleghanian (with Alleghanian metamorphism and plutons). Probably accreted during the Mississippian (Neocadian) or Pennsylvanian (early Alleghanian)

Siluro-Devonian metasedimentary rocks deposited on Ordovician(?) oceanic crust and older continental basement (?) fragments and intruded by Devonian and Mississippian granites derived from in situ melting of the sedimentary rocks. Detrital zircons include 400, 500, and 600 Ma, and 1.1, 1.2, 1.4, 1.9, 2.5, 2.8 Ga suites. Accreted during the Neocadian (~350 Ma).

Neoproterozoic to Cambrian metasedimentary and rift (?) metavolcanic rocks (Tallulah Falls/Ashe Fm., Chauga R. Fm.) deposited on late Neoproterozoic to Cambrian oceanic crust and 1.1 Ga basement fragments (Tallulah Falls & Toxaway domes), unconformably overlain by Middle Ordovician arc to MORB metabasalt, quartzite/felsic tuff, and marble (Poor Mtn. Fm) and intruded by Early (Henderson Gneiss) to Middle (Whiteside Granite, Dysartsville Tonalite, and related) Ordovician, Devonian (Rabun, Yonah, Looking Glass), and Pennsylvanian (Elberton, Stone Mtn., GA) granitic plutons. Detrital zircons include 1.1, 1.2, 1.3, 1.4, 1.5 Ga suites.

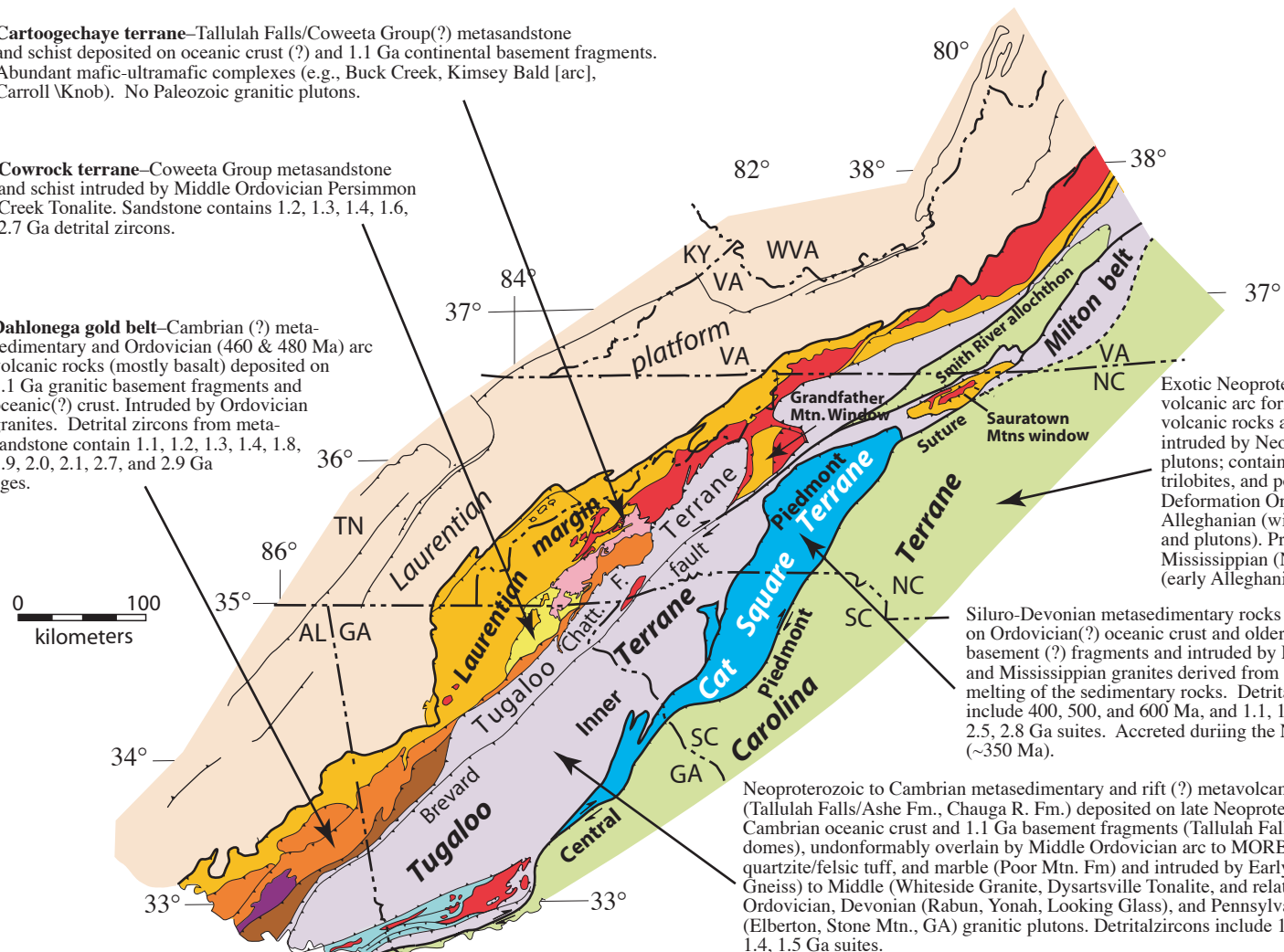


Figure 5-1. Southern Appalachian tectonostratigraphic terranes. Modified from Hatcher (2002). Note that descriptions are included only for terranes relevant to this study.

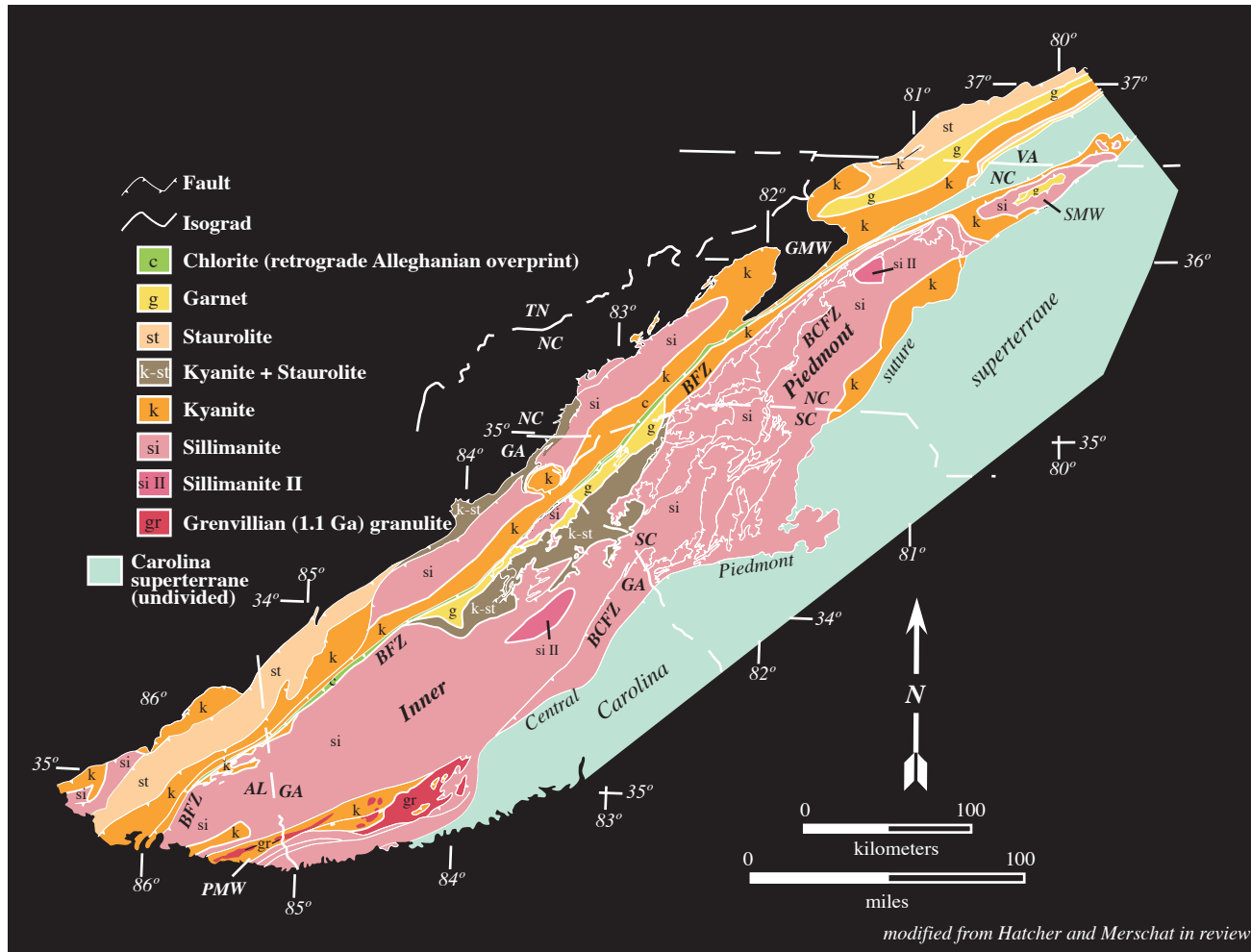


Figure 5-3. Metamorphic isograd map of the southern Appalachian crystalline core. Abbreviations: PMW=Pine Mountain window; BFZ=Brevard fault zone; BCFZ=Brindle Creek fault zone; GMW=Grandfather Mountain window; SMW=Sauratown Mountains window. Figure modified from Hatcher and Merschat (2006).

staurolite and garnet grade near the southeastern terminus of the IP and the CPS (Fig. 5-3; Reed and Bryant, 1964; Bryant and Reed, 1970; Goldsmith et al., 1988; Butler, 1991; Bier et al., 2002; Merschat and Kalbas, 2002). Migmatization occurs throughout the IP, except near the flanks. P-T estimates for IP lithologies range from 500-800°C and 3-8 kbar (Davis, 1993b; Yanagihara, 1994; Hill, 1999; Mirante and Patino Douce, 2000; Bier et al., 2002; Merschat, 2003; Part II, this study). Prograde Barrovian-type metamorphism is indicated by uniform garnet zoning profiles and P-T estimates revealing an increase in temperature from garnet cores to rims for both eastern and western IP terranes, suggesting that peak metamorphism occurred after BCFZ emplacement (Davis, 1993b; Bier et al., 2002; Merschat and Kalbas, 2002). Retrograde greenschist facies metamorphism is largely restricted to the BFZ and results from Alleghanian reactivation of the BFZ (Reed and Bryant, 1964; Bryant and Reed, 1970; Hatcher, 2001a).

A series of six deformation events can be recognized in the northeastern IP (Table 5-1). Relative timing constraints are provided by crosscutting relationships and absolute timing constraints are afforded by geochronologic data. Deformation sequences identified here mostly correspond to those recognized by previous investigators (e.g. Davis, 1993b; Yanagihara, 1994; Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; Merschat, 2003), with modifications to incorporate new data and observations.

New data indicate that initial high-temperature deformation events contrast in deformational style and timing across the BCFZ (Part III, this study). Western IP D_1 timing is loosely delimited by age relationships and truncation of structures in the footwall of the Tumblebug Creek fault zone (TCFZ). Neoproterozoic detrital zircons and crystallization ages of metaigneous bodies (e.g., ~490 Ma Henderson Gneiss; Carrigan et al., 2001) also provide an upper bounds on D_{1WIP} . The timing of early deformation within the eastern IP is better constrained. D_1 structures postdate ~430 Ma detrital zircons and are likely related to Early Devonian anatectic magmatism in the Cat Square terrane. New geochronologic data presented herein provide additional timing limits for D_{1EIP} . Subsequent D_2 and D_3 ductile deformation produced penetrative fabrics in the IP during the first shared tectonothermal event between eastern and western IP terranes. This high-temperature event is documented by consistent 360-340 Ma hornblende cooling, zircon rim, and monazite ages for eastern and western IP lithologies (Dallmeyer et al., 1988; Dennis and Wright, 1997a, 1997b; Bream et al., 2000; Mirante and Patino-Douce, 2000; Carrigan et al., 2001; Kohn, 2001; Mirante, 2001; Kalbas et al., 2002). Lower-temperature ductile and semi-brittle deformation later affected the IP during

Table 5-1. Deformation hierarchy and relative timing of deformation events in the northeastern IP, North Carolina*.

			STRUCTURES			METAMORPHIC CONDITIONS	REGIONAL EVENTS	OROGENY & TIMING
			FABRICS	FOLDS	FAULTS			
DEFORMATION EVENTS	D₁	D_{1wIP}	S ₁ local foliation preserved in boudins	F _{1wIP} : intrafolial, rootless folds; folds preserved in boudins; map-scale folds in TCFZ footwall	TCFZ emplacement	moderate pressure and temperature	arc accretion to Laurentian margin and deposition of western IP Ordovician bimodal volcanics	Taconian orogeny 480-450 Ma
		D_{1eIP}	S ₁ regional axial planar foliation	F _{1eIP} : intrafolial and rootless folds; folds preserved in boudins; refolded recumbent, and isoclinal folds	development of CPS	high pressure, upper amphibolite, kyanite-grade; above minimum melt conditions	initial subduction of Cat Square terrane sediments beneath Carolina terrane	Acadian Orogeny intrusion of ~407 Ma Walker Top Gneiss in eIP, followed by development of PSSZ
	D₂		S ₂ : penetrative foliation; L ₂ : mineral lineation	F ₂ : reclined, tight to isoclinal, and recumbent folds; meso- and macroscale SW-vergent passive flow sheath folds	emplacement of BCFZ and truncation of PSSZ; early movement along Neoacadian BFZ	high temperature, upper amphibolite (granulite?) facies; sillimanite I and II grade; first shared thermal event between eIP and wIP	transpressional accretion of eastern IP and Carolina terrane; SW-directed ductile extrusion and crustal flow of IP	Neoacadian orogeny 360-340 Ma
	D₃		S ₃ : rare mesoscopic foliation, subparallel to S ₂	F ₃ : folding of BCFZ; reclined, open to tight, NW-vergent folds	continued movement along ductile fault zones; initial SW-deflection of IP thrust sheets	high temperature, lower pressure conditions; sillimanite I grade	continued emplacement of eastern IP and Carolina terrane; uplift, unroofing, and cooling of IP	Late Neoacadian orogeny
	D₄		dextral S-C and shear-related fabrics in MSFZ, TCFZ, BCFZ, and PSSZ	F ₄ : Inclined to upright, tight to closed, NW-SE trending, SW-vergent folds	ductile reactivation of BFZ; dextral oblique-slip motion on MSFZ and BCFZ in northeastern IP	lower pressure and temperature retrograde greenschist conditions	emplacement of composite Blue Ridge-Piedmont type C thrust sheet; regional dextral strike-slip motion along large faults	Alleghanian orogeny ~325 Ma
	D₅		Joints	F ₅ : regional open, broad, trend NE & NW	brittle reactivation and dextral strike-slip motion along BFZ	low pressure and temperature brittle conditions	regional uplift, unroofing, and cooling followed by rifting	late Alleghanian uplift; Mesozoic extension
	D₆		Joints	F ₆ : regional broad, open folds, trend NE	Meso- and macroscale normal faults	low pressure and temperature brittle conditions	continued rifting and uplift	Cenozoic uplift

*Modified from Davis, 1993; Yanagihara, 1994; Bream, 1999; Giorgis, 1999; Hill, 1999; Williams, 2000; Bier, 2001; Kalbas, 2003; and Mersch, 2003. BCFZ=Brindle Creek fault zone; BFZ=Brevard fault zone; CPS=Central Piedmont suture; MSFZ=Mill Spring fault zone; PSSZ=Poplar Springs shear zone; TCFZ=Tumblebug Creek fault zone.

Alleghanian dextral strike-slip movement along the BFZ, producing SW-vergent folds and crenulations, S-C and related fabrics, and ubiquitous top-to-the-SW shear sense indicators. Successive D_5 and D_6 brittle fabrics overprint all earlier structures and are most likely related to uplift, exhumation, and extension during the late Alleghanian Blue Ridge-Piedmont megathrust sheet.

ANALYTICAL METHODS

Sensitive high-resolution ion microprobe U-Pb analyses of zircon separates presented here were collected in two sessions at Stanford University during the summer of 2005 using the SHRIMP RG (sensitive high-resolution ion microprobe reverse geometry). Standard SHRIMP RG operating conditions and procedures for zircon U-Pb analyses (Bacon et al., 2002) were utilized and are summarized below. Sample material was collected, crushed, and separated using standard mineral separation techniques to concentrate heavy nonferromagnetic phases. Next, zircon grains were hand picked and mounted with standards in epoxy. Standards used consisted of zircon sample R33 and VP10 (~419 and ~1260 Ma, respectively; SUMAC facility at Stanford University) and U standard SL13 (238 ppm). Samples were then polished to the approximate center of average-size grains and covered with a 10 nm gold coat. Before performing SHRIMP RG analyses, surficial features, internal zonation patterns and inclusions were identified from cathodoluminescence (CL) images of each grain, and a combination of reflected and transmitted light microscopy. A primary $^{16}\text{O}_2^-$ ion beam at ~15 nA was focused to produce a beam of 30 to 40 μm in diameter. Grains were rastered for 4 to 5 minutes to remove the gold coat and surface contamination. Five cycles were completed at Zr_2O , ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{238}U , ^{232}Th , ^{16}O , and $^{238}\text{U}^{16}\text{O}$, for each spot. All data were corrected for common Pb with a minor ^{204}Pb correction, and regressed using SQUID software (Ludwig, 2001a). All data were plotted on standard concordia diagrams, discordia lines were constructed as needed (see below), and concordia ages (Ludwig, 1998) were calculated using Isoplot/Ex software (Ludwig, 1991; 2001b). Calculated concordia ages, which provide a measure of concordance and utilize both $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ values simultaneously (Ludwig, 1998), were determined with decay constant errors (Ludwig, 2000) using Isoplot/Ex. Anomalous ages of grains that experienced Pb-loss or core-rim overlap were removed to obtain some of the reported $^{206}\text{Pb}/^{238}\text{U}$ and concordia ages. Additionally, reversely discordant analyses >10% discordant, interpreted to represent Pb-loss (Dickin, 2005), were removed from most samples in order to obtain reasonable probabilities of concordance and MSWDs.

SAMPLES

All geochronologic samples included in this study are from the Brushy Mountains of western North Carolina (Fig. 5-4; Plate 3). Brushy Mountain lithostratigraphies are those typical of the IP metamorphic core, and correspond to similar rock units recognized to the southwest in the South Mountains and Columbus Promontory. Samples were chosen based on their location relative to important structural observations and, to a lesser extent, outcrop accessibility. Fresh samples were collected at roadcuts, clear-cut ridges and exfoliated balds, and in streams. Detailed geologic mapping in the Brushy Mountains allows for the comparison of analyses from distal samples from the same lithology and easy identification of important structural relationships which are temporally constrained by geochronologic data. Metaigneous samples were selected to provide absolute upper bounds on crosscutting relative timing relationships and to reevaluate previously dated similar lithologic units to the southwest (e.g. Mapes, 2002). Metasedimentary samples were selected for comparison with detrital zircon data from Bream (2003), which indicate the presence of both Laurentian and peri-Gondwanan sediment sources. These data will provide additional limits on the timing of deposition, metamorphism, plutonism, and deformation in the northeastern IP. The geographic coordinates of all geochronologic sample localities for this study are listed in Table 5-2.

Igneous and Metaigneous Lithologies

Walker Top Granite

The Walker Top Granite is the most easily distinguished lithology in the eastern IP. This lithology was originally recognized in the South Mountains by Giorgis (1999), and dated by Mapes (2002), who determined a magmatic age of 366 ± 3 Ma using modern ion probe techniques. Its occurrence is restricted to the eastern IP and is easily recognized by its characteristic porphyritic texture of variably sheared K-feldspar megacrysts in a biotite matrix. Tabular-shaped sill-like bodies of the Walker Top Granite are continuous along strike in the Brushy Mountains for >30 km and are exhumed by map-scale shear zones (Fig. 5-4; Plate 3). Macroscale geometries suggest that these bodies exist near the lowermost portions of the Brindle Creek thrust sheet. The Walker Top Granite is penetratively deformed, with a well developed S-L tectonite fabric. The sample locality (MV-19) is Russell Gap, a roadcut ~4 km from the intersection of NC18 and Russell Gap Rd (Table 5-2).

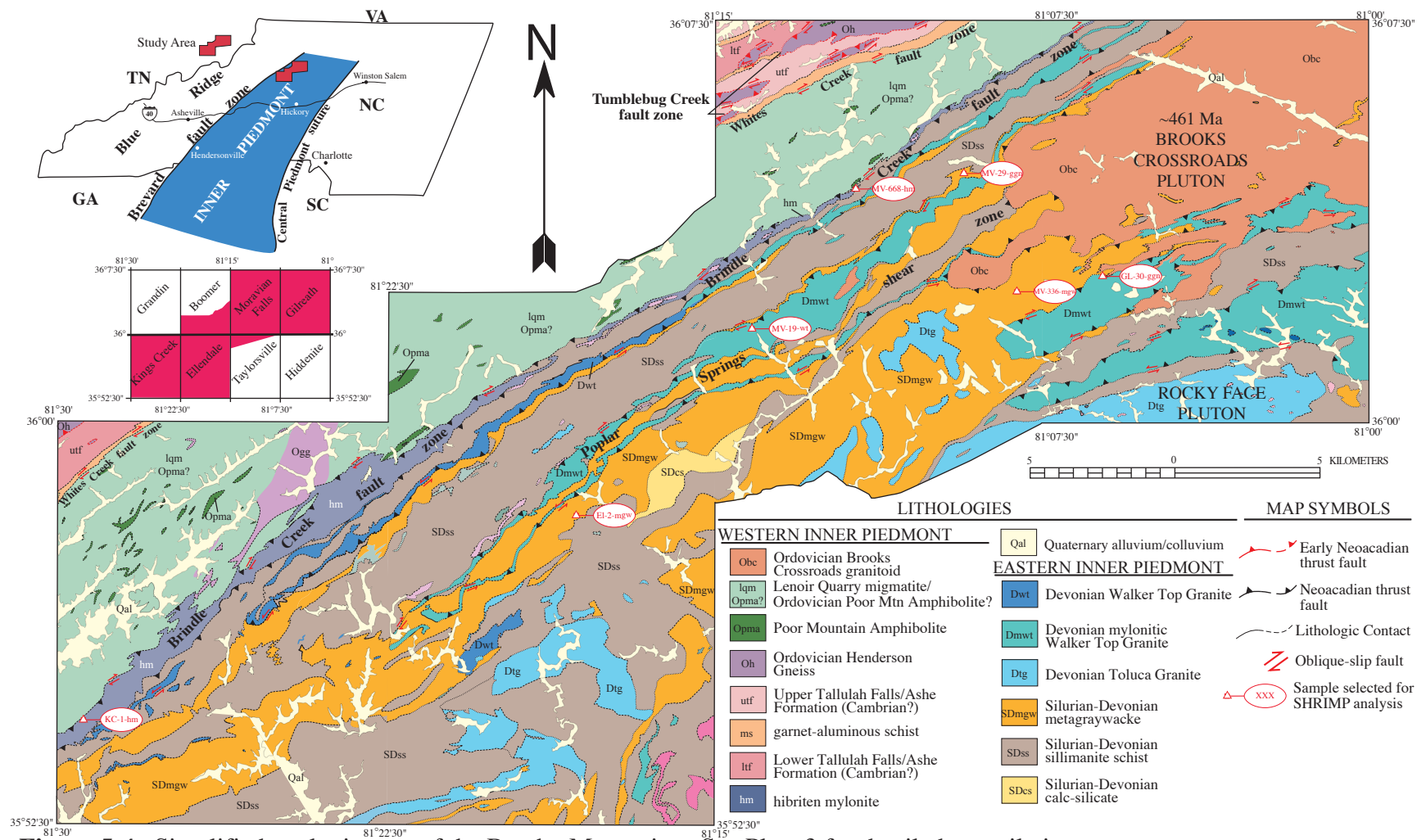


Table 5-2. Sample location and formation association.

Sample	Figure 2 Location	Formation or unit name	7.5-minute quadrangle	County (State)	Locality	Latitude (°N)	Longitude (°W)
Magmatic							
MV-19-wt	1	Walker Top Granite	Moravian Falls	Wilkes (NC)	Russell Gap	36°01'50"	081°14'10"
MV-668-hm	2	Hibriten mylonite/Lenoir Quarry migmatite/Call Pluton	Moravian Falls	Wilkes (NC)	Moravian Creek	36°04'24"	081°11'47"
KC-1-hm	3	Hibriten mylonite/Lenoir Quarry migmatite/Call Pluton	Kings Creek	Caldwell (NC)	Hibriten Mtn.	35°54'25"	081°29'26"
MV-29-ggn	4	granitoid	Moravian Falls	Wilkes (NC)	Brocktown Rd.	36°04'38"	081°09'22"
GL-30-ggn	5	granitoid	Gilreath	Wilkes (NC)	Bethany Church	36°02'42"	081°06'00"
Detrital							
MV-336-mgw	6	eastern Inner Piedmont metagraywacke	Moravian Falls	Wilkes (NC)	Rocky Creek	36°02'27"	081°08'07"
EL-2-mgw	7	eastern Inner Piedmont metagraywacke	Ellendale	Alexander (NC)	White Creek	35°57'07"	081°19'27"

Coordinates are NAD27 CONUS

Zircons from this lithology are characteristically large (200-300 μm) grains with bright cores and dark rims (Fig. 5-5a). Consistent oscillatory zoning is evident in all grains (Fig. 5-5a), indicating a magmatic origin for this lithology. All zircons from this sample contain conspicuously dark metamorphic overgrowths that range from 20-50 μm (Fig. 5-5a). Except for analyses of the metamorphic rims, an effort was made to analyze oscillatory zoned regions of zircons from this sample (Fig. 5-5a).

Hibriten Mylonite

The BCFZ is recognized based on the occurrence of this unit in the Brushy Mountains. The name Hibriten mylonite does not refer to an individual lithology. Rather, it imparts the presence of variable eastern and western IP lithologies caught up in a crustal-scale shear zone. The heterogeneous nature of the Hibriten mylonite and its occurrence proximal to the BCFZ was first recognized in the southwestern Brushy Mountains by Kalbas (2003) near Hibriten Mountain in the Kings Creek quadrangle and Mersch (2003) in the Ellendale and Boomer quadrangles. However, they interpreted it as mylonitic western IP lithologies in the immediate footwall of a ductile fault. New observations have revealed the presence of eastern and western IP lithologies occurring as a tectonic block-in-matrix structure within the BCFZ.

Due to the heterogeneous nature of this unit, two samples ~28 km apart were collected for zircon geochronology (Fig. 5-4; Plate 3). For each locality, similar matrix lithologies of biotite-plagioclase-hornblende gneiss were selected. Sample KC-1 was obtained near the crest of Hibriten Mountain, in the southwesternmost portion of the Kings Creek quadrangle (Fig. 5-4; Plate 3; Table 5-2), originally mapped by Kalbas (2003). It consists of a strongly deformed and migmatitic plagioclase-hornblende-biotite gneiss dominated by S-C fabrics consistently indicating dextral shear. Sample MV-668 was collected from the BCFZ in the Moravian Falls quadrangle near Moravian Creek (Fig. 5-4; Table 5-2; Plate 3). Sample MV-668 also consists of a mylonitic plagioclase-hornblende-biotite gneiss and is texturally and petrographically similar to sample KC-1, but this sample has been more strongly deformed than KC-1 and contains an L-S tectonite fabric. Both of these lithologies are likely Poor Mountain Formation metavolcanic equivalents in the northeastern IP and therefore represent BCFZ footwall blocks caught up within the fault zone.

Zircon grains from these samples clearly indicate a magmatic origin for this lithology (Fig. 5-5b and c). Zircon separates typically have acicular morphologies and range from 150-400 μm (Fig. 5-5b and c). All grains exhibit dark metamorphic

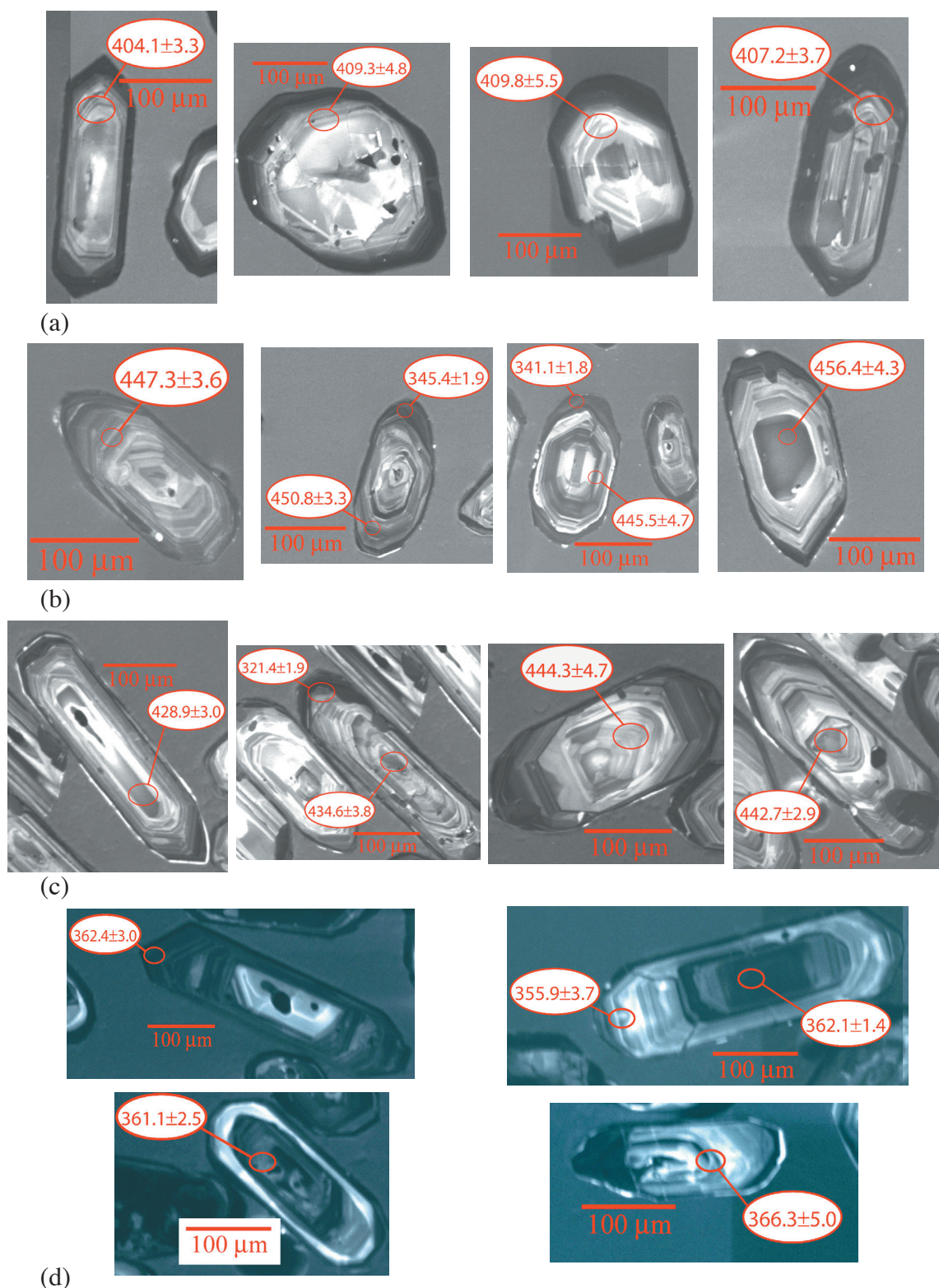


Figure 5-5. Representative images of zircon grains from geochronology samples. (a) Walker Top Granite (MV-19-WT). (b) Hibriten mylonite (MV-668-hm). (c) Hibriten mylonite (KC-1-hm). (d) Crosscutting intrusive (MV-29-ggn).

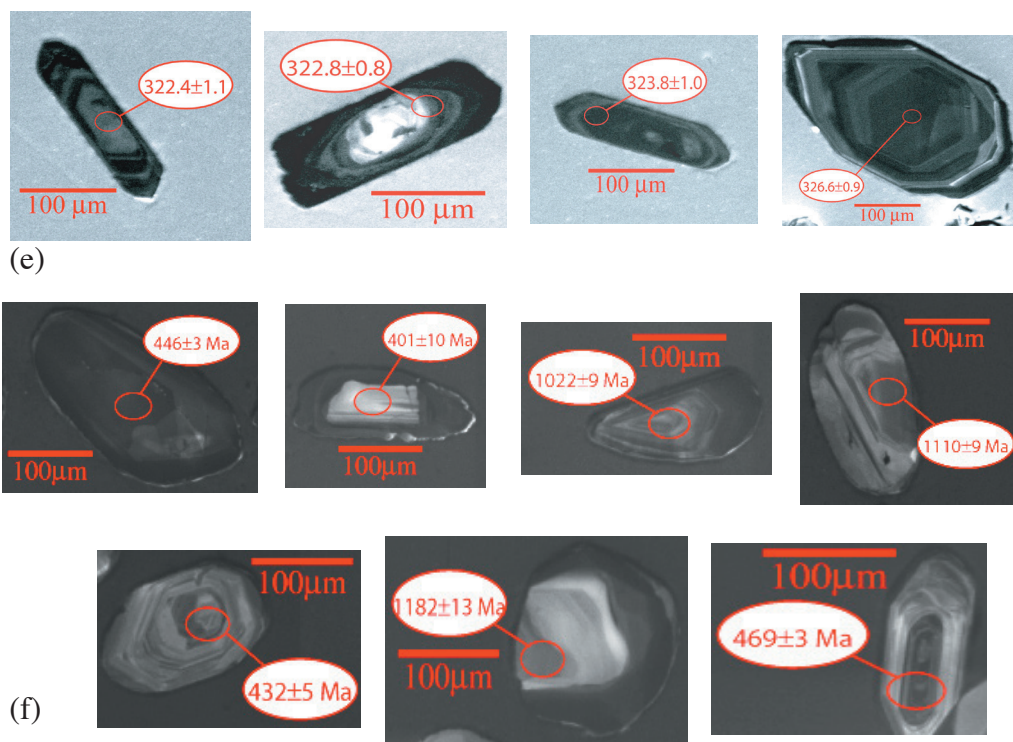


Figure 5-5 continued. (e) Crosscutting intrusive (GL-30-ggn). (f) Detrital zircons from eastern IP metagraywacke (MV-336-mgw and EL-2-mgw).

overgrowths (Fig. 5-5b and c).

Granitic Intrusives

Two small intrusive granitic bodies were also chosen for geochronologic analysis based on their truncation of deformation fabrics, and delimit the timing of deformation in the northeastern IP (Figs. 5-6 and 5-7). Crystallization ages for these intrusives provide an upper bound on the timing of fabric development of truncated structures. A felsic granitic body that truncates F_1 and F_2 folds in an eastern IP metagraywacke/calc-silicate, was selected for analysis to date the timing of these fold generations. This granite body is poorly foliated, medium-grained, and crosscuts the dominant foliation in the metagraywacke/calc-silicate lithology (Fig. 5-6). This sample was collected off of Brocktown Road, ~3 km from the intersection of NC 16 (Fig. 5-4; Table 5-2; Plate 3).

Another granitic sample selected for geochronologic analysis truncates the dominant foliation in the Walker Top Granite body occupying the northwestern limb of the PSSZ (Figs. 5-4 and 5-7). Although apparently undeformed at outcrop-scale, myrmekitic rims on K-feldspar indicate that some strain occurs in this unit, but a clear truncation of the penetrative S_2 fabric can be observed in outcrop and the magmatic age of this granitic body must postdate S_2 penetrative fabric development. This sample was obtained from an exfoliation outcrop along a bald off of Bethany Church Road near Rocky Creek (Fig. 5-4; Table 5-2; Plate 3).

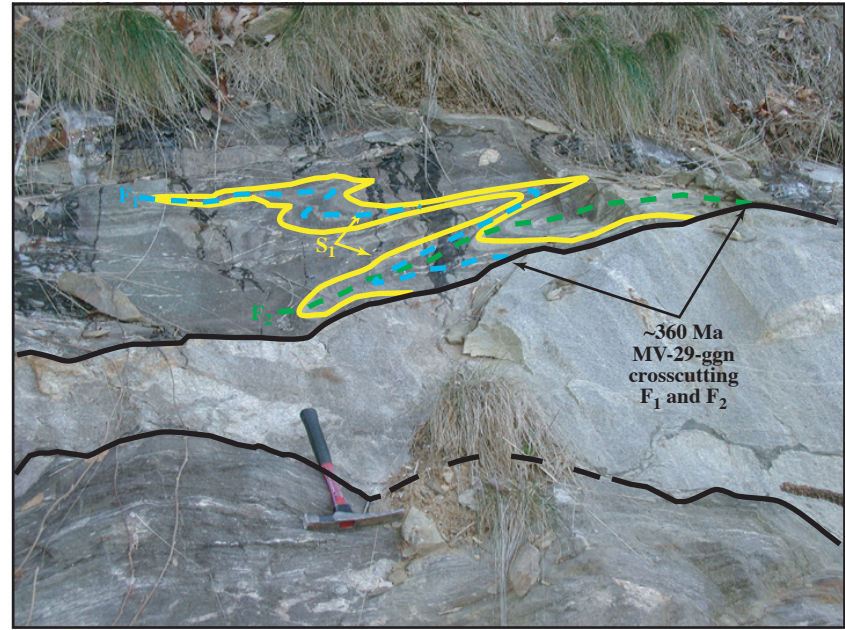
Zircon separates from these lithologies exhibit a range of sizes and shapes, with varied internal morphologies (Fig. 5-5d and e). Complex zonation patterns and truncation of oscillatory zoning in some grains is likely a product of inheritance (Fig. 5-5d and 5e). Areas of complex zoning were avoided for analyses to obtain crystallization ages from areas of oscillatory zoning (Fig. 5-5d and 5e).

Metasedimentary Lithologies

Two eastern IP metagraywacke lithologies were chosen for detrital zircon geochronology, to determine if previously recognized suites of ~400 Ma and ~500 Ma zircons are present. Eastern IP metagraywacke lithologies are the most areally extensive metasedimentary units in the northeastern IP and consist of a locally migmatitic K-feldspar-plagioclase-muscovite-biotite-quartz paragneiss. Minor constituents consist of clinozoisite, garnet, sillimanite, hornblende, apatite, sphene, and opaques (Part II). Samples collected for this study were collected from Rocky Creek (MV--336) in the Moravian Falls quadrangle and from near White Creek (EL-2) in the Ellendale



(a)

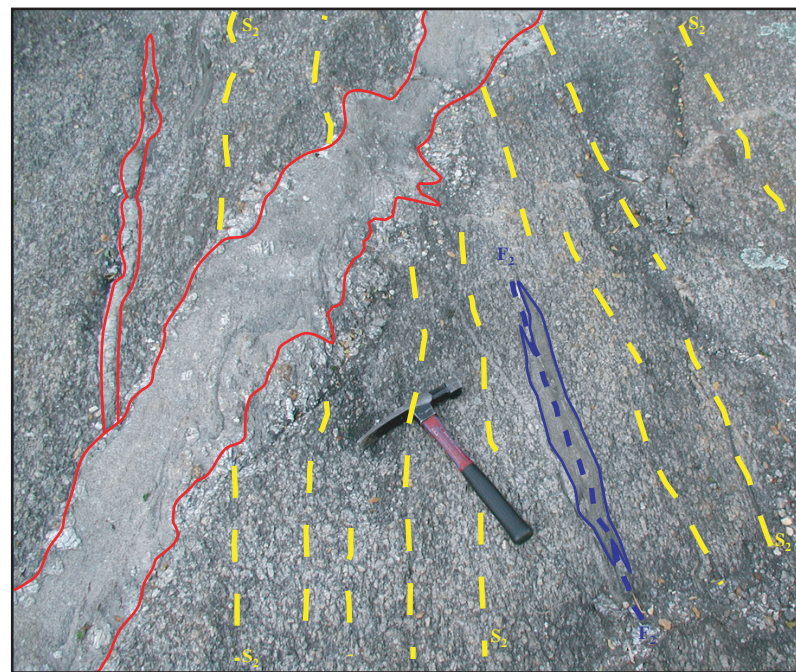


(b)

Figure 5-6. Outcrop photograph of geochronology sample MV-29-ggn. (a) Outcrop photograph. (b) Outcrop photograph and sketch of truncated structures. Note that both F_1 and F_2 are truncated and that the granite is partially transposed into the foliation. Photo by RDH.



(a)



(b)

Figure 5-7. Truncation of Walker Top Granite by granitic dike (GL-30-ggn). (a) Outcrop photograph. (b) Sketch of truncated structures. Photo by RDH.

quadrangle (Fig. 5-4; Table 5-2; Plate 3). Fresh material was collected for similar lithologies from an along-strike distance of ~20 km (Fig. 5-4) to maximize age populations.

Detrital zircon separates from eastern IP metagraywacke lithologies vary in size and morphology and display complex zoning (Fig. 5-5f). Most grains have rounded edges and convoluted cores, with some internal features (oscillatory zoning) reminiscent of a magmatic origin (Fig. 5-5f). All detrital grains have dark metamorphic rims ranging in size from 10-30 μm (Fig. 5-5f).

RESULTS

Geochronologic data obtained for all samples are listed in Table 5-3. For igneous and metaigneous lithologies, magmatic ages are presented in Table 5-4, with the relevant statistics for the pooled $^{206}\text{Pb}/^{238}\text{U}$ concordia ages. Most data are concordant (Table 5-3).

Detrital

Detrital zircons from eastern IP metasedimentary lithologies were combined to produce probability plots for $^{206}\text{Pb}/^{238}\text{U}$ ages, due to difficulties in obtaining a large number of grains. It should be noted, however, that these lithologies are texturally and mineralogically identical and were collected from the same unit (Fig. 5-4). A concordia diagram for pooled eastern IP metapsammite lithologies shows a range of detrital components from 1600-400 Ma, with clusters at ~1500 Ma, ~1100 Ma, ~1000 Ma, ~610 Ma, ~465 Ma, and ~430 Ma (Fig. 5-8a). Summed probability plots for $^{206}\text{Pb}/^{238}\text{U}$ ages of metasedimentary lithologies (Fig. 5-8b) should be viewed as relative abundances of coherent age groups because of the limited number of analyses for each division, separation and analytical bias, and multiple analyses of zircon grains with unique ages. A summed probability plot for pooled eastern IP metasedimentary samples reveals a dominance of Paleozoic (~430 Ma and ~465 Ma) detrital components, with lesser contributions from mid-Proterozoic (~1025 Ma, 1160 Ma, and ~1515 Ma) components (Fig. 5-8b). Although too few analyses were performed to determine statistically accurate provenance for eastern IP metasedimentary rocks (Anderson, 2005), the existence of these age populations is significant and has important tectonic implications (discussed below).

Table 5-3. U-Pb SHRIMP zircon data. C-core. IC-inherited core. R-rim. RC-rim and core overlap.

Analysis Label	Zone ⁽¹⁾	U Th		Radiogenic Ratios																Ages (in Ma) ⁽²⁾					
		(in ppm)	Th/U	²⁰⁶ Pb/ ²³⁸ Pb	% err	f206 % ⁽²⁾	²³⁸ U/ ²⁰⁶ Pb ⁽³⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽³⁾	% err	²³⁸ U/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²³⁸ U ⁽⁴⁾	% err	²⁰⁶ Pb/ ²³⁸ U ⁽⁴⁾	% err	err corr.	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	% Conc ⁽⁵⁾	
MV19-1.1	C	422.7	117.0	0.29	0.000038	65	<0.0001	15.28	0.9	0.0543	1.6	15.29	0.9	0.0539	1.8	0.484	2.0	0.065	0.9	0.439	408	3	370	40	110
MV19-1.2 [†]	C	131.3	108.2	0.85	0.000613	41	0.2677	15.43	1.3	0.0570	2.8	15.60	1.4	0.0479	8.5	0.424	8.6	0.064	1.4	0.166	400	6	96	200	419
MV19-2.1	C	3896.5	768.6	0.20	0.000047	29	<0.0001	14.47	0.3	0.0554	0.5	14.49	0.3	0.0547	0.6	0.521	0.7	0.069	0.3	0.415	430	1	401	14	107
MV19-3.1 [†]	R	131.9	70.9	0.56	0.000516	45	0.2051	16.59	1.3	0.0558	2.8	16.75	1.4	0.0482	7.8	0.397	8.0	0.060	1.4	0.177	374	5	108	185	345
MV19-4.1	C	161.6	80.0	0.51	0.000132	50	0.1238	15.23	1.2	0.0559	2.4	15.26	1.2	0.0540	3.1	0.488	3.3	0.066	1.2	0.356	409	5	371	69	110
MV19-5.1 [†]	R	129.4	81.8	0.65	0.000307	76	0.2542	16.92	1.4	0.0560	2.9	17.02	1.5	0.0515	7.4	0.417	7.6	0.059	1.5	0.193	368	5	264	171	140
MV19-5.2	C	578.9	165.7	0.30	0.000019	99	0.2102	15.49	0.7	0.0565	1.3	15.50	0.7	0.0562	1.4	0.500	1.6	0.065	0.7	0.416	403	3	460	32	88
MV19-6.1 [†]	C	256.4	162.7	0.66	0.000299	53	<0.0001	14.98	0.9	0.0551	1.9	15.06	1.0	0.0507	5.1	0.464	5.2	0.066	1.0	0.189	414	4	226	118	183
MV19-6.2	C	932.2	265.7	0.29	0.000066	50	0.0672	15.69	0.5	0.0552	1.3	15.71	0.5	0.0542	1.6	0.476	1.6	0.064	0.5	0.285	398	2	380	35	105
MV19-7.1	C	193.6	112.9	0.60	0.000118	50	0.3885	15.80	1.1	0.0577	2.6	15.83	1.1	0.0560	3.1	0.488	3.3	0.063	1.1	0.343	395	4	452	70	87
MV19-7.2	C	3536.3	532.3	0.16	0.000050	30	<0.0001	14.50	0.2	0.0552	0.6	14.51	0.2	0.0544	0.7	0.517	0.8	0.069	0.2	0.299	430	1	389	16	110
MV19-8.1 [†]	C	866.7	287.5	0.34	0.002589	11	4.4054	14.81	0.4	0.0904	5.5	15.54	0.7	0.0525	13.1	0.465	13.1	0.064	0.7	0.057	402	3	305	297	132
MV19-9.1 [†]	C	329.3	162.9	0.51	0.000194	45	0.1177	14.74	0.7	0.0562	2.2	14.79	0.7	0.0534	3.3	0.498	3.4	0.068	0.7	0.219	422	3	345	76	122
MV19-10.1	C	1442.5	412.6	0.30	0.000238	19	0.3815	15.05	0.3	0.0581	1.3	15.12	0.3	0.0546	1.8	0.498	1.9	0.066	0.3	0.186	413	1	397	41	104
MV19-10.2	C	261.2	118.1	0.47	0.000128	46	0.2222	15.42	0.8	0.0566	2.2	15.46	0.8	0.0547	2.8	0.488	2.9	0.065	0.8	0.285	404	3	401	63	101
MV19-11.1 [†]	C	148.0	90.6	0.63	0.000566	35	<0.0001	14.93	1.1	0.0536	3.1	15.08	1.2	0.0453	7.6	0.414	7.7	0.066	1.2	0.155	414	5	42	184	997
MV19-12.1	C	3131.8	643.6	0.21	0.000017	52	<0.0001	14.08	0.2	0.0554	0.6	14.08	0.2	0.0552	0.7	0.540	0.7	0.071	0.2	0.334	442	1	419	15	106
MV19-13.1	C	247.2	220.8	0.92	0.001240	34	2.2546	14.84	0.8	0.0732	7.6	15.18	1.2	0.0551	15.5	0.501	15.5	0.066	1.2	0.074	411	5	416	346	99
MV19-14.1 [†]	C	190.3	147.0	0.80	0.000343	50	<0.0001	15.38	1.0	0.0545	2.7	15.47	1.0	0.0495	5.9	0.441	6.0	0.065	1.0	0.173	404	4	171	139	237
MV19-15.1	C	121.3	75.0	0.64	0.000174	50	0.6739	15.21	1.2	0.0603	3.1	15.25	1.2	0.0567	4.0	0.523	4.1	0.066	1.2	0.294	409	5	455	87	90
MV19-16.1	C	322.4	134.8	0.43	0.000048	66	0.1254	15.46	0.7	0.0558	2.0	15.47	0.7	0.0551	2.2	0.491	2.3	0.065	0.7	0.322	404	3	416	49	97
MV19-17.1	C	96.3	52.4	0.56	0.000326	50	0.2179	15.15	1.4	0.0567	3.7	15.24	1.4	0.0492	6.1	0.470	6.3	0.066	1.4	0.222	410	6	377	140	109
MV19-18.1	C	216.7	105.9	0.51	0.000213	50	0.0634	15.28	0.9	0.0554	2.4	15.34	0.9	0.0540	4.0	0.470	4.1	0.065	0.9	0.228	407	4	386	90	105
MV19-19.1 [†]	C	151.9	85.2	0.58	0.000409	50	0.5204	14.98	1.1	0.0593	3.4	15.10	1.1	0.0533	6.8	0.487	6.9	0.066	1.1	0.166	413	5	340	154	121
MV668-1.1 [†]	C	252.2	130.3	0.53	0.007549	13	0.5475	13.82	0.8	0.0603	2.1	15.99	2.3	-	-	-	-	0.063	2.3	-	391	9	-	-	-
MV668-2.1	R	1137.3	5.2	0.00	0.000080	41	<0.0001	17.85	0.4	0.0534	1.2	17.88	0.4	0.0522	1.5	0.403	1.6	0.056	0.4	0.263	351	1	322	35	109
MV668-3.1 [†]	C	343.7	201.8	0.61	0.000098	50	<0.0001	13.53	0.7	0.0558	1.9	13.55	0.7	0.0544	2.3	0.553	2.4	0.074	0.7	0.292	459	3	386	52	119
MV668-4.1	C	186.5	262.4	1.45	0.000076	66	0.2055	13.61	1.0	0.0578	2.5	13.63	1.0	0.0567	2.9	0.573	3.0	0.073	1.0	0.321	456	4	478	63	95
MV668-5.1 [†]	R	916.7	25.8	0.03	0.000310	25	0.0970	19.06	0.5	0.0538	1.4	19.17	0.5	0.0492	2.8	0.354	2.8	0.052	0.5	0.174	328	2	159	65	206
MV668-6.1	C	603.4	807.0	1.38	0.000076	45	0.1007	13.83	0.5	0.0567	1.4	13.84	0.5	0.0556	1.7	0.554	1.8	0.072	0.5	0.308	450	2	438	37	103
MV668-7.1	R	1448.2	19.6	0.01	0.000123	35	0.2072	18.04	0.4	0.0551	1.1	18.08	0.4	0.0533	1.6	0.407	1.7	0.055	0.4	0.232	347	1	342	37	102
MV668-8.1	C	231.5	151.8	0.68	<0.000001	-	<0.0001	13.40	0.9	0.0563	3.6	13.40	0.9	0.0563	3.6	0.579	3.7	0.075	0.9	0.233	464	4	462	80	100
MV668-9.1 [†]	C	301.4	189.2	0.65	0.000216	41	<0.0001	13.75	0.8	0.0556	2.0	13.80	0.8	0.0525	3.2	0.524	3.3	0.072	0.8	0.230	451	3	305	74	148
MV668-9.2	R	720.9	9.4	0.01	0.000119	62	<0.0001	18.13	0.6	0.0527	1.6	18.17	0.6	0.0509	2.7	0.386	2.7	0.055	0.6	0.207	345	2	237	62	146
MV668-10.1	C	312.2	180.3	0.60	0.000310	33	0.4878	14.26	0.8	0.0595	1.9	14.34	0.8	0.0550	3.5	0.529	3.6	0.070	0.8	0.219	435	3	412	78	106
MV668-11.1	R	1401.2	57.7	0.04	0.000047	50	<0.0001	18.24	0.4	0.0531	1.1	18.26	0.4	0.0525	1.3	0.396	1.4	0.055	0.4	0.289	344	1	313	30	110
MV668-12.1	C	210.5	131.6	0.65	<0.000001	-	0.2280	14.06	0.9	0.0576	2.4	14.06	0.9	0.0576	2.4	0.565	2.5	0.071	0.9	0.358	443	4	514	52	86
MV668-13.1	C	298.2	269.7	0.93	0.000096	66	<0.0001	13.89	0.8	0.0553	2.0	13.91	0.8	0.0539	2.7	0.534	2.8	0.072	0.8	0.275	447	3	409	61	109
MV668-14.1 [†]	C	177.1	114.3	0.67	0.000265	45	0.1438	13.75	1.0	0.0572	2.6	13.82	1.0	0.0533	4.3	0.532	4.4	0.072	1.0	0.233	450	4	340	97	132
MV668-15.1	R	684.0	12.3	0.02	0.000092	50	<0.0001	18.37	0.5	0.0532	1.6	18.40	0.5	0.0519	2.1	0.389	2.1	0.054	0.5	0.255	341	2	311	47	110
MV668-15.2	C	141.9	119.3	0.87	<0.000001	-	<0.0001	14.00	1.1	0.0555	2.9	13.97	1.1	0.0568	3.1	0.561	3.3	0.072	1.1	0.330	446	5	486	69	92
MV668-16.1	C	399.3	327.9	0.85	<0.000001	-	0.0675	14.15	0.7	0.0562	1.8	14.15	0.7	0.0562	1.8	0.548	1.9	0.071	0.7	0.353	440	3	462	39	95
MV668-17.1 [†]	C	265.5	138.2	0.54	0.000216	45	0.0781	13.86	0.8	0.0565	2.1	13.92	0.8	0.0534	3.5	0.529	3.6	0.072	0.8	0.229	447	4	345	79	130

Table 5-3. continued.

Analysis Label	Zone ⁽¹⁾	U Th		Radiogenic Ratios																Ages (in Ma) ⁽²⁾					
		(in ppm)	Th/U	²⁰⁴ Pb/ ²⁰⁶ Pb	%err	f206 % ⁽³⁾	²³⁸ U/ ²⁰⁶ Pb ⁽³⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽³⁾	% err	²³⁵ U/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²³⁵ U ⁽⁴⁾	% err	²⁰⁶ Pb/ ²³⁸ U ⁽⁴⁾	% err	err corr.	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	% Conc ⁽⁵⁾	
KC1-1.1	C	201.7	147.6	0.76	0.000056	67	0.2265	13.69	0.9	0.0579	2.0	13.71	0.9	0.0570	2.2	0.574	2.4	0.073	0.9	0.362	454	4	493	49	92
KC1-2.1	R	955.9	4.4	0.00	0.000016	66	0.0392	18.11	0.4	0.0537	1.1	18.11	0.4	0.0535	1.1	0.407	1.2	0.055	0.4	0.354	346	1	350	25	99
KC1-3.1	C	173.6	133.2	0.79	<0.000001	-	0.0419	14.02	0.9	0.0561	2.6	14.02	0.9	0.0561	2.6	0.552	2.8	0.071	0.9	0.342	444	4	457	58	97
KC1-4.1 [†]	R	1938.5	33.0	0.02	0.000044	43	0.3048	21.16	0.3	0.0547	0.9	21.18	0.3	0.0541	1.0	0.352	1.1	0.047	0.3	0.314	297	1	374	23	80
KC1-5.1	C	189.9	187.6	1.02	<0.000001	-	0.0247	14.41	0.9	0.0557	2.2	14.41	0.9	0.0557	2.2	0.533	2.4	0.069	0.9	0.390	433	4	440	49	98
KC1-6.1	C	162.4	138.1	0.88	<0.000001	-	0.1580	14.38	1.0	0.0568	2.3	14.38	1.0	0.0568	2.3	0.545	2.5	0.070	1.0	0.400	433	4	483	51	90
KC1-7.1	R	670.0	12.2	0.02	0.000441	25	0.2636	19.95	0.6	0.0548	2.2	20.11	0.6	0.0483	4.5	0.331	4.6	0.050	0.6	0.131	313	2	114	107	275
KC1-8.1	R	1152.0	457.9	0.41	0.000314	20	0.3627	19.45	0.4	0.0558	1.0	19.56	0.5	0.0512	2.4	0.361	2.4	0.051	0.5	0.186	321	1	248	55	130
KC1-8.2 [†]	C	169.8	118.3	0.72	0.000061	66	<0.0001	14.32	0.9	0.0546	2.1	14.34	0.9	0.0537	2.4	0.517	2.6	0.070	0.9	0.348	435	4	360	55	121
KC1-9.1	C	279.5	319.5	1.18	<0.000001	-	0.1312	14.54	0.7	0.0565	1.7	14.54	0.7	0.0565	1.7	0.536	1.9	0.069	0.7	0.392	429	3	471	38	91
KC1-10.1	C	413.0	371.8	0.93	0.000064	70	0.1067	14.55	0.6	0.0563	1.4	14.57	0.6	0.0553	1.8	0.524	1.9	0.069	0.6	0.308	428	2	425	41	101
KC1-11.1	R	734.2	8.1	0.01	0.000284	29	0.0185	17.41	0.5	0.0539	1.2	17.50	0.5	0.0497	3.0	0.392	3.0	0.057	0.5	0.171	358	2	181	69	198
KC1-12.1	C	101.4	62.1	0.63	0.000146	40	0.3150	13.80	1.2	0.0585	2.7	13.84	1.2	0.0564	3.2	0.561	3.4	0.072	1.2	0.344	450	5	466	70	96
KC1-13.1	R	820.6	34.8	0.04	0.000104	50	0.1060	18.16	0.6	0.0542	1.2	18.20	0.6	0.0527	2.0	0.399	2.0	0.055	0.6	0.277	345	2	317	45	109
KC1-14.1 [†]	C	146.5	90.9	0.64	0.000192	44	-0.2249	15.06	1.0	0.0533	4.1	15.11	1.0	0.0504	5.1	0.460	5.2	0.066	1.0	0.198	413	4	215	118	192
KC1-15.1	R	859.3	417.5	0.50	0.000589	32	0.5403	20.27	0.6	0.0569	1.5	20.49	0.7	0.0482	6.5	0.324	6.6	0.049	0.7	0.103	307	2	109	155	281
KC1-16.1	R	253.2	4.2	0.02	0.002073	18	0.5936	19.52	1.1	0.0576	2.9	20.28	1.3	0.0262	27.4	0.178	27.5	0.049	1.3	0.048	310	4	-1594	932	-19
KC1-17.1	C	111.3	65.6	0.61	0.000093	66	0.1066	13.99	1.1	0.0567	2.5	14.02	1.1	0.0553	3.1	0.544	3.3	0.071	1.1	0.337	444	5	425	69	105
KC1-18.1	R	1291.6	9.1	0.01	<0.000001	-	0.1489	19.06	0.6	0.0542	0.9	19.06	0.6	0.0542	0.9	0.392	1.1	0.052	0.6	0.536	330	2	380	20	87
KC1-19.1	R	793.2	7.2	0.01	<0.000001	-	0.2242	19.25	0.5	0.0547	1.2	19.25	0.5	0.0547	1.2	0.392	1.3	0.052	0.5	0.364	326	2	401	28	81
KC1-20.1	C	226.1	135.2	0.62	<0.000001	-	<0.0001	14.07	0.9	0.0546	1.9	14.07	0.9	0.0546	1.9	0.535	2.1	0.071	0.9	0.437	443	4	394	42	112
KC1-20.2	RC	476.3	308.2	0.67	0.000025	66	0.0743	15.23	0.5	0.0555	1.3	15.23	0.5	0.0552	1.4	0.499	1.5	0.066	0.5	0.368	410	2	420	31	98
KC1-21.1 [†]	C	145.8	123.9	0.88	0.000102	39	<0.0001	14.22	1.0	0.0551	2.3	14.25	1.0	0.0536	2.6	0.519	2.8	0.070	1.0	0.349	437	4	354	59	124
KC1-22.1 [†]	C	120.5	62.8	0.54	0.000232	38	0.2292	14.65	1.1	0.0572	2.4	14.71	1.1	0.0538	3.6	0.504	3.8	0.068	1.1	0.283	424	4	361	82	117
MV29-1.1 [†]	IC	349.5	52.6	0.16	0.000362	33	0.3851	13.23	0.8	0.0595	1.8	13.31	0.8	0.0542	4.0	0.562	4.1	0.075	0.8	0.194	467	4	381	90	123
MV29-2.1	R	686.6	97.9	0.15	<0.000001	-	0.0213	17.29	0.4	0.0540	1.3	17.29	0.4	0.0540	1.3	0.430	1.4	0.058	0.4	0.305	362	2	370	30	98
MV29-2.2	IC	79.5	55.3	0.72	<0.000001	-	0.0975	16.84	1.3	0.0548	3.6	16.84	1.3	0.0548	3.6	0.449	3.8	0.059	1.3	0.339	372	5	404	80	92
MV29-3.1	RC	293.3	156.0	0.55	0.000177	50	0.1165	17.30	0.7	0.0547	1.9	17.36	0.7	0.0521	3.3	0.414	3.4	0.058	0.7	0.208	361	2	377	75	96
MV29-3.2 [†]	R	788.2	102.1	0.13	0.000248	20	<0.0001	15.07	0.5	0.0535	1.4	15.14	0.5	0.0498	2.3	0.454	2.4	0.066	0.5	0.215	412	2	187	54	220
MV29-4.1	R	5206.7	114.7	0.02	0.000053	22	0.0378	18.26	0.2	0.0537	0.5	18.27	0.2	0.0529	0.6	0.399	0.6	0.055	0.2	0.264	343	1	323	14	106
MV29-5.1 [†]	IC	56.2	38.8	0.71	0.000177	67	<0.0001	13.90	1.5	0.0510	4.6	13.94	1.5	0.0484	6.1	0.478	6.2	0.072	1.5	0.237	447	6	117	143	382
MV29-6.1 [†]	IC	153.8	173.1	1.16	0.003457	13	5.4337	13.41	0.9	0.0997	3.7	14.30	1.2	0.0488	21.2	0.471	21.2	0.070	1.2	0.056	436	5	139	498	314
MV29-7.1	IC	278.7	177.0	0.66	0.000060	65	0.1249	13.81	0.7	0.0570	1.7	13.83	0.7	0.0561	2.0	0.559	2.2	0.072	0.7	0.311	450	3	456	45	99
MV29-8.1	RC	236.6	171.7	0.75	<0.000001	-	0.1685	17.63	0.8	0.0550	2.2	17.63	0.8	0.0550	2.2	0.430	2.3	0.057	0.8	0.331	356	3	367	49	97
MV29-9.1	RC	110.1	42.7	0.40	<0.000001	-	0.3450	17.62	1.1	0.0564	3.1	17.62	1.1	0.0564	3.1	0.441	3.2	0.057	1.1	0.335	356	4	391	68	91
MV29-9.2	RC	868.4	475.0	0.57	0.000019	63	<0.0001	17.30	0.4	0.0536	1.1	17.31	0.4	0.0533	1.2	0.425	1.2	0.058	0.4	0.317	362	1	343	26	105
MV29-10.1	C	275.5	286.5	1.07	0.000036	67	0.0268	14.28	0.6	0.0558	1.7	14.28	0.6	0.0553	1.9	0.534	2.0	0.070	0.6	0.330	436	3	424	41	103
MV29-11.1	RC	255.0	108.0	0.44	0.000047	67	0.3432	17.09	0.7	0.0566	2.0	17.10	0.7	0.0559	2.2	0.451	2.3	0.058	0.7	0.310	366	3	401	48	91
MV29-12.1	IC	285.1	209.8	0.76	0.000032	66	0.0988	13.41	0.6	0.0571	1.6	13.41	0.6	0.0566	1.7	0.582	1.9	0.075	0.6	0.339	464	3	476	39	97
MV29-13.1	C	435.4	463.8	1.10	<0.000001	-	0.1419	14.67	0.5	0.0565	1.4	14.67	0.5	0.0565	1.4	0.531	1.5	0.068	0.5	0.351	425	2	470	32	90
MV29-13.2	R	934.1	3.6	0.00	0.000330	20	0.5422	19.61	0.4	0.0571	1.1	19.73	0.4	0.0523	2.5	0.366	2.5	0.051	0.4	0.155	319	1	298	57	107
MV29-14.1 [†]	C	57.0	35.3	0.64	0.015028	10	27.7731	11.09	1.4	0.2793	2.6	15.22	4.0	0.0618	79.5	0.560	79.6	0.066	4.0	0.051	410	16	666	1703	62
MV29-15.1	RC	601.3	543.7	0.93	0.001206	12	2.1984	15.64	0.5	0.0722	2.3	15.98	0.5	0.0546	6.5	0.471	6.6	0.063	0.5	0.081	391	2	396	147	99

Table 5-3. continued.

Analysis Label	Zone ⁽¹⁾	U Th		Th/U	Radiogenic Ratios																Ages (in Ma) ⁽⁴⁾							
		(in ppm)			²⁰⁶ Pb/ ²⁰⁶ Pb	% err	f206 % ⁽²⁾	²³⁸ U/ ²⁰⁶ Pb ⁽³⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽³⁾	% err	²³⁸ U/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²³⁸ U ⁽⁴⁾	% err	²⁰⁶ Pb/ ²³⁸ U ⁽⁴⁾	% err	err corr.	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	% Conc ⁽⁵⁾			
MV29-16.1	R	1689.5	22.8	0.01	0.000176	25	0.3211	19.53	0.3	0.0554	0.8	19.60	0.3	0.0528	1.6	0.372	1.6	0.051	0.3	0.204	321	1	321	36	100			
MV29-16.2 [†]	C	101.9	82.0	0.83	0.000206	39	0.2545	18.75	1.1	0.0552	3.3	18.82	1.1	0.0522	4.2	0.382	4.4	0.053	1.1	0.263	334	4	292	96	114			
MV29-17.1	RC	1750.9	628.3	0.37	0.000021	2	0.0882	18.26	0.3	0.0541	0.8	18.26	0.3	0.0537	0.8	0.406	0.9	0.055	0.3	0.366	344	1	360	18	95			
MV29-18.1	IC	1734.3	812.8	0.48	0.000154	20	0.2852	14.08	1.2	0.0580	0.7	14.12	1.2	0.0558	1.2	0.545	1.7	0.071	1.2	0.717	441	5	444	27	99			
MV29-19.1	IC	71.7	85.8	1.24	0.000399	48	0.2638	13.99	1.3	0.0579	3.3	14.09	1.3	0.0521	6.7	0.510	6.8	0.071	1.3	0.192	442	6	409	153	108			
MV29-20.1	IC	56.7	32.8	0.60	0.000238	40	0.2847	13.97	1.4	0.0581	3.8	14.03	1.4	0.0546	4.8	0.537	5.0	0.071	1.4	0.287	444	6	397	108	112			
MV29-21.1	R	2185.8	61.8	0.03	0.000164	20	0.3712	19.08	0.3	0.0560	0.8	19.14	0.3	0.0536	1.3	0.386	1.4	0.052	0.3	0.209	328	1	353	30	93			
GL30-1.1 [†]	C	1594.1	315.5	0.20	0.000720	14	1.1271	17.97	0.3	0.0625	2.4	18.21	0.4	0.0519	4.9	0.393	4.9	0.055	0.4	0.074	345	1	281	111	122			
GL30-2.1	C	300.6	60.0	0.21	0.000050	65	<0.0001	13.34	0.6	0.0560	1.6	13.36	0.6	0.0553	1.8	0.571	1.9	0.075	0.6	0.317	465	3	425	41	110			
GL30-3.1 [†]	RC	1607.3	356.1	0.23	0.000110	27	0.0869	19.64	0.3	0.0535	0.9	19.68	0.3	0.0519	1.3	0.363	1.3	0.051	0.3	0.260	320	1	280	29	114			
GL30-4.1 [†]	C	123.2	51.3	0.43	<0.000001	-	0.6291	7.17	0.9	0.0722	1.6	7.17	0.9	0.0722	1.6	1.389	1.8	0.140	0.9	0.465	842	7	991	33	85			
GL30-5.1	RC	1342.4	78.6	0.06	<0.000001	-	0.1208	19.80	0.3	0.0537	1.0	19.80	0.3	0.0537	1.0	0.374	1.0	0.051	0.3	0.324	318	1	359	22	89			
GL30-6.1	RC	2339.4	255.5	0.11	0.000012	67	0.0534	19.47	0.2	0.0533	0.7	19.48	0.2	0.0531	0.8	0.376	0.8	0.051	0.2	0.310	323	1	334	17	97			
GL30-7.1	R	1674.4	78.4	0.05	0.000483	18	0.9582	20.85	0.3	0.0600	1.0	21.03	0.4	0.0529	3.2	0.347	3.2	0.048	0.4	0.115	299	1	326	72	92			
GL30-8.1 [†]	C	184.0	135.6	0.76	0.000101	39	0.5266	16.49	0.8	0.0584	2.2	16.52	0.8	0.0569	2.5	0.475	2.6	0.061	0.8	0.315	379	3	489	55	78			
GL30-9.1	C	352.4	95.4	0.28	0.000091	17	0.2959	15.01	0.5	0.0574	2.1	15.04	0.5	0.0561	2.2	0.514	2.3	0.066	0.5	0.233	415	2	457	49	91			
GL30-9.2	RC	3829.9	142.9	0.04	0.000171	14	0.2307	18.45	0.2	0.0551	0.6	18.51	0.2	0.0526	1.1	0.392	1.1	0.054	0.2	0.190	339	1	312	24	109			
GL30-10.1	RC	1402.7	124.0	0.09	0.000100	30	0.2153	19.38	0.3	0.0546	0.9	19.41	0.3	0.0531	1.3	0.377	1.3	0.052	0.3	0.236	324	1	335	29	97			
GL30-11.1	C	306.7	129.0	0.43	0.000053	39	0.1574	15.94	0.6	0.0558	1.6	15.95	0.6	0.0550	1.8	0.475	1.9	0.063	0.6	0.330	392	2	412	40	95			
GL30-11.2	C	1649.3	108.7	0.07	0.000079	37	0.1789	18.93	0.3	0.0545	0.8	18.96	0.3	0.0533	1.2	0.388	1.2	0.053	0.3	0.229	331	1	344	26	96			
GL30-12.1 [†]	C	1182.3	107.4	0.09	<0.000001	-	0.1714	19.68	0.3	0.0542	1.0	19.67	0.3	0.0543	1.0	0.380	1.0	0.051	0.3	0.323	320	1	381	21	84			
GL30-13.1	RC	1454.5	103.7	0.07	0.000017	45	0.0642	19.24	0.3	0.0535	1.0	19.41	0.3	0.0531	1.0	0.381	1.0	0.052	0.3	0.288	327	1	338	22	97			
GL30-14.1	RC	1165.7	86.6	0.08	0.000044	24	0.1628	19.48	0.3	0.0542	1.0	19.50	0.3	0.0535	1.0	0.378	1.1	0.051	0.3	0.310	322	1	351	23	92			
GL30-15.1	IC	177.5	130.4	0.76	0.000102	45	0.2865	14.33	0.8	0.0579	2.0	14.35	0.8	0.0564	2.4	0.542	2.6	0.070	0.8	0.306	434	3	467	54	93			
GL30-16.1	C	2060.2	250.7	0.13	0.000011	17	0.0347	17.08	0.2	0.0542	0.7	17.08	0.2	0.0540	0.7	0.436	0.7	0.059	0.2	0.333	367	1	371	16	99			
GL30-16.2	RC	2960.7	127.5	0.04	0.000046	30	0.0980	20.06	0.2	0.0534	0.9	20.07	0.2	0.0528	1.0	0.362	1.1	0.050	0.2	0.202	313	1	318	23	99			
MV336-1	R	9589.6	455.7	0.05	0.000014	35	<0.0001	15.82	0.2	0.0540	0.4	15.82	0.2	0.0538	0.4	0.469	0.5	0.063	0.2	0.376	395	1	364	10	109			
MV336-2.1	R	4468.3	230.0	0.05	<0.000001	-	0.0453	16.69	0.3	0.0545	0.6	16.69	0.3	0.0545	0.6	0.450	0.7	0.060	0.3	0.389	375	1	390	14	96			
MV336-3.1 [†]	C	145.6	70.8	0.50	0.000640	50	0.4777	16.45	1.4	0.0580	4.2	16.64	1.5	0.0486	11.1	0.403	11.2	0.060	1.5	0.138	376	6	130	260	290			
MV336-3.2	C	5005.9	1127.6	0.23	0.004137	5	7.4726	13.26	0.2	0.1160	1.9	14.33	0.6	0.0557	7.3	0.536	7.3	0.070	0.6	0.088	435	3	440	163	99			
MV336-4.1 [†]	C	522.0	397.7	0.79	0.000756	17	3.0805	5.83	0.6	0.0979	0.8	5.91	0.7	0.0873	2.3	2.037	2.4	0.169	0.7	0.276	1008	6	1367	44	74			
MV336-5.1	R	1489.2	116.1	0.08	0.000023	50	0.1156	17.23	0.5	0.0547	1.1	17.24	0.5	0.0544	1.1	0.435	1.2	0.058	0.5	0.369	364	2	388	26	94			
MV336-6.1	R	3068.4	196.1	0.07	0.000032	45	0.0670	16.81	0.3	0.0546	0.7	16.82	0.3	0.0541	0.8	0.443	0.9	0.059	0.3	0.348	372	1	375	19	99			
MV336-7.1	R	299.0	208.2	0.72	<0.000001	-	0.0195	15.36	1.0	0.0550	2.3	15.36	1.0	0.0550	2.3	0.494	2.5	0.065	1.0	0.391	407	4	413	51	98			
MV336-8.1 [†]	C	176.8	126.5	0.74	0.000061	99	<0.0001	15.22	1.3	0.0530	3.0	15.24	1.3	0.0521	3.5	0.472	3.8	0.066	1.3	0.338	410	5	291	81	141			
MV336-9.1	R	5251.5	136.1	0.03	0.000006	64	<0.0001	16.64	0.2	0.0540	0.6	16.65	0.2	0.0539	0.6	0.446	0.6	0.060	0.2	0.380	376	1	365	13	103			
EL2-1.1 [†]	C	145.4	82.7	0.59	<0.000001	-	<0.0001	15.50	1.3	0.0521	3.3	15.50	1.3	0.0521	3.3	0.463	3.5	0.065	1.3	0.379	403	5	289	75	139			
EL2-1.2 [†]	R	214.5	100.8	0.49	0.000194	58	0.8616	15.83	1.1	0.0615	2.5	15.89	1.1	0.0586	3.8	0.509	4.0	0.063	1.1	0.280	393	4	553	84	71			
EL2-2.1 [†]	C	288.2	77.1	0.28	0.001798	24	3.4441	15.14	1.0	0.0825	2.2	15.65	1.3	0.0563	11.8	0.496	11.9	0.064	1.3	0.111	399	5	463	262	86			
EL2-2.2	R	812.2	78.7	0.10	0.000118	41	0.3931	13.39	0.6	0.0594	1.3	13.42	0.6	0.0577	1.8	0.593	1.9	0.075	0.6	0.309	463	3	520	39	89			
EL2-3.1	C	319.1	193.9	0.63	<0.000001	-	0.4739	5.09	0.7	0.0822	1.0	5.08	0.7	0.0827	1.1	2.241	1.3	0.197	0.7	0.548	1157	8	1261	22	92			

Table 5-3. continued.

Analysis Label	Zone ⁽¹⁾	U Th		Radiogenic Ratios																Ages (in Ma) ⁽⁴⁾					
		(in ppm)	Th/U	²⁰⁶ Pb/ ²⁰⁶ Pb	% err	f206 % ⁽²⁾	²³⁸ U/ ²⁰⁶ Pb ⁽³⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽³⁾	% err	²³⁸ U/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽⁴⁾	% err	²⁰⁷ Pb/ ²³⁸ U ⁽⁴⁾	% err	err corr.	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	% Conc ⁽⁵⁾			
EL2-4.1	C	321.5	110.3	0.35	0.000093	58	0.5864	7.01	0.8	0.0724	2.5	7.02	0.8	0.0711	2.8	1.397	2.9	0.143	0.8	0.273	859	6	960	56	89
EL2-5.1	C	58.5	57.8	1.02	0.000085	58	1.0263	3.58	1.6	0.1062	1.8	3.58	1.6	0.1051	2.0	4.045	2.5	0.279	1.6	0.638	1587	23	1716	36	93
EL2-5.2	C	725.2	213.7	0.30	0.000022	54	1.1292	3.78	0.5	0.1031	0.5	3.79	0.5	0.1028	0.6	3.745	0.7	0.264	0.5	0.639	1511	6	1675	11	90
EL2-6.1	C	56.0	30.8	0.57	<0.000001	-	<0.0001	6.53	1.9	0.0667	3.1	6.50	1.9	0.0694	4.7	1.471	5.0	0.154	1.9	0.375	922	16	910	96	101
EL2-7.1	C	488.6	334.0	0.71	0.000048	58	0.1225	13.95	0.7	0.0568	1.7	13.96	0.7	0.0561	1.9	0.554	2.0	0.072	0.7	0.372	446	3	457	41	98
EL2-8.1	R	52.1	29.5	0.58	0.001232	50	0.3120	15.22	2.3	0.0574	5.2	15.56	2.6	0.0391	25.3	0.346	25.4	0.064	2.6	0.101	401	10	410	660	98
EL2-9.1 [†]	C	424.5	156.2	0.38	0.000032	58	2.1109	4.42	0.7	0.1018	0.9	4.42	0.7	0.1014	1.0	3.160	1.2	0.226	0.7	0.561	1314	8	1649	18	80
EL2-10.1 [†]	C	17.0	6.7	0.41	0.000802	71	0.6372	5.34	3.3	0.0815	4.8	5.42	3.4	0.0701	13.1	1.783	13.5	0.185	3.4	0.254	1092	35	930	269	117
EL2-11.1	C	61.9	29.9	0.50	<0.000001	-	0.0071	3.73	1.6	0.0953	3.9	3.73	1.6	0.0953	3.9	3.527	4.3	0.268	1.6	0.380	1533	22	1534	74	100
EL2-12.1 [†]	C	79.8	53.5	0.69	0.000293	58	<0.0001	5.53	1.5	0.0745	2.6	5.56	1.5	0.0703	4.4	1.743	4.7	0.180	1.5	0.325	1066	15	937	91	114
EL2-13.1	C	252.1	152.2	0.62	0.000032	58	0.1406	5.32	0.9	0.0777	1.3	5.32	0.9	0.0772	1.3	2.000	1.6	0.188	0.9	0.554	1110	9	1128	26	98
EL2-14.1	C	130.1	48.6	0.39	0.000117	71	0.6339	5.90	1.2	0.0779	1.9	5.91	1.2	0.0763	2.5	1.778	2.7	0.169	1.2	0.445	1007	11	1102	49	91
EL2-15.1 [†]	C	76.6	72.7	0.98	0.000290	50	<0.0001	5.77	1.5	0.0685	2.5	5.80	1.5	0.0643	4.3	1.529	4.5	0.172	1.5	0.341	1026	15	751	90	137
EL2-16.1 [†]	C	170.4	96.4	0.58	<0.000001	-	<0.0001	3.48	1.0	0.0917	1.2	3.48	1.0	0.0917	1.2	3.638	1.5	0.288	1.0	0.644	1630	14	1461	22	112
EL2-17.1 [†]	C	126.5	97.7	0.80	0.000443	45	<0.0001	13.34	1.5	0.0547	3.4	13.44	1.5	0.0482	7.2	0.494	7.4	0.074	1.5	0.205	463	7	107	171	433
EL2-18.1 [†]	C	907.2	229.5	0.26	0.000059	45	2.4148	7.16	0.5	0.0866	0.8	7.16	0.5	0.0857	0.9	1.650	1.0	0.140	0.5	0.477	842	4	1332	17	63
EL2-19.1	C	1474.1	303.1	0.21	-0.000021	58	2.5022	7.18	0.4	0.0872	0.6	7.18	0.4	0.0874	0.6	1.679	0.7	0.139	0.4	0.526	840	3	1370	12	61
EL2-20.1	C	98.0	21.3	0.22	0.000193	45	0.9085	3.73	1.3	0.1023	1.5	3.75	1.3	0.0996	2.0	3.666	2.4	0.267	1.3	0.551	1525	18	1617	37	94
EL2-21.1 [†]	C	504.4	175.7	0.36	<0.000001	-	0.5488	6.34	0.6	0.0749	1.0	6.34	0.6	0.0749	1.0	1.630	1.2	0.158	0.6	0.531	944	6	1067	20	88
EL2-22.1	R	889.2	60.4	0.07	0.000180	46	0.3681	17.56	0.6	0.0566	1.4	17.62	0.6	0.0540	2.7	0.422	2.8	0.057	0.6	0.218	356	2	370	60	96
EL2-23.1 [†]	C	235.0	86.8	0.38	0.000438	41	0.4945	13.37	1.1	0.0603	2.4	13.48	1.1	0.0539	5.7	0.551	5.8	0.074	1.1	0.197	461	5	365	128	126
EL2-24.1	C	155.6	78.2	0.52	0.000144	45	0.3690	4.31	1.1	0.0893	1.4	4.32	1.1	0.0873	1.8	2.787	2.1	0.232	1.1	0.521	1343	13	1366	34	98
EL2-25.1	C	233.0	71.5	0.32	0.000045	58	0.0931	5.82	0.9	0.0741	1.5	5.82	0.9	0.0734	1.6	1.739	1.8	0.172	0.9	0.509	1022	9	1026	32	100
EL2-26.1	C	85.6	27.5	0.33	0.000178	58	<0.0001	3.96	1.4	0.0872	1.8	3.97	1.4	0.0847	2.5	2.937	2.9	0.252	1.4	0.499	1447	19	1308	49	111
EL2-27.1	C	207.4	98.5	0.49	0.000064	80	0.3580	5.81	0.9	0.0762	1.5	5.82	0.9	0.0753	1.8	1.784	2.0	0.172	0.9	0.469	1022	9	1076	36	95
EL2-28.1	C	254.3	197.1	0.80	0.000026	58	<0.0001	4.69	0.8	0.0808	1.2	4.69	0.8	0.0805	1.2	2.365	1.5	0.213	0.8	0.566	1246	9	1208	24	103
EL2-29.1	C	49.3	39.7	0.83	<0.000001	-	0.1717	5.61	2.0	0.0759	3.1	5.61	2.0	0.0763	3.1	1.876	3.7	0.178	2.0	0.543	1057	20	1104	62	96
EL2-30.1	C	222.0	71.4	0.33	<0.000001	-	<0.0001	14.45	1.1	0.0547	2.6	14.42	1.1	0.0563	3.4	0.538	3.6	0.069	1.1	0.311	432	5	464	76	93
EL2-31.1 [†]	C	484.0	595.1	1.27	0.000149	50	<0.0001	13.59	0.7	0.0558	1.7	13.63	0.8	0.0536	2.7	0.543	2.8	0.073	0.8	0.272	456	3	356	61	128
EL2-32.1 [†]	C	89.3	35.3	0.41	<0.000001	-	0.8821	5.91	1.5	0.0798	2.2	5.91	1.5	0.0798	2.2	1.862	2.7	0.169	1.5	0.561	1007	14	1193	44	84
EL2-33.1	C	796.1	780.3	1.01	0.000050	50	0.1500	10.00	0.5	0.0615	1.1	10.00	0.5	0.0608	1.2	0.838	1.4	0.100	0.5	0.394	614	3	632	27	97
EL2-34.1	C	134.6	24.0	0.18	0.000079	65	0.1646	4.96	1.2	0.0808	1.7	4.97	1.2	0.0797	1.9	2.211	2.3	0.201	1.2	0.519	1182	13	1189	38	99
EL2-35.1 [†]	R	631.0	90.3	0.15	0.001261	14	1.8720	12.87	0.7	0.0717	2.2	13.17	0.7	0.0533	5.9	0.558	5.9	0.076	0.7	0.126	472	3	341	133	138
EL2-35.2 [†]	C	263.7	214.8	0.84	0.000252	45	0.7398	13.46	1.0	0.0622	2.3	13.52	1.1	0.0585	3.8	0.597	3.9	0.074	1.1	0.269	460	5	548	82	84
EL2-36.1 [†]	C	17.2	13.6	0.82	0.001138	58	0.3001	6.01	3.3	0.0746	5.0	6.13	3.5	0.0581	18.0	1.306	18.4	0.163	3.5	0.189	974	31	533	395	183
EL2-37.1 [†]	R	1108.8	122.9	0.11	0.000023	51	<0.0001	13.08	0.5	0.0548	1.1	13.09	0.5	0.0545	1.1	0.574	1.2	0.076	0.5	0.380	475	2	392	26	121
EL2-37.2 [†]	C	136.2	241.3	1.83	<0.000001	-	0.8432	7.83	1.2	0.0718	4.0	7.83	1.2	0.0718	4.0	1.263	4.2	0.128	1.2	0.293	775	9	980	81	79
EL2-38.1	C	364.2	40.8	0.12	0.000049	58	0.0263	6.27	0.7	0.0711	1.2	6.28	0.7	0.0704	1.3	1.547	1.5	0.159	0.7	0.485	953	6	940	27	101
EL2-39.1	C	287.2	32.1	0.12	0.000075	58	0.0652	13.48	0.9	0.0567	2.1	13.50	0.9	0.0556	2.4	0.568	2.6	0.074	0.9	0.358	461	4	438	54	105
EL2-39.2	C	558.6	232.3	0.43	<0.000001	-	<0.0001	13.24	0.7	0.0556	1.5	13.24	0.7	0.0556	1.5	0.579	1.6	0.076	0.7	0.405	469	3	437	33	107

Notes: (1) Zones: R=Rim; C=Core; IC=Inherited core; RC=Rim and core overlap.

(2) f206% denotes the percentage of ²⁰⁶Pb that is common Pb.(3) Data not corrected for ²⁰⁴Pb.(4) Common Pb corrected using measured ²⁰⁴Pb.

(5) % Conc. = [(206Pb/238U Age)/(207Pb/206Pb Age)]*100, where values >100% are reversely discordant and values <100% are normally discordant.

(†) Data points excluded from ages and probability plots.

Table 5-4. Pooled $^{206}\text{Pb}/^{238}\text{U}$ and Concordia ages for magmatic samples.

	Walker Top Granite (MV-19-WT)	Hibriten mylonite				Crosscutting intrusive granites	
		(Lenoir Quarry migmatite) (MV-668-hm)	(Lenoir Quarry migmatite) (KC-1-hm) older and younger cores		MV-29-granitic gneiss older (inherited) cores and younger magmatic rims	GL-30-granitic gneiss	
	n=14/24	n=9/18	n=6/14	n=8/14	n=5/14	n=5/14	n=7/11
$^{206}\text{Pb}/^{238}\text{U}$ Age	408.3±2.1 Ma	449.3±2.4 Ma	441.9±3.5 Ma	432.5±3.0 Ma	439.2±4.0 Ma	362.9±1.8 Ma	321.8±2.8 Ma
MSWD	1.50	1.02	1.20	1.30	0.65	1.19	1.90
Concordia Age	406.0±2.0 Ma (n=9/14)	448.7±1.3 Ma (n=8/9)	444.0±3.7 Ma (n=4/6)	434.7±1.8 Ma (n=5/8)	436.7±2.1 Ma (n=4/5)	360.4±1.1 Ma (n=4/5)	323.4±0.5 (n=5/11)
equivalence prob.	0.74 (1.20)	0.42 (1.02)	0.29 (1.12)	0.62 (1.90)	0.63 (0.61)	0.31 (1.30)	0.41 (0.24)
concordance prob.	0.87 (0.23)	0.26 (1.30)	1.20 (0.22)	0.80 (0.63)	0.64 (0.29)	0.87 (0.53)	0.03 (0.44)

*MSWD=mean square of the weighted deviate.

**Probabilities in parentheses calculated for Concordia age MSWDs.

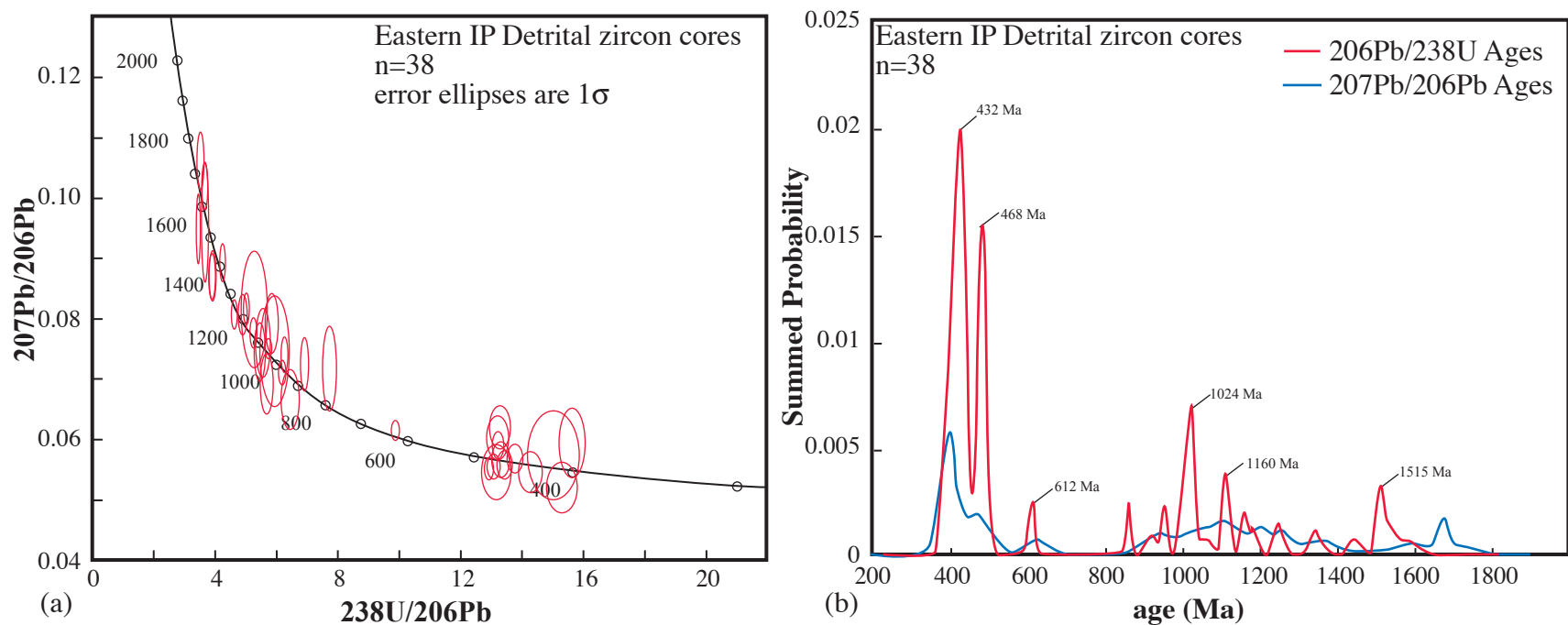


Figure 5-8. Concordia and summed probability plots for eastern IP detrital zircon samples. (a) Tera-Wasserburg concordia plot of eastern IP detrital zircon cores. (b) Summed probability plot of data from eastern IP metagraywacke zircon cores (MV-336 and EL-2).

Magmatic

Zircons from igneous and metaigneous samples do not indicate the presence of Grenvillian or older inheritance, although MV-29 does retain peri-Gondwanan inherited cores (discussed below). Most grains are acicular, sub- to euhedral, and display prominent concentric (magmatic) zoning. Metamorphic overgrowths and embayed textures are common along zircon rims and vary in size.

Walker Top Granite

Summed probabilities of twenty-four $^{206}\text{Pb}/^{238}\text{U}$ ages for this sample reveal a significant peak at ~407 Ma, with smaller peaks at ~430 and ~443 Ma (Fig. 5-9a). Omission of discordant data, however, indicates a single peak at ~407 Ma (Fig. 5-9a). Excluding two analyses of metamorphic overgrowths and seven reversely discordant zircon cores, pooled $^{206}\text{Pb}/^{238}\text{U}$ ages for fourteen analyses of zircon cores yield an age of 408.3 ± 2.1 Ma (Table 5-4). Nine concordant analyses were used to obtain a concordia age of 406.0 ± 2.0 Ma (Fig. 5-10a; Table 5-4). This age probably represents time of crystallization of the Walker Top Granite based on zircon morphology and textures (Fig. 5-5a). Two analyses of metamorphic zircon rims from this sample yielded $^{206}\text{Pb}/^{238}\text{U}$ ages of 374 ± 5 and 368 ± 5 Ma, although, both are reversely discordant.

The nature and extent of the Walker Top Granite in the IP is a topic of considerable debate. Mapes (2002) reported a 366 ± 3 Ma ion microprobe U-Pb zircon crystallization age for a sample of Walker Top Granite collected from Icy Knob in the South Mountains about 1 km from the type locality (SW of the current study area). Correlation of lithologies from the Brushy Mountains to those of the South Mountains is based on reconnaissance mapping (e.g., Rankin et al., 1972; Espenshade et al., 1975; Goldsmith et al., 1988), textural and mineralogical similarities of lithologies, and similar lithostratigraphic assemblages separated by similar structures. Clearly a continuation of structures and lithologies from the South Mountains exists across the Morganton Basin and into the Brushy Mountains. Conflicting crystallization ages for this lithology, however, suggest that these are not correlative units. Considering the timing of high-grade Neocadian metamorphism in the IP (360-340 Ma; Dallmeyer, 1988; Dennis and Wright, 1997a, 1997b; Bream et al., 2000; Mirante and Patino-Douce, 2000; Carrigan et al., 2001; Kohn, 2001; Mirante, 2001; Kalbas et al., 2002; Bream, 2003), it is likely that the ~366 Ma crystallization age for the Walker Top Granite from the South Mountains represents a Pb-loss event and a complete thermal resetting of the zircons during the initial stages of peak metamorphism. Thus, a crystallization age of ~406 Ma is favored

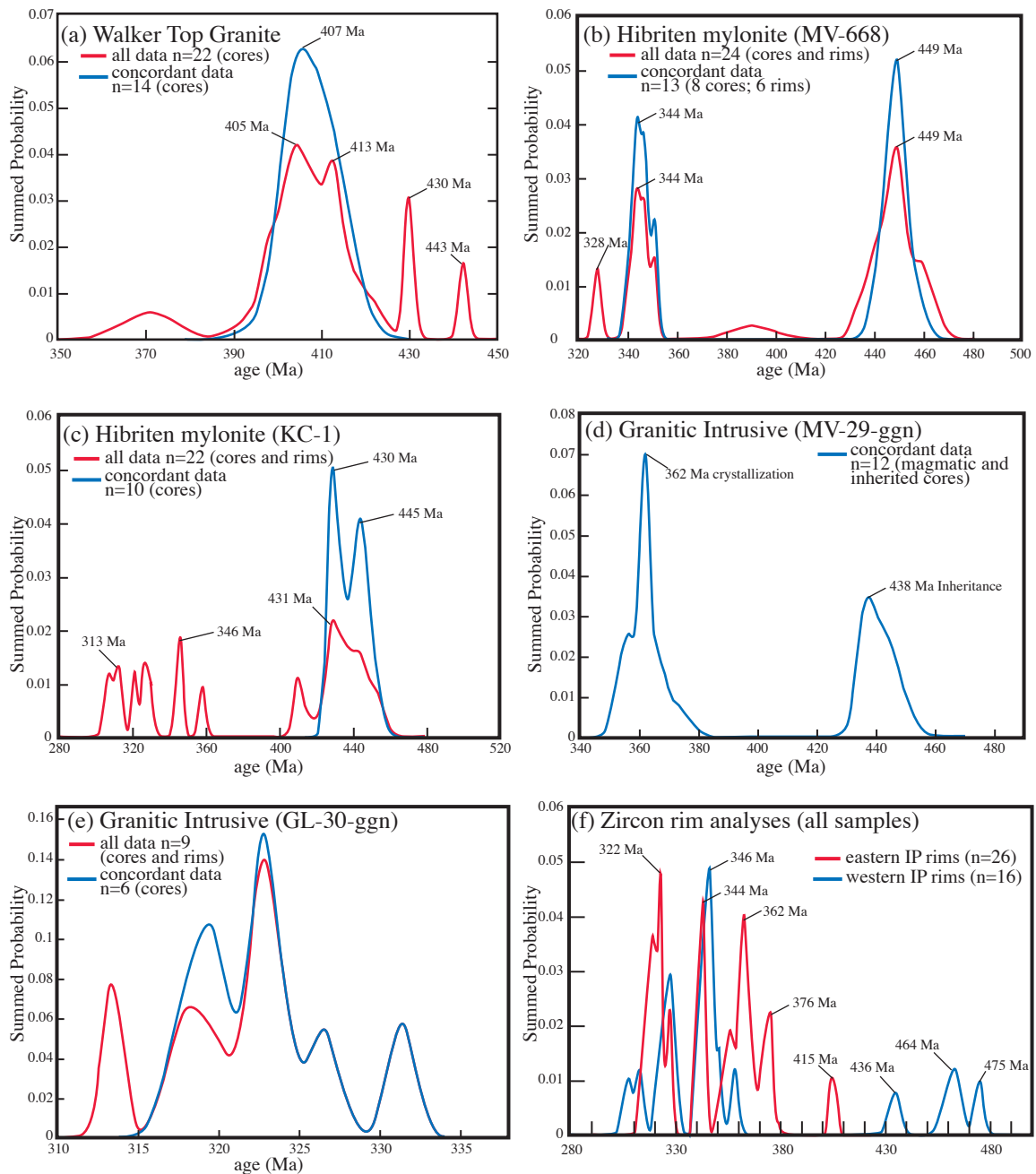


Figure 5-9. Summed probability plots of individual analyses of magmatic and metamorphic zircon samples. Note that in (a-e) red lines correspond to all data and blue lines represent concordant data only. (a) Walker Top Granite. (b) Hibriten mylonite (MV-668-hm). (c) Hibriten mylonite (KC-1-hm). (d) Crosscutting intrusive granite (MV-29-ggn). (e) Cross-cutting intrusive granite (Gl-30-ggn). (f) All zircon rim analyses. Note that the red line corresponds to eastern IP zircon rims and the blue line corresponds to western IP zircon rims.

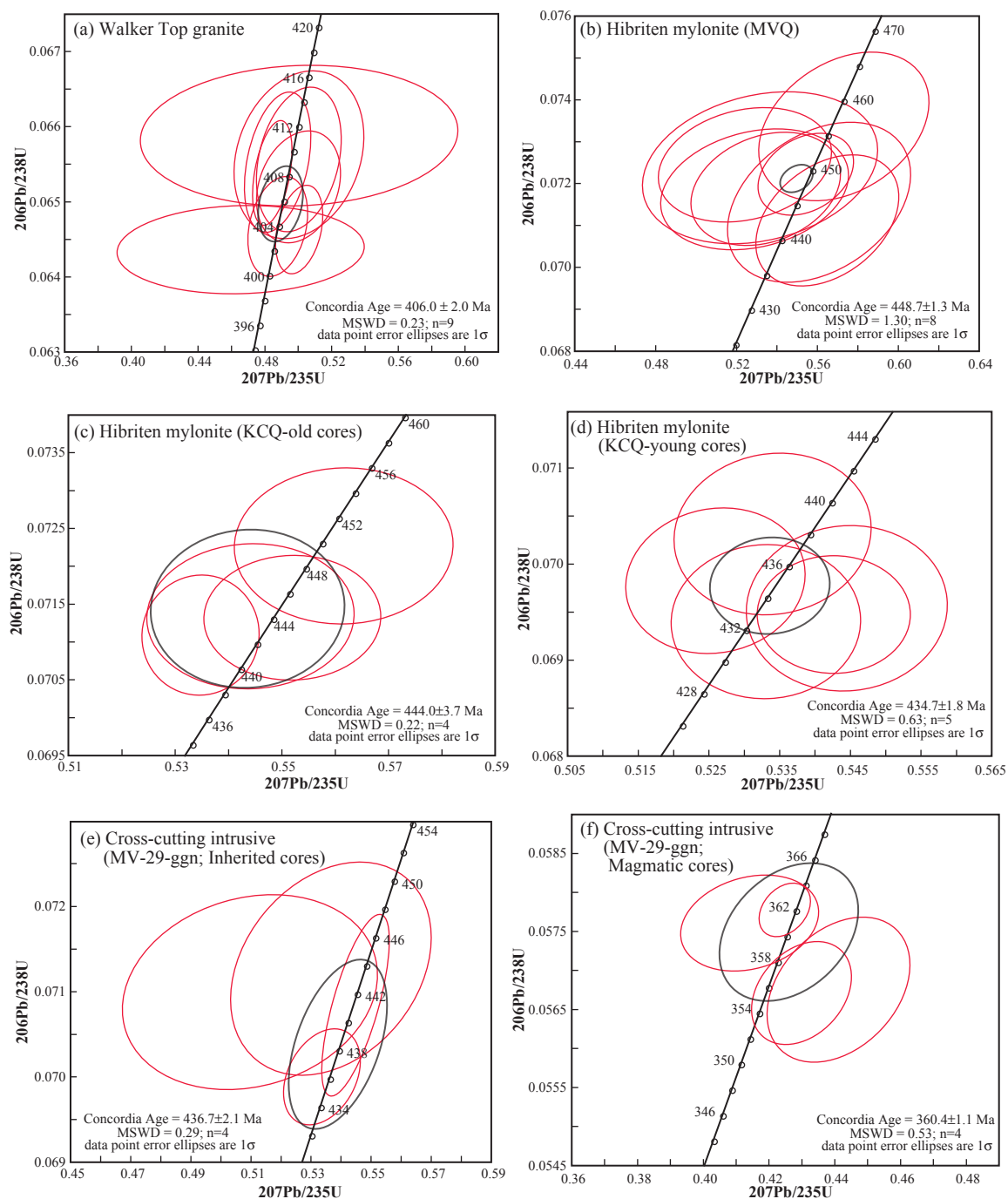


Figure 5-10. Concordia plots of ^{204}Pb -corrected SHRIMP data for magmatic and metamorphic zircon samples. (a) Walker Top Granite. (b) Hibriten mylonite (MVQ). (c) Hibriten mylonite (KCQ; old cores). (d) Hibriten mylonite (KCQ; young cores). (e) Crosscutting intrusive granite (MV-29-ggn; inherited cores). (f) Cross-cutting intrusive granite (MV-29-ggn; magmatic cores). Note that red ellipses correspond to 1σ and black ellipses are concordia ages. Abbreviations: MVQ=Moravian Falls quadrangle; KCQ=Kings Creek quadrangle.

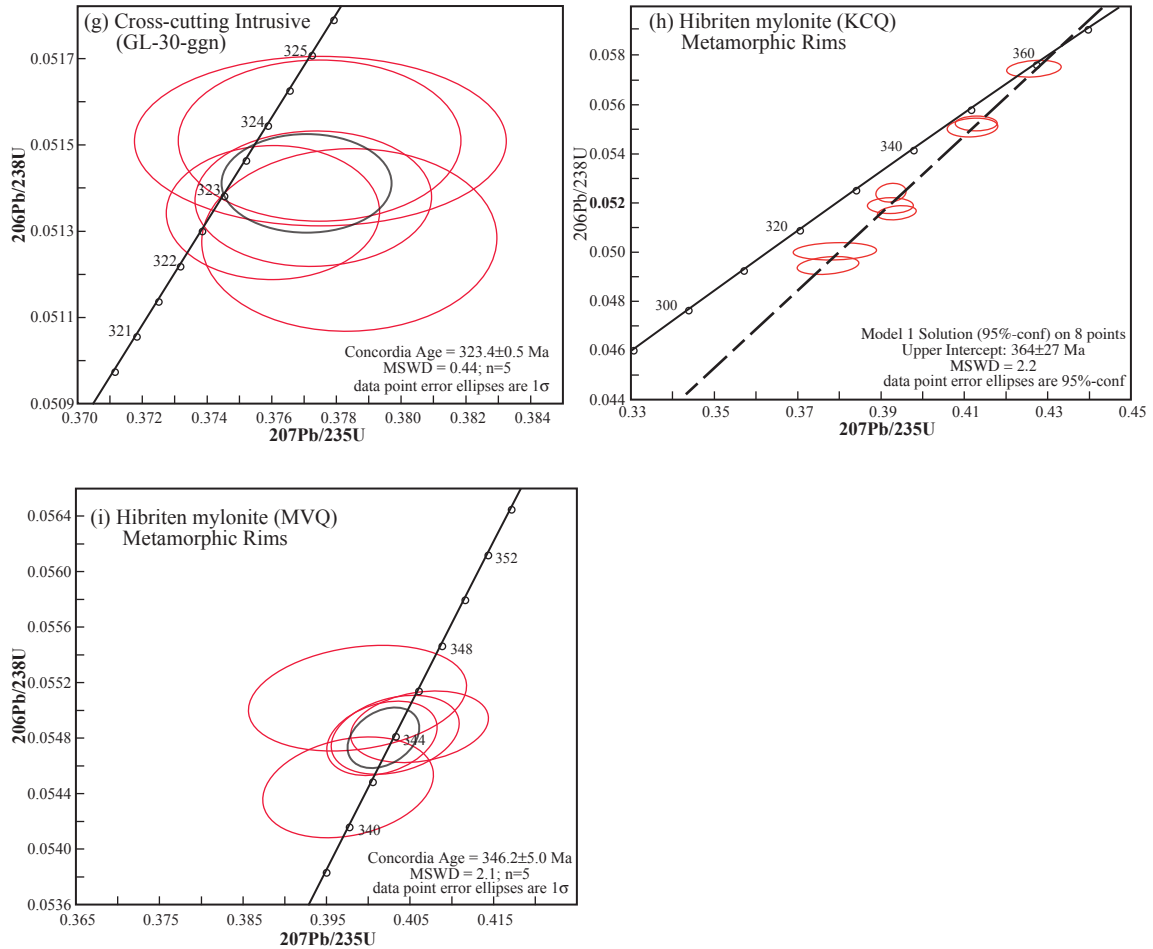


Figure 5-10 continued. (g) Crosscutting intrusive (Gl-30-ggn). (h) Discordia plot of regressed metamorphic zircon rim data (KC-1-hm). (i) Concordia plot of metamorphic zircon rim data (MV-668-hm). Note that red ellipses correspond to 1σ (except in (h), where they are 95% confidence) and black ellipses are concordia ages. Abbreviations: MVQ=Moravian Falls quadrangle; KCQ=Kings Creek quadrangle.

here.

Hibriten mylonite

Pooled $^{206}\text{Pb}/^{238}\text{U}$ ages for twenty-four zircon analyses from the northeastern Brushy Mountains Hibriten mylonite (MV-668-hm) reveal three populations of ~ 328 Ma, ~ 344 Ma, and ~ 449 Ma (Fig. 5-9b). Thirteen concordant data analyses, however, only indicate the presence of ~ 344 and ~ 449 Ma populations (Fig. 5-9b). Nine concordant zircon core analyses yielded a $^{206}\text{Pb}/^{238}\text{U}$ age of 449.3 ± 2.4 Ma (Table 5-4). Eight of these analyses were used to calculate a concordia age of 448.7 ± 1.3 Ma, interpreted here to be a magmatic age based on zircon morphology and textures (Table 5-4; Figs. 5-5b and 4-10b). Five of six metamorphic overgrowth analyses are remarkably concordant and yield a concordia age of 346.2 ± 5.0 Ma (Fig. 5-10i).

An additional sample collected from the southwestern Brushy Mountains (KC-1-hm) was analyzed for comparison with the results above. This sample contains two concordant populations of zircon cores at ~ 430 and ~ 445 Ma (Fig. 5-9c). Pooled $^{206}\text{Pb}/^{238}\text{U}$ ages for these populations reveal ages of 441.9 ± 3.5 Ma ($n = 6/14$) and 432.5 ± 1.8 Ma ($n = 8/14$), with corresponding concordia ages of 444.0 ± 3.7 Ma ($n = 5/6$) and 434.7 ± 1.8 Ma ($n = 5/8$), respectively (Table 5-4; Fig 5-10c and 10d). Similar internal zoning morphologies for zircon cores suggest these ages are true populations and represent continuous magmatism from ~ 445 Ma to ~ 435 Ma. Normally discordant analyses of zircon rims from this sample fall along a regressed discordia with an upper intercept of 364 ± 27 Ma, which is interpreted to represent a Pb-loss episode during a thermal event (Fig. 5-10h).

Remarkable similarities in magmatic ages are likely the result of sampling identical lithologies from an overall heterogeneous unit. Together, these samples indicate a crystallization history from ~ 445 to ~ 435 Ma, and record two episodes of metamorphism, occurring at ~ 364 and ~ 345 Ma, which may represent a single protracted metamorphic event during the Neoacadian.

Granitic Intrusives

Two populations of summed $^{206}\text{Pb}/^{238}\text{U}$ ages, ~ 362 Ma and ~ 438 Ma, are indicated by concordant zircon core analyses from a granitoid intrusion (MV-29-ggn), which truncates early fold generations in metasedimentary lithologies (Figs. 5-6 and 5-9d and 5-9e). Pooled analyses yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 362.9 ± 1.8 Ma ($n = 5$) and 439.2 ± 4.0 Ma ($n = 5$) for this lithology (Table 5-4), which correspond to concordia ages of $360.4 \pm$

1.1 Ma and 436.7 ± 2.1 Ma, respectively. Complex oscillatory zonation in these grains suggest that they have undergone a polyphase thermal history and contain inherited cores (Fig. 5-5). Excluding inheritance, magmatic cores and oscillatory zoned rims indicate a crystallization age of ~ 360 Ma.

Summed probabilities for nine zircon cores and magmatic rims from a cross-cutting granitoid (GL-30-ggn) indicate the presence of a younger (320-330) suite of ages than other samples (Fig. 5-9e). Pooled $^{206}\text{Pb}/^{238}\text{U}$ ages for seven of eleven analyses from this sample yielded an age of 321.8 ± 2.8 Ma (Table 5-4). A concordia age of 323.4 ± 0.5 Ma was calculated using five of these analyses (Fig. 5-10g; Table 5-4). The presence of inherited cores is indicated by three analyses, which produced $^{206}\text{Pb}/^{238}\text{U}$ ages of 415 ± 2 Ma, 434 ± 3 Ma, and 465 ± 3 Ma, although these single analyses are discordant and insufficient to represent a significant population.

Metamorphic

Metamorphic overgrowths on zircon rims from all samples are conspicuous, contain more U and less Th, and range in age from ~ 322 Ma to ~ 475 Ma (Fig. 5-9f). Eastern and western IP lithologies contain metamorphic overgrowths with ages of ~ 376 Ma, ~ 360 Ma, ~ 345 Ma, ~ 328 Ma, and ~ 325 Ma (Fig. 5-9f). It should be noted, however, that eastern IP lithologies contain no metamorphic overgrowths older than ~ 415 Ma, and that 436-475 Ma metamorphic ages are restricted to the western IP (Fig. 5-9f). Zircon rims were analyzed in all samples.

DISCUSSION

An array of proposed tectonic settings and developmental models for the IP proposed over the last five decades is partially related to an incomplete understanding of the tectonic evolution of the southern Appalachian crystalline core. This incomplete understanding results from a general lack of detailed mapping and a paucity of geochemical and or geochronological studies, which incorporate all available data into coherent developmental models. Furthermore, polyphase deformation and metamorphism in the IP have obscured most primary (and some secondary) stratigraphic and structural features, creating a complex geological conundrum that is difficult to unravel. Recent detailed studies of the structure and composition of the IP and modern advances in geochemical and geochronologic techniques have revolutionized approaches to complex geological problems and their applications to IP geology have provided for great advances in our understanding of its development over the past decade. The

following will attempt to incorporate new geochronologic and structural data from this study with existing models and constraints to produce a coherent tectonic model for the Paleozoic development of the northeastern IP.

Depositional Constraints

U-Pb SHRIMP analyses of detrital zircons can determine multiple source ages in sedimentary and metasedimentary rocks, and provide timing constraints on the beginning and ending of deposition. Using detrital zircon data from southern Appalachian crystalline core paragneisses, Bream (2002, 2003) showed a predominance of Grenvillian magmatic (1000-1250 Ma) and metamorphic (850-1000 Ma) detrital zircons for all tectonic subdivisions therein, except for the eastern IP, which revealed a unique suite of Neoproterozoic and early Paleozoic detrital zircon ages. Based on these data, a Laurentian derivation was favored for all tectonic subdivisions with the exception of the eastern IP, for which combined sediment input from Laurentian (1.1, 1.4, 1.8, 2.8 Ga) and peri-Gondwanan (500, 600 Ma) sources were indicated (Bream, 2002, 2003; Bream et al., 2004). The most probable peri-Gondwanan source for Neoproterozoic detrital input is the adjacent Carolina superterrane (Fig. 5-1). Merschat and Hatcher (in press) establish a minimum age of ~430 Ma for eastern IP metasedimentary lithologies and concluded that these assemblages represent a relict Siluro-Devonian ocean basin that existed between Laurentia and the approaching Carolina superterrane.

Data from this study confirm the presence of significant early- to mid-Paleozoic detrital components, with less-significant Neoproterozoic and Grenvillian components in eastern IP metasedimentary assemblages. Slightly different timing constraints and tectonic implications are preferred here, however, based on new data. Use of the youngest detrital zircon age to provide an upper bound on timing of sediment deposition for eastern IP sediments has previously restricted this event to post ~430 Ma (Bream, 2002; Merschat and Hatcher, in press). These data, combined with metamorphic overgrowths as old as ~400 Ma, have delimited a 30 Ma time interval in which eastern IP sediments were deposited and metamorphosed to upper-amphibolite grade (Bream, 2002; Merschat and Hatcher, in press). A substantial detrital component as young as ~432 Ma is recognized here as the youngest coherent age group for eastern IP metasediments, which supports the interpretation of Bream (2002) that the eastern IP is composed of metasedimentary sequences, which were still being deposited after Ordovician plutonism and volcanism in the Tugaloo terrane. However, these observations, combined with the oldest metamorphic zircon rim age of ~415 Ma, present somewhat of a problem, in that

this provides only an ~15 m.y. window of time in which eastern IP sediments were buried and metamorphosed to upper-amphibolite conditions. A likely scenario is one in which initial subduction of eastern IP sediments by the Carolina superterrane began as early as ~415 Ma, with continued subduction, metamorphism, and plutonism until the Neoacadian orogeny and accretion of the eastern IP and Carolina terrane, causing the first shared thermal event between eastern and western IP terranes. Initial subduction of the eastern IP as early as ~415 Ma coincides with the earliest anatectic magmatism (~406 Ma Walker Top Granite) in the eastern IP, which further supports this conclusion. This interpretation allows for deposition of eastern IP sediments, derived from eastern and western sources, after western IP Ordovician magmatism, but before Neoacadian (~360 Ma) accretion to the Devonian Laurentian margin.

Magmatic Constraints

Taking into account the polyphase thermal history of the IP, U-Pb zircon and whole-rock Rb-Sr ages are not surprisingly difficult to interpret and to incorporate into coherent tectonic reconstructions. Recently, advances in geochronologic techniques have permitted a number of previously undated or loosely constrained plutons to be dated accurately. Based on geochronologic data, isotopic evidence, and trace element concentrations, Mapes et al. (2002) suggested that eastern and western IP magmatic histories are temporally and petrogenetically distinct from one another and are mutually exclusive. Hatcher (2002) noted that regional structural relationships support this subdivision across the BCFZ. Western IP granitoids correspond to a sizeable suite of Middle Ordovician (mainly 460-470 Ma) plutons (Ranson et al., 1999; Vinson, 1999), while Late Silurian to Late Carboniferous granitoids comprise the eastern IP igneous/metagneous suite (Mapes, 2002).

Western IP

The Henderson Gneiss is the most areally extensive igneous body in the western IP, and, although extensively studied, its origin remains somewhat of an enigma. Many techniques have been employed to resolve the crystallization and metamorphic ages of the Henderson Gneiss, and most have produced conflicting results. Reported U-Pb zircon ages for the Henderson Gneiss range from 593 Ma as a crystallization age for the upper intercept of a U-Pb discordia, with metamorphic pulses at 456 Ma and 360-390 Ma (Sinha and Glover, 1978), to crystallization at 538 Ma for a regressed suite of discordant U-Pb analyses (Odom and Fullagar, 1978), to a 490 Ma ion

microprobe age for zircon rims, which would more likely represent a metamorphic age (Carrigan et al., 2001). Whole-rock geochronologic techniques have yielded ages of: 535 ± 27 Ma [Rb-Sr] for crystallization and 256 ± 8 Ma for metamorphism (Odom and Fullagar, 1973); crystallization ages of 438 ± 22 Ma for mylonitic and 440 ± 22 Ma for undeformed Henderson Gneiss (Odom and Russel, 1975); 460 ± 9 Ma [Rb-Sr] for crystallization (Harper and Fullagar, 1981); and 513 ± 34 Ma crystallization with 445 ± 20 Ma metamorphism (Fullagar et al., 1997). Clearly, polyphase metamorphism and deformation have complicated the geochronologic history of the Henderson Gneiss. Using conventional ion microprobe techniques, Vinson (1999) reported a range of U-Pb zircon ages from 350 to 490 Ma with groupings at 420, 445, 471, and 492 Ma, for a Henderson Gneiss sample from Vulcan Materials Company Quarry in Hendersonville, NC. These ages correspond well with unpublished data (Miller and Meschter McDowell, unpublished data) from another sample of Henderson Gneiss from the Moffitt Hill quadrangle, which revealed a similar age range with a single Middle Ordovician grouping, thought to represent the crystallization age of the Henderson Gneiss.

Aside from the Henderson Gneiss, several other western IP granitoids have yielded Ordovician crystallization ages. U-Pb ion microprobe data from an augen and banded gneiss from near Caesars Head State Park in South Carolina revealed ~ 470 Ma (Middle Ordovician) crystallization ages from oscillatory zoned grains, with Grenvillian and Neoproterozoic inherited cores (Ranson, 1999). Additional Middle Ordovician crystallization ages reported for western IP granitoids include: ~ 463 Ma Brooks Crossroads, NC (Vinson, 1999); ~ 465 Ma Dysartsville, NC (Bream, 2003); ~ 490 Ma Sugarloaf Mountain gneiss, NC (Vinson, 1999); ~ 460 Toccoa, GA (Bream, 2003); and several unnamed western IP Ordovician and Silurian plutons (Nelson et al., 1998).

Kalbas et al. (2002) and Bream (2003) reported an age of ~ 460 Ma for zircon separates from a sample of Poor Mountain felsic tuff, which they interpreted to be a magmatic age. This interpretation favors a volcanic or immature volcanoclastic protolith for this unit. Geochemical characteristics of interlayered amphibolite suggest that these have a probable oceanic affinity (Davis, 1993b; Yanigihara, 1994; Bream, 1999; Kalbas, 2003). The presence of migmatitic bimodal plutonic and volcanic lithologies occurring in the same structural position as the Poor Mountain Formation recognized during this study further supports the conclusion that these may represent the volcanic equivalent of the large plutonic belt in the western IP. These lithologies are continuous throughout the IP and their presence has long been recognized by numerous investigators (e.g., Rankin et al., 1972; Espenshade et al., 1975; Goldsmith et al., 1988). The nature of this

unit, however, has mostly gone unrecognized, with most workers identifying it as an “intermediate granitoid with frequent septa of amphibolite” or simply as a plutonic body (Call Pluton of Rankin et al., 1972). The heterogeneous nature of this unit, consisting of large bodies of amphibolite interlayered with more felsic and intermediate material attest to its bimodal nature. Additionally complicating matters, this unit is highly migmatitic, occurring in the immediate footwall of the BCFZ, which masks many primary features. These observations suggest a complex magmatic, volcanic, and depositional setting for the western IP during the Middle Ordovician.

If these lithologies are the product of Middle Ordovician volcanism near the eastern Laurentian margin, then they beg the question “Where is the arc?” An absence of subduction-related geochemical signatures for western IP granitoids (Vinson, 1999; Miller et al., 2000; McDowell et al., 2002) suggests their derivation from collisional or postcollisional crustal-thickened, isotopically evolved crust, not the subduction-related magmatic arc or continental margin arc as depicted in several tectonic models (e. g., Harper and Fullagar, 1981; Hatcher, 1989; Sinha et al., 1989; Hibbard, 2000). A model has been proposed in which a small ocean basin analogous to the Sea of Okhotsk west of Kamchatka (Hatcher, 1978) or the Gulf of California (Thomas et al., 2001), may have opened with an apex of what is now North Carolina and closed during the Ordovician (McDowell et al., 2002). Alternatively, it has been hypothesized that arc-related rocks are either eroded or deeply buried (Thomas et al., 2001). Bream (2003) noted the possibility of western IP 440–480 Ma intrusive and extrusive igneous lithologies being produced in both continental (within-plate) and volcanic-arc settings (arc/MORB), and suggested that Poor Mountain Formation lithologies may represent volcanic equivalents of the voluminous western IP Ordovician magmatic belt. This interpretation implies that the western IP (and eastern Blue Ridge) were accreted to the eastern Laurentian margin during the closure of a small ocean basin throughout the southern Appalachian Taconic orogeny.

Western IP U-Pb zircon data from this study indicate the presence of a plutonic and/or volcanic event occurring from 435–445 Ma. Lithologies selected for analysis were collected from a mylonitic and migmatitic phase of the Poor Mountain Formation equivalent (Fig. 5-4). Citing geochemical similarities, Kalbas (2003) noted that a likely candidate for the mafic protolith of this unit is the Poor Mountain Amphibolite. The dominance of plagioclase and absence of K-feldspar in this metaigneous lithology indicates that it belongs the heterogeneous migmatite unit located in the immediate footwall of the BCFZ (Fig. 5-4). It should be noted, however, that zircon textures and

morphologies indicate an igneous (not a volcanic) origin for this lithology. Nevertheless, an Ordovician magmatic event is indicated for the western IP by these data, and the bimodal nature of this lithology could represent a plutonic equivalent to the bimodal volcanic Poor Mountain Formation. If so, this further supports the presence of a large volcanic arc just off of the Laurentian margin during the Middle Ordovician, which had accreted by ~440 Ma. Clearly more geochemical evidence is required to support such conclusions, and the true nature of this Middle Ordovician tectonic event in the western IP remains poorly constrained. Regardless of tectonic settings, crystallization age dates for this unit correspond to the western IP plutonic/volcanic suite, and further support large-scale magmatism during the Middle Ordovician.

Eastern IP

As previously noted, eastern IP granitoids belong to a Late Silurian to Late Carboniferous plutonic suite and are petrogenetically distinct from western IP plutons. Eastern IP metaigneous lithologies are intraplate, anatectic magmas (Giorgis, 1999; Bier, 2001), are similar in age (Bream, 2002), occur exclusively in the eastern IP, and are likely pre- to synmetamorphic. Modern geochronologic techniques have been applied to many eastern IP granitoids recently, producing ages of: ~415 Ma Anderson Mill, SC (Mapes, 2002); ~357 Ma Gray Court, SC (Mapes, 2002); ~364 Ma Pelham, SC (Mapes, 2002); ~325 Ma Reedy River, SC (Mapes, 2002); ~380 Ma Toluca (Mapes, 2002); and ~406 Ma Walker Top (this study). An age of ~406 Ma obtained here for the Walker Top Granite in the northeastern Brushy Mountains is interpreted to be a magmatic age based on zircon morphologies and concentric internal zoning. A contrasting age of ~366 Ma was determined for the same lithology to the SW, and is here interpreted to represent a thermal resetting of zircon during high-grade Neocadian metamorphism (>700°C). The preferred ~407 Ma age determined here most likely records initial subduction of eastern IP sediments by the Carolina superterrane at ~415 Ma. This age coincides well with metamorphic zircon rim data, which suggest initial metamorphism of eastern IP paragneisses occurred ~415 Ma, and with Late Silurian-Early Devonian intrusion of the Concord (~408 Ma) and Salisbury (~378 Ma) plutonic suites in the overriding Carolina superterrane (Butler and Fullagar, 1978; McSween et al., 1984, 1991; McSween and Harvey, 1997; Esawi, 2004). The Walker Top pluton is catazonal, however, and presents somewhat of a problem when subduction rates are considered. If this pluton intruded at a depth of ~15 km, then it would have had to be subducted to these depths in ~10 Ma. It is possible, however, that the Walker Top Granite intruded at shallower depths,

and was successively metamorphosed to upper-amphibolite facies contemporaneously with enveloping metasedimentary lithologies during continued burial and subduction. A similar scenario is also favored for the ~415 Ma Anderson Mill pluton in South Carolina (Mapes, 2002). This interpretation favors initial convergence of the Carolina superterrane and subduction of the eastern IP prior to Neoacadian collision with and accretion to the eastern Laurentian margin.

Metamorphic and Deformational Constraints

Polydeformed and metamorphosed terranes often preclude a simple interpretation of their temporal characteristics due to overprinting and retrograding processes. Numerous recent studies have recognized the effects of one or more widespread thermal events taking place in the IP between 360 Ma and 320 Ma (e.g., Dennis and Wright, 1997a; 1997b; Bream et al., 2000; Mirante and Patino-Douce, 2000; Carrigan et al., 2001; Mirante, 2001; Kohn, 2001; Kalbas et al., 2002). This range and an absence of older ages supports the single prograde Neoacadian event as proposed by Davis (1993a, 1993b).

Metamorphic overgrowth U-Pb zircon data clearly reveals a dominance of 360-340 Ma metamorphism throughout the IP (Fig. 5-9f). Although evidence for thermal events earlier than ~415 Ma is provided by zircon rims from the western IP, these ages are limited in number, restricted to the western IP, and are overprinted by later events (Fig. 5-9f). It should be pointed out, however, that these 435-475 Ma ages, although sparse, correspond with the Middle to Late Ordovician thermal and magmatic event discussed above. An early (~415 Ma) event is recognized for the eastern IP by small peaks in summed probability plots (Fig. 5-9f), and is interpreted to coincide with initial subduction of eastern IP paragneisses by the Carolina superterrane and Early Devonian anatectic magmatism (discussed above). This early thermal event, however, is overshadowed by later metamorphic events occurring at ~376 Ma, ~362 Ma, ~344 Ma, and ~322 Ma (Fig. 5-9f). A metamorphic pulse at ~376 Ma in the eastern IP (Fig. 5-9f) coincides well with anatectic melting and intrusion of the ~378 Ma Toluca Granite, likely caused by continued subduction beneath the Carolina superterrane.

Peak metamorphism occurred between ~360 and ~340 Ma, corresponding to the Neoacadian orogeny, and is recorded by eastern and western IP zircon rims (Figs. 5-9 and 5-10h and i) and monazite ages. This high-grade tectonothermal event is responsible for the first shared thermal event between eastern and western IP terranes, achieved peak conditions of sillimanite I and local sillimanite II grade (Kish, 1997; Mersch, 2003), corresponds to eastern and western IP overlaps on a summed probability plot of zircon

rim data (Fig. 5-9f), and overprints all previous metamorphic pulses (Dennis, 1995). Environmental conditions for the eastern IP during the Neoacadian were hot enough to produce kyanite-grade assemblages followed by sillimanite I and local sillimanite II grade assemblages (Wilson, 2006; Part II, this study). Eastern IP lithologies also underwent extensive migmatization and anatexis melting at this time (Mapes, 2002). A lack of zircon inheritance in Neoacadian granitoids provides further evidence for high-temperature conditions during this time, as zircons were resorbed into high-temperature melts (Mapes, 2002; Miller, 2003). P-T estimates from the eastern IP record this progression from kyanite- to sillimanite-grade conditions over the course of the Neoacadian (Fig. 5-11). A conspicuous gap in metamorphic ages exists between ~360 and ~345 Ma (Fig. 5-9f), which may represent a period of uplift and cooling between tectonothermal pulses, although this is highly speculative. Another possibility is that this gap reflects a period of uplift and the transition from initial NW- to SW-directed tectonic transport after buttressing of IP thrust sheets against the primordial BFZ at the northwestern terminus of the IP. Consistent 360-340 Ma metamorphic ages most likely represent long-term A-type subduction of the IP beneath the Carolina superterrane, and record its docking with the eastern Laurentian margin during the Middle to Late Devonian.

A final pulse of metamorphism is evident in the IP at ~322 Ma (Fig. 5-9f), which likely resulted from Alleghanian continent-continent collision and final emplacement of IP thrust sheets. Younger monazite and metamorphic zircon rims of 325-320 Ma (Dennis and Wright, 1997; Bream, 2003) document the occurrence of this younger metamorphic event, which coincided with the emplacement of Carboniferous granitoids (Mapes, 2002). Textures and mineral assemblages indicate that metamorphic grade again reached sillimanite grade conditions during this event, producing a second generation of sillimanite oriented obliquely to earlier generations (Part II). This evidence alone does not necessarily imply that conditions fell below those of the sillimanite stability field after Neoacadian metamorphism ended, and once again reached sillimanite grade during a later metamorphic event; it simply indicates that late sillimanite fibers developed in a different orientation than earlier ones (Figs. 5-9f and 5-11). Following this metamorphic pulse, IP rocks cooled to <600° C by ~315 Ma and to <225° C by 300-280 Ma (van Breeman and Dallmeyer, 1984; Naeser et al., 2001).

Combining structural and crosscutting relationships with P-T and geochronologic data allows for delimiting timing constraints for northeastern IP tectonometamorphic pulses (Figs. 5-11 and 5-12; Table 5-1). Crosscutting intrusive bodies used for

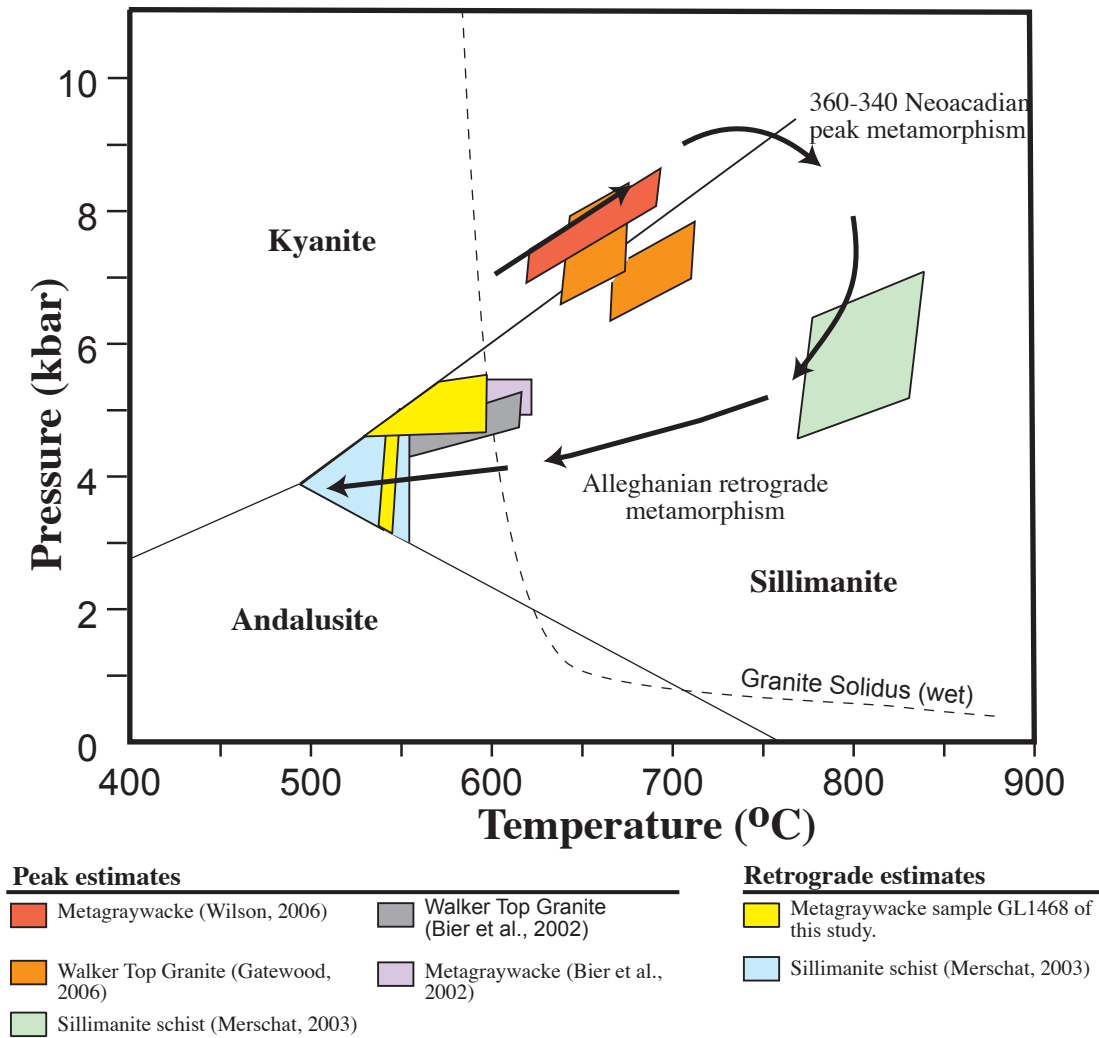


Figure 5-11. Projected P-T-t path for the Brindle Creek thrust sheet (arrows). Modified from Wilson (2006).

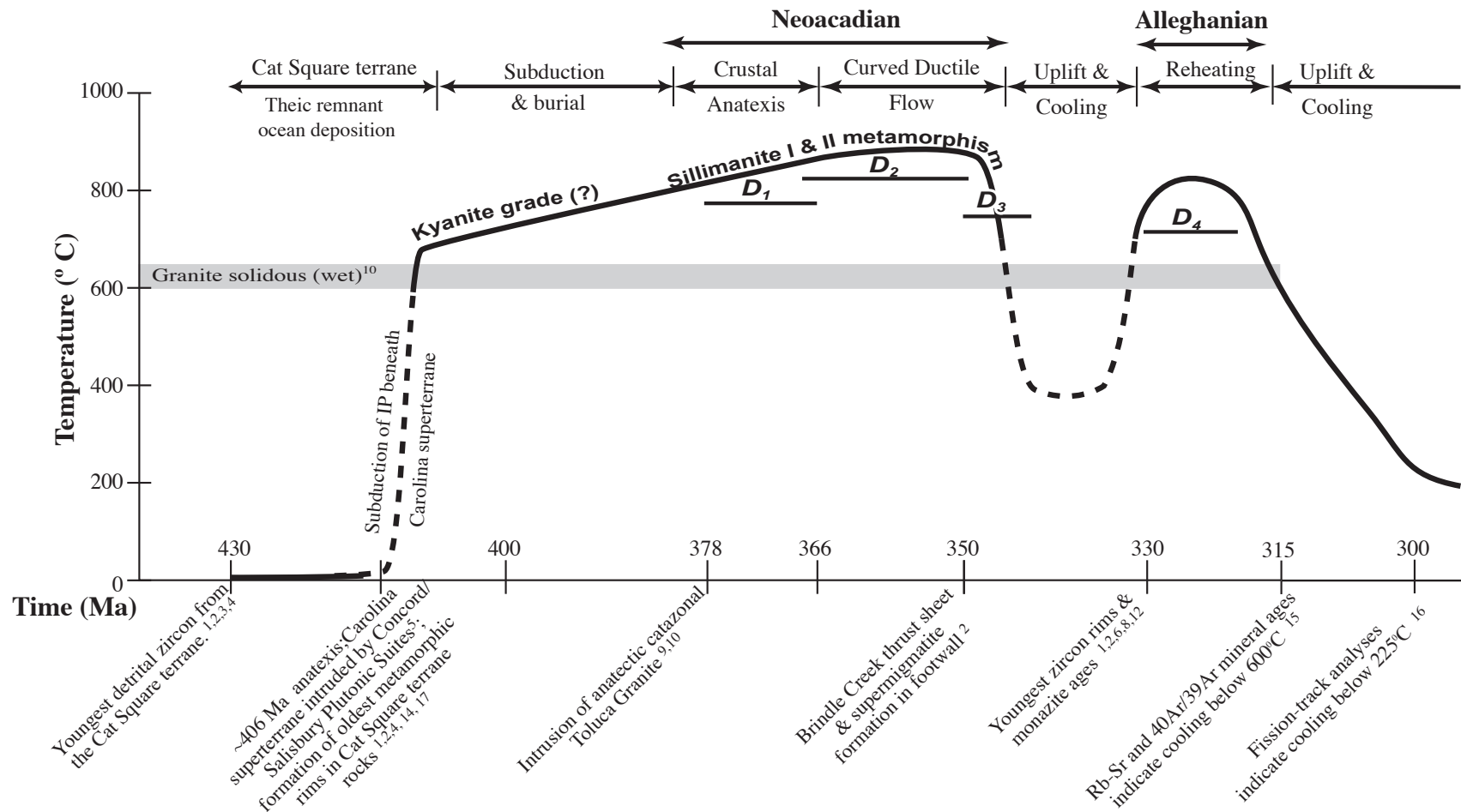


Figure 5-12. Tectonothermal history of the eastern Inner Piedmont. Modified from Wilson (2006). Data from: 1-Bream (2002); 2-Bream (2003); 3-Bream et al. (2001); 4-Bream et al. (2004); 5-McSween et al. (1984, 1991); 6-Carrigan et al. (2001); 7-Davis (1993b); 8-Dennis and Wright (1997a, 1997b); 9-Giorgis et al. (2002); 10-Luth et al. (1964); 11-Mapes (2002); 12-Mapes et al. (2001); 13-Mirante and Patino-Douce (2000); 14-Gatewood (this study); 15-van-Breeman and Dallmeyer (1984); 16-Naeser et al. (2001); 18-Butler and Fullagar (1978).

constraining the timing of IP deformation yield crystallization ages of ~360 Ma and ~323 Ma (Figs. 5-6 and 5-7; Table 5-4). These results indicate that the major penetrative (D_2) fabrics present in the IP were developed prior to ~360 Ma. An incomplete transposition of one of these intrusive bodies (MV-29-ggn) suggests that it intruded contemporaneously with or soon after the development of D_2 at ~360 Ma and may have been partially transposed during D_3 (Fig. 5-6). Later deformation fabrics overprint these and are mostly related to S-C and shear-related fabrics developed during D_4 and dextral reactivation of northeastern IP fault zones. D_4 deformational styles suggest that a transition from ductile to brittle conditions occurred during its development. Thus, initial D_4 deformation likely took place under ductile conditions and occurred contemporaneously with the development of a second generation of sillimanite (discussed above).

CONCEPTUAL MODEL

Tectonic reconstructions are the end-products of studies such as these, which incorporate structural, petrologic, and geochronologic data. Data collected from this and other recent studies allows for the development of a new tectonic model for the Paleozoic development of the southern Appalachian IP, modifying those of Bream and Hatcher (2002) and Merschat and Hatcher (in press). Incorporation of geochronologic data into models such as these provided absolute timing constraints, thus improving the quality.

Neoproterozoic-Early Paleozoic Rifting and Passive Margin Evolution

The eastern margin of North America developed a passive continental margin after the close of the Grenville orogeny, which consisted of highlands that were eroded down to sea level by the beginning of the Cambrian. According to Thomas (1991) the late Precambrian eastern margin of North America consisted of an irregular rifted margin bounded by block and transform faults. Evidence for the rifted nature of the late Precambrian-Early Cambrian southern Laurentian margin exists as late Precambrian-Early Cambrian clastics of the rift-facies, followed by continuous deposition of clastic and carbonate sediments (Rast and Kohles, 1986). By late Early Cambrian time the transition from rift-to-drift had occurred, and the North American margin faced open ocean, indicating that the opening of the Iapetus had occurred (Hatcher, 1989). The Late Proterozoic stratigraphy of the southern Appalachians exhibits this rift-to-drift character in that the Ocoee Supergroup, clastics with a western source, was deposited directly on Grenville basement (Fig. 5-13a). After the opening of Iapetus ocean, passive margin clastic and carbonate sedimentation continued during the Cambrian, with fine clastics

(b) 460 - 420 Ma (post Taconic orogeny)

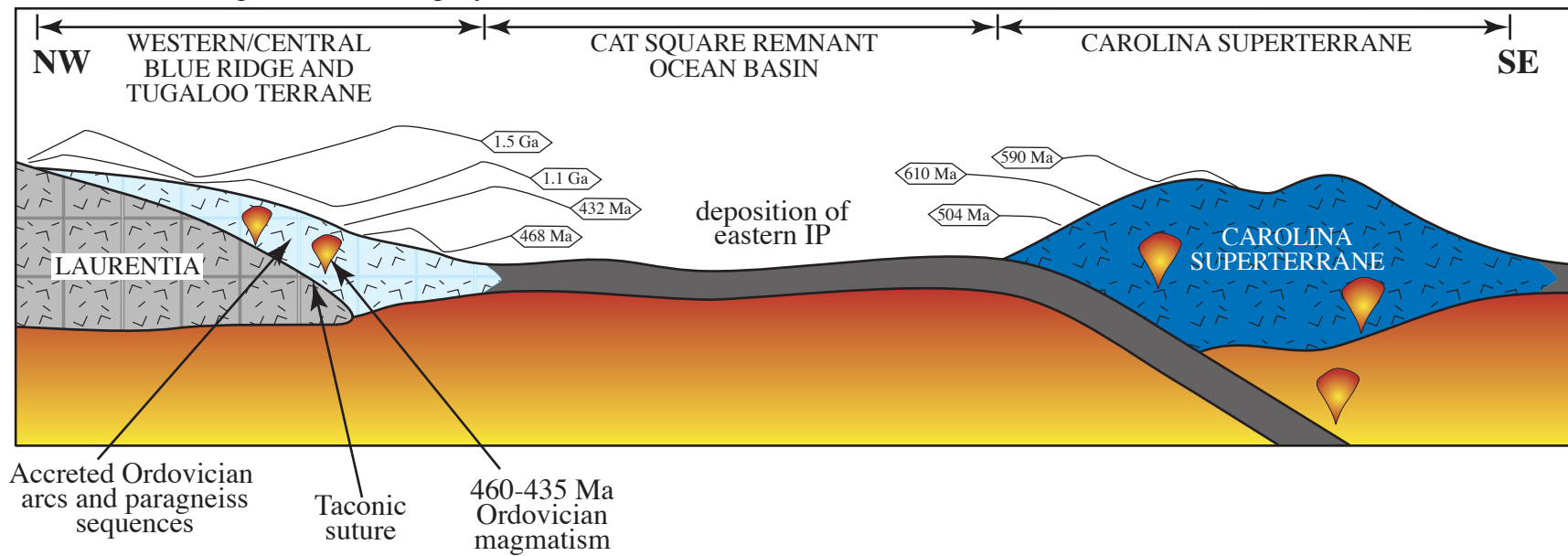


Figure 5-13 continued. (b) Accretion of Early Ordovician volcanic arc complex to the eastern Laurentian margin with continued magmatism in the Tugalo and Carolina terranes and deposition of eastern IP sediments.

(c) 415-375 Ma (Acadian orogeny?)

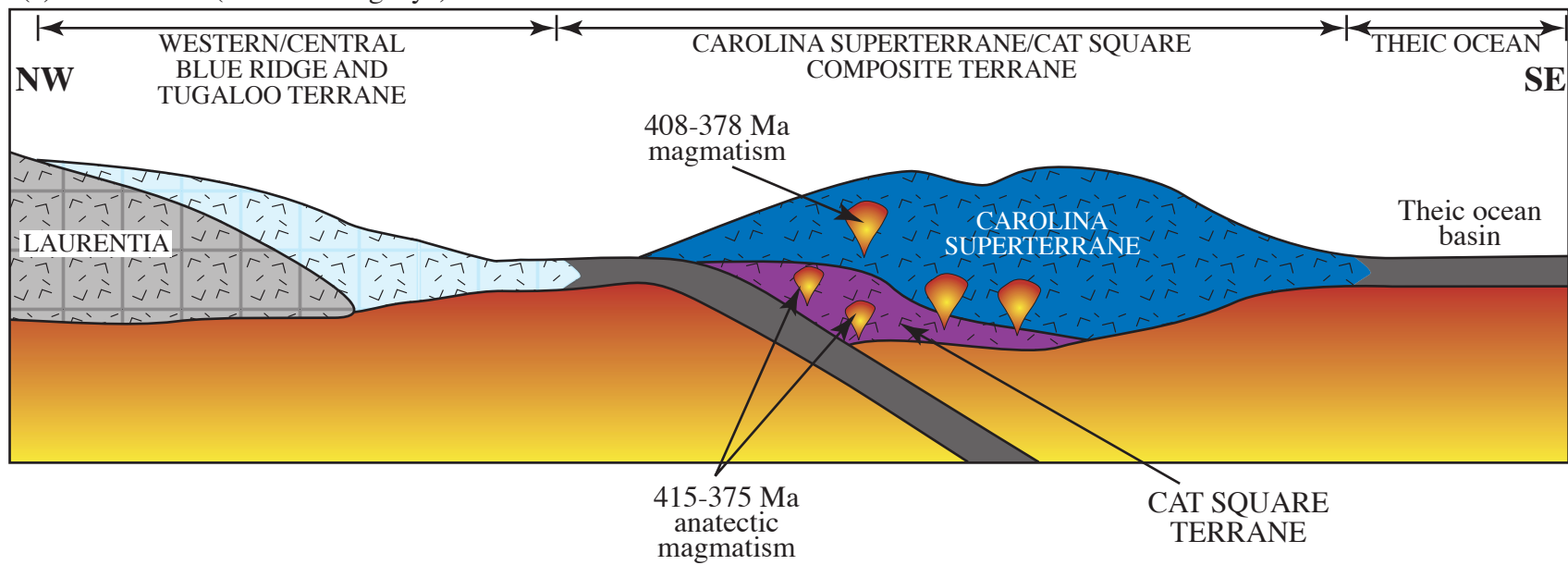


Figure 5-13 continued. (c) Initial subduction of Cat Square terrane by the Carolina superterrane with Devonian anatectic magmatism in the Cat Square terrane.

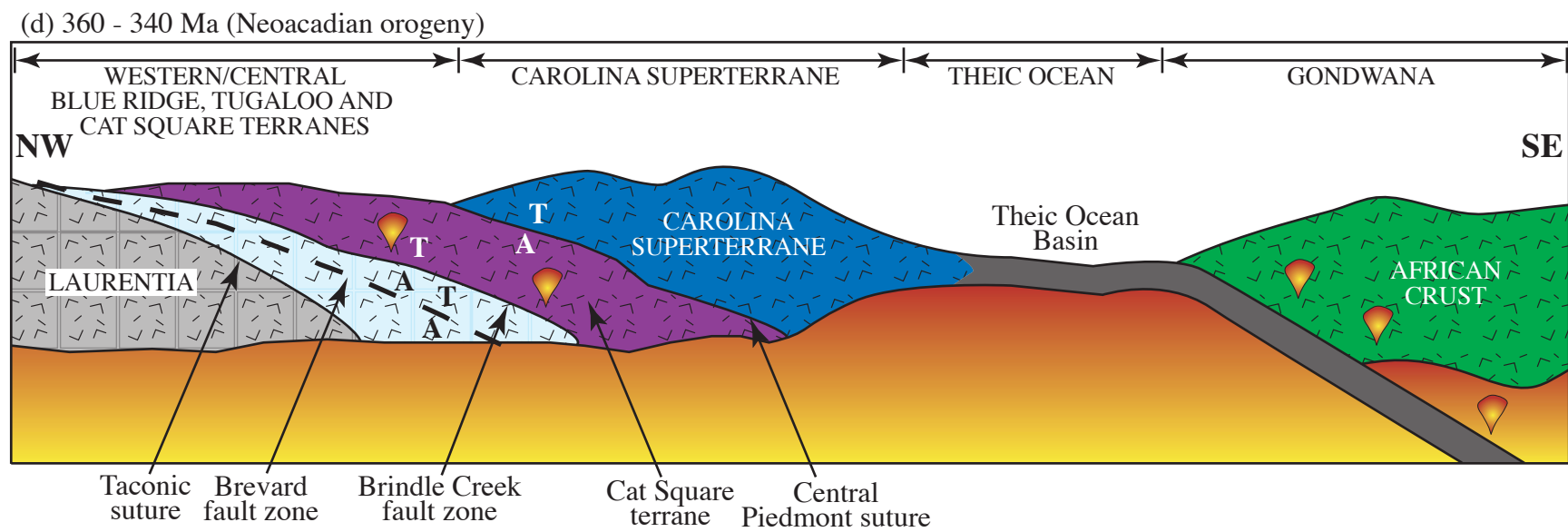


Figure 5-13 continued. (d) Accretion of the composite Cat Square/Carolina terrane during the Neoacadian orogeny.

(Chilhowee Group and Rome Formation) being deposited on the continental platform; their source being to the west (Rast and Kohles, 1986). Further east of the platform, carbonate sedimentation continued during the Middle Cambrian. The clastics in the west (Chilhowee Group and Rome Fm.) and the carbonates in the east (Conasauga Group) were later overlain by a carbonate bank (Knox Group), which covered the entire platform (Rast and Kohles, 1986). These events would set the stage for long-lived convergence and ocean closure along the eastern Laurentian margin during the Paleozoic.

Taconic Events

Early Ordovician crystallization ages of intermediate arc/MORB and within-plate plutons of ~480 Ma (Elkahatchee Quartz Diorite and Henderson Gneiss; Drummond et al., 1997; Vinson, 1999) record the earliest development of a volcanic arc system off the eastern Laurentian margin (Fig. 5-13a). A 455-460 Ma magmatic-volcanic suite (Hillabee, Ropes Creek, Slippery Creek, Poor Mountain, etc.) in the southern Appalachians have an oceanic MORB to arc affinity (Davis, 1993; Yanagihara, 1994; Bream, 1999; Kalbas, 2003). The presence of two arcs is indicated by the spatial separation of two arc-related terranes, the Dahlonge gold belt (Hopson, 1989; Settles, 2001), and western IP (Vinson, 1999; Bream, 2003), by the Tallulah Falls Formation stratigraphy (Ocoee Series equivalent). The Tallulah Falls Formation was likely caught between two volcanic arcs and accreted to the Laurentian margin during 470-440 Taconic arc accretion (Fig. 5-13b). Older metamorphic and plutonic ages from more internal portions of the southern Appalachians range from 480-450 (Drake et al., 1989). More recent U-Pb zircon data confirm that eastern Blue Ridge and western IP plutons were emplaced within this time frame (Ranson et al., 1999; Vinson, 1999; Miller et al., 2000; McDowell et al., 2002) and that granulite facies metamorphism occurred ~470 Ma (Moecher and Miller, 2000). Eclogite formation in the eastern Blue Ridge occurred ~460 Ma (Stewart and Miller, 2001). Dahlonge gold belt mafic and ultramafic rocks also have Ordovician ages (Thomas, 2001).

The above evidence supports Taconic arc development 490-480 Ma (Fig. 5-13a) and accretion of these with successive metamorphism and plutonism in the eastern Blue Ridge and western IP (Tugaloo terrane of Hatcher, 2001b) by 460 Ma. Numerous models place the Iapetus (Taconic) suture of exotic accreted components onto the Laurentian margin at the southeastern boundary of the western Blue Ridge (e.g., Rankin et al., 1989; Rankin, 1994). However, the development of an accretionary wedge does not necessarily indicate a non-Laurentian derivation for rocks of the eastern Blue Ridge (Rankin,

1994). Other studies have suggested that the Iapetian suture is manifested by the pre-Alleghanian BFZ, which separates the IP to the SE from an accretionary wedge (Ashe metamorphic suite) to the NE (Abbott and Raymond, 1994). These models require that eastern Blue Ridge metasedimentary assemblages be younger than and largely derived from the western IP, which discounts numerous field studies showing that the same mappable stratigraphy occurs on both sides of the BFZ. Furthermore, detrital zircon and Nd isotopic studies (e.g., Bream, 2003) strongly favor a Laurentian derivation of eastern Blue Ridge and western IP metasedimentary assemblages. Therefore, the exotic nature of these terranes is precluded in this model (Fig. 5-13a and b).

Taconic events brought on initial A-subduction of the eastern Laurentian margin as several oceanic and arc assemblages were obducted onto the margin with the accompaniment of the central Blue Ridge Dahlonaga gold belt, Cowrock, and Cartoogechaye terranes (Hatcher, 2004). Subsequent magmatism and volcanism occurred along the eastern Laurentian margin until ~440 Ma, during which the continued development of the eastern Blue Ridge and western IP magmatic belt took place, which may account for combined volcanic arc and continental arc geochemical signatures of Tugalo terrane granitoids (Bream, 2003), and the bimodal nature of Ordovician volcanism in the western IP. A gap in western IP metamorphic dates from ~436 Ma to ~360 Ma (Fig. 5-9f) and lack of a significant population of plutons of this age likely represents a period of post-collisional uplift and cooling of eastern Blue Ridge and western IP accreted terranes.

Acadian Events

Events occurring between ~440 Ma and ~370 Ma are restricted to the eastern IP. Based on differences in stratigraphy, age of detrital zircons, and age and character of granitoid plutonism, Hatcher (2002) suggested that eastern IP assemblages between the BCFZ and the Central Piedmont suture be called the Cat Square terrane, a suspect terrane that was accreted during the Neoacadian orogeny. Bream (2003) documented the presence of both Laurentian (1.1, 1.4, 1.8, and 2.8 Ga) and peri-Gondwanan (500, 600 Ma) detrital components in this terrane and concluded that these lithologies contain a mixed crustal affinity. Citing petrologic characteristics and the youngest detrital zircon age population, Merschat and Hatcher (in press) concluded that the Cat Square terrane is composed of a remnant ocean basin, for which they established a maximum age of ~430 Ma and a minimum age of ~380 Ma for basin inception. Detrital zircon data from this study also indicate the presence of Ordovician detrital components and support the post-

430 Ma age for deposition of Cat Square terrane sediments (Fig. 5-8). New metamorphic zircon ages, however, indicate a minimum age of ~415 Ma for initial subduction of eastern IP paragneisses by the Carolina superterrane. Furthermore, early anatectic melts from the Cat Square terrane yield crystallization ages of ~407 Ma (Walker Top Granite; this study) and ~415 Ma (Anderson Mill; Mapes, 2002). These ages correspond well with the intrusion of magmatic belts in the overriding Carolina superterrane (discussed above). Therefore, closure of the Cat Square ocean basin and subduction of the eastern IP likely occurred as early as ~415 Ma, before Neoacadian accretion to the eastern Laurentian margin (Fig. 5-13c).

Neoacadian Events

The Neoacadian orogenic event in the southern Appalachians corresponds to the 360-340 Ma accretion of the composite Cat Square and Carolina superterrane, and marks the first shared thermal event between eastern and western IP terranes (Fig. 5-13d). Buttressing of IP thrust sheets against the primordial BFZ created the complex structural fabrics of the IP. This event is also responsible for magmatism in the eastern IP and high-grade metamorphism in the eastern and western IP.

Alleghanian Events

The final collisional event recorded by the southern Appalachian crystalline core occurred during continent-continent collision during the Alleghanian and final emplacement of the composite Blue Ridge-Piedmont megathrust sheet (Fig. 5-13e). Sillimanite-grade conditions were once again attained during a strike-slip dominated orogenic pulse ~325 Ma. Reactivation of earlier ductile fault zones as dextral strike-slip faults was responsible for developing S-C and shear-related fabrics in the IP. Carboniferous plutonic bodies, which cut earlier fabrics, and intrude all southern Appalachian crystalline core terranes intruded during this time. Late Alleghanian head-on collision produced the composite Blue Ridge-Piedmont megathrust sheet that deformed the foreland as it moved over the Laurentian margin (Hatcher, 2002b).

CONCLUSIONS

1. Rocks of the northeastern IP retain evidence of long-term Paleozoic convergence along the eastern Laurentian margin.
2. Early Ordovician crystallization ages for eastern Blue Ridge and western IP granitoids of mixed arc and continental affinity signify the initial development

of Ordovician arcs off of the eastern Laurentian margin. Structural relationships indicate that a series of arcs was present.

3. Taconic arc accretion likely occurred 480-460 Ma as indicated by extensive eastern Blue Ridge and western IP plutonic and volcanic belts.
4. Crystallization ages of 445-435 Ma for western IP metaigneous lithologies record a late Taconic plutonic-volcanic event in the western IP after arc accretion.
5. Eastern IP metasedimentary rocks contain detrital components of ~1500 Ma, ~1100 Ma, ~1000 Ma, ~600 Ma, ~465 Ma, and ~430 Ma and were derived from both Laurentian and peri-Gondwanan sources. The ~430 Ma age provides a maximum age of basin inception for Cat Square terrane metasedimentary lithologies.
6. Metamorphic zircon rims and anatectic magmatism from 415-405 Ma record the initial subduction of Cat Square terrane sediments beneath the Carolina superterrane and provide a minimum age constraint for eastern IP paragneisses, thereby requiring these sediments to be deposited between 430-415 Ma.
7. The Neoacadian orogeny occurred from 360-340 Ma in the southern Appalachians, and represents the first shared thermal event between eastern and western IP terranes. Peak metamorphism was achieved during this time and penetrative fabrics were developed throughout the IP.
8. A final high-temperature event occurred during the Alleghanian orogeny from 330-320 Ma. Environmental conditions once again attained upper-amphibolite facies, during strike-slip reactivation of IP ductile fault zones, and final emplacement of crystalline thrust sheets.

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PART VI: Conclusions

1. New mapping indicates that units originally recognized in the southwestern Brushy Mountains are continuous to the northeast.
2. Two lithotectonic packages are recognized for the northeastern IP and consist of fourteen distinctive lithologies.
3. The three-part stratigraphy of the Tallulah Falls Formation can be recognized in the study area, consisting of upper and lower graywacke-amphibolite units separated by a thin garnet-aluminous schist member.
4. Outcrop patterns and mylonitic textures proximal to lithologic contacts indicate a fault contact between disconnected pods and map-scale boudins of Henderson Gneiss and the underlying Tallulah Falls Formation.
5. The Brindle Creek fault is continuous throughout the Moravian Falls quadrangle and folded to the northeast, exposing western IP lithologies in a reentrant.
6. Textural evidence suggests that the contact between the Silurian Brooks Crossroads pluton and the Brindle Creek thrust sheet is faulted, and the pluton is exposed in a window.
7. The Hibriten gneiss is located entirely within the BCFZ, consists of various eastern and western IP lithologies, displays prominent block-in-matrix structure, contains lithologies ranging from mylonite to ultramylonite, and represents a crustal-scale lithologic blending zone. These relationships warrant renaming of this lithology to the Hibriten mylonite.
8. The Walker Top Granite occurs within the BCFZ in the northeastern IP, indicating a sill-like intrusive body located along the base of the Brindle Creek thrust sheet, exposed along deep crustal shear zones and faults.
9. Metamorphic mineral assemblages, pseudomorph textures, and ubiquitous migmatization suggest a prograde metamorphic path from kyanite-grade conditions to sillimanite-grade conditions.
10. Sillimanite II assemblages are not present in pelitic metasedimentary or metaigneous units in the study area. Only sillimanite I assemblages were observed in hand sample and thin section.
11. Retrograde greenschist metamorphic overprint is restricted to the Alleghanian BFZ northwest of the Mill Spring fault.
12. Garnets from selected EMP samples are chemically zoned with respect to

FeO, MgO, CaO, and MnO, and display chemical zonation profiles typical of thermal diffusion.

13. P-T estimates from the Walker Top Granite yield peak-metamorphic conditions of 745°C and 7.1 kbar, during Neoacadian metamorphism.
14. A prograde, clockwise (Barrovian) metamorphic path, reaching upper-amphibolite facies is recorded by garnets from the base of the Brindle Creek thrust sheet. The validity of this path is supported by prograde mineral assemblage textures of sillimanite pseudomorphing kyanite.
15. Four map-scale shear zones, the TCFZ, the MSFZ, the BCFZ, and the PSSZ, are present in the study area and are orogen parallel, striking northeast-southwest across the Moravian Falls quadrangle.
16. Six successive deformation events can be recognized in the northeastern IP, roughly corresponding to those outlined by previous investigators.
17. Eastern and western IP terranes experienced separate D_1 events, as indicated by deformational style and geochronologic constraints, before being deformed and metamorphosed together during D_2 .
18. Truncated macroscale F_1 folds in the TCFZ footwall must have formed earlier than the crystallization age of the Henderson Gneiss (~490 Ma).
19. Development of the TCFZ must postdate the age of the Henderson Gneiss, and is likely related late Taconian to early Neoacadian thrust emplacement.
20. The Walker Top and Toluca Granites occur exclusively southeast of the BCFZ and must have intruded eastern IP lithologies before BCFZ emplacement.
21. Map patterns show laterally continuous tabular bodies of Walker Top Granite occurring in map-scale shear zones throughout the study area, suggesting that these bodies are present in the lowermost portions of the Brindle Creek thrust sheet and are exhumed along fault zones as the thrust sheet is successively imbricated to the SE.
22. Developments of both the PSSZ and the BCFZ must postdate the crystallization age of the Walker Top Granite (~407 Ma).
23. Truncation of PSSZ by the BCFZ further constrains the timing of PSSZ development to 407-360 Ma.
24. Penetrative D_2 structures in the Moravian Falls quadrangle were developed during the Neoacadian tectonothermal event and are orogen-parallel.
25. As evidenced from F_2 and F_3 fold interference patterns D_2 and D_3 structures represent an initial and continued emplacement of the BCFZ.

26. L_2 mineral lineations parallel hinge lines of SW-directed F_2 sheath folds and NW-vergent F_3 folds in eastern and western IP terranes, suggesting their simultaneous development during initial NW- followed by SW-, and finally NW-directed thrust sheet emplacement during the Neoacadian. These fabrics define a flow lineation developed in response to high-grade metamorphism and migmatization during the Neoacadian, causing SW-directed crustal flow and extrusion of material. Ubiquitous top-to-the-SW shear sense indicators further support this hypothesis.
27. Persistent D_4 folds and shear fabrics indicate SW-directed transport and overprint earlier NW-vergent structures.
28. The MSFZ is a dextral strike-slip fault, which truncates NW-vergent D_2 and D_3 fabrics, and likely coincides with SW-directed transport during D_4 .
29. Dismemberment of the Henderson Gneiss body in the northeastern IP could have occurred either during Neoacadian thrust emplacement (D_2 and D_3) or early dextral reactivation of the Neoacadian BFZ (early D_4), but must have occurred before the development of the MSFZ.
30. The transition from ductile to brittle deformation in the northeastern IP likely took place over the course of D_4 as indicated from the transition from passive to flexural fold styles.
31. Foliation patterns permit subdivision of the study area into three distinct domains.
32. The zone of constricted flow corresponds to domain I and encompasses most of the study area. Domain II is recognized by a deflection of foliations near the BCFZ. Domain III shows similar patterns to domain I, but is separated by differences in dip direction and magnitude.
33. Mineral lineations are consistently oriented throughout the study area and no curvature or deflection of linear fabrics is apparent. The proximity of the BFZ to the study area may account for this apparent constriction of fabrics.
34. Kinematic indicators show a dominance top-to-the-SW shear sense most likely resulting from dextral strike-slip movement during D_2 and D_4 . A significant component of orogen-parallel simple shear would be required to overprint NW-vergent fabrics developed during earlier deformational events. However, overprinted F_2 and F_3 folds are asymmetric and indicate initial NW-directed transport.
35. Structures in the study area are overprinted by two younger generations of

open folds and joint sets.

36. Structural observations and analyses provide evidence for a qualitative model in which initial NW-directed convergence and subduction of eastern IP lithologies evolved to NW-directed terrane accretion and orogenesis and were ultimately followed by SW-directed orogen parallel transport between thrust sheets. Structures produced during these events are successively overprinted by later brittle fabrics developed during extension and uplift.
37. Two retrograde shear zones in the northeastern IP each contain an entire suite of mylonitic granitic gneisses ranging from protomylonite to ultramylonite, and were initially developed under amphibolite facies conditions.
38. Regional linear fabric patterns reflect the SW-directed transport of material and constricted fluid flow through ductile shear zones in the northeastern IP.
39. Deformation in the mylonites occurred by crystal plastic mechanisms operating at temperatures $>400^{\circ}\text{C}$.
40. Increase of Al_2O_3 , ΣFe , MnO , MgO , Na_2O , TiO_2 , and P_2O_5 , immobile trace elements, and REE in the ultramylonites relative to the protomylonites likely result from significant volume loss.
41. Depletion of SiO_2 , K_2O , Na_2O , and LOI in the ultramylonites relative to the protomylonites is consistent with dissolution and recrystallization of alkali feldspar and the formation of myrmekite. Enrichment of ΣFe and MgO in the ultramylonites may be attributed to a higher modal abundance of ferromagnesian phyllosilicate phases than in the protomylonites.
42. Isocon analyses suggest volume losses of 41 and 48% during mylonitization in the TCFZ and the BCFZ, respectively. Steep slopes and good fits to regression lines for the immobile elements ΣFe , MnO , TiO_2 , P_2O_5 , Y, V, and Zr indicate their increased relative concentrations in the mylonites, which imply significant negative volume changes. These values seem reasonable when compared to other shear zones of similar width and protolith composition.
43. Rocks of the northeastern IP retain evidence of long-term Paleozoic convergence along the eastern Laurentian margin.
44. Early Ordovician crystallization ages for eastern Blue Ridge and western IP granitoids of mixed arc and continental affinity signify the initial development of Ordovician arcs off of the eastern Laurentian margin. Structural relationships indicate that a series of arcs was present.
45. Taconic arc accretion likely occurred 480–460 Ma as indicated by extensive

eastern Blue Ridge and western IP plutonic and volcanic belts.

46. Crystallization ages of 445-435 Ma for western IP metaigneous lithologies record a late Taconic plutonic-volcanic event in the western IP after arc accretion.
47. Eastern IP metasedimentary rocks contain detrital components of ~1500 Ma, ~1100 Ma, ~1000 Ma, ~600 Ma, ~465 Ma, and ~430 Ma and were derived from both Laurentian and peri-Gondwanan sources. The ~430 Ma age provides a maximum age of basin inception for Cat Square terrane metasedimentary lithologies.
48. Metamorphic zircon rims and anatectic magmatism from 415-405 Ma record the initial subduction of Cat Square terrane sediments beneath the Carolina superterrane and provide a minimum age constraint for eastern IP paragneisses, thereby requiring these sediments to be deposited between 430-415 Ma.
49. The Neoacadian orogeny occurred from 360-340 Ma in the southern Appalachians, and represents the first shared thermal event between eastern and western IP terranes. Peak metamorphism was achieved during this time and penetrative fabrics were developed throughout the IP.
50. A final high-temperature event occurred during the Alleghanian orogeny from 330-320 Ma. Environmental conditions once again attained upper-amphibolite facies, during strike-slip reactivation of IP ductile fault zones, and final emplacement of crystalline thrust sheets.

Appendices

Appendix A:
Electron Microprobe Data

Table A-1. Garnet analyses from sample GL-1.

	gC10.15.s avg. core		gC10.15.t avg. core		gC10.15.a rim		gC10.22.d rim		gC10.15.f rim		gC10.15.j rim		gC10.8.b core		gC10.8.x rim		gC10.8.15 rim		gC10.8.6 rim		gC10.8.24 rim		gC10.8.4 rim		gC10.15.k core	
# of analyses	7		9		4		3		5		3		4		8		1		1		1		1		4	
SiO ₂	37.3	(4)	37.0	(8)	38.0	(1)	38.0	(2)	37.1	(3)	37.1	(1)	36.9	(1)	37.3	(2)	37.3		37.0		37.2		37.3		37.5	(2)
TiO ₂	nd		0.04	(3)	nd		0.03	(1)	nd		nd		nd		nd		0.03		nd		nd		nd		0.05	(2)
Al ₂ O ₃	21.2	(2)	21.2	(1)	21.5	(1)	21.3	(1)	21.0	(2)	21.0	(2)	21.0	(1)	21.2	(1)	21.1		21.2		21.4		21.2		21.3	(4)
Cr ₂ O ₃	nd		0.03	(2)	nd		nd		0.04	(1)	nd		nd		nd		0.04		0.05		nd		nd		nd	
Y ₂ O ₃	0.04	(8)	0.03	(17)	0.05	(3)	0.05	(2)	0.10	(1)	0.05	(2)	nd		0.05	(1)	0.06		0.06		0.05		0.04		0.07	(1)
MgO	3.39	(3)	3.71	(5)	3.63	(12)	3.99	(13)	3.44	(4)	3.04	(4)	2.85	(16)	4.29	(4)	3.56		3.53		4.03		3.39		4.47	(2)
CaO	4.70	(1)	3.61	(5)	4.66	(9)	3.20	(6)	4.13	(12)	5.39	(5)	5.61	(9)	3.51	(5)	3.53		3.57		3.53		4.70		4.25	(4)
MnO	3.80	(7)	3.72	(8)	3.42	(16)	3.43	(7)	4.17	(8)	4.28	(2)	4.19	(12)	2.65	(8)	3.98		4.02		3.49		3.80		2.56	(11)
FeO	29.5	(3)	30.9	(9)	29.6	(3)	30.7	(4)	29.8	(4)	28.0	(7)	29.1	(8)	30.7	(2)	30.6		30.6		30.9		29.5		29.9	(1)
Na ₂ O	0.03		nd		nd		nd		nd		nd		nd		nd		nd		nd		nd		nd		nd	
Σ	100.4		100.1		100.9		100.7		99.75		98.89		99.73		99.70		100.3		100.0		100.6		100.0		100.2	
Cations based on 12 oxygens																										
Si	2.984		2.959		2.994		3.007		2.976		2.996		2.969		2.980		2.979		2.968		2.958		2.984		2.976	
Ti	-		0.002		-		0.002		-		-		-		-		0.002		-		-		-		0.003	
Al	1.993		2.001		2.003		1.984		1.990		1.995		1.989		1.994		1.991		1.999		2.004		1.993		1.992	
Cr	-		0.002		-		-		0.002		-		-		-		0.003		0.003		-		-		-	
Y	0.002		0.001		0.002		0.003		0.004		0.002		-		0.002		0.002		0.003		0.002		0.002		0.003	
Mg	0.404		0.443		0.427		0.470		0.411		0.366		0.342		0.511		0.424		0.422		0.477		0.404		0.529	
Ca	0.403		0.309		0.394		0.271		0.355		0.466		0.483		0.301		0.303		0.307		0.301		0.403		0.361	
Mn	0.257		0.252		0.229		0.229		0.284		0.293		0.286		0.180		0.270		0.273		0.235		0.257		0.172	
Fe ²⁺	1.974		2.066		1.951		2.031		1.998		1.887		1.961		2.049		2.047		2.051		2.055		1.974		1.983	
Na	-		-		-		-		-		-		-		-		-		-		-		-		-	
Σ	8.022		8.038		7.999		7.997		8.020		8.004		8.030		8.017		8.024		8.029		8.040		8.022		8.026	
Fe/(Fe+Mg)	0.830		0.823		0.820		0.812		0.829		0.838		0.851		0.800		0.828		0.829		0.812		0.830		0.789	
X Almandine	0.650		0.673		0.650		0.677		0.656		0.626		0.638		0.674		0.672		0.672		0.670		0.650		0.651	
X Pyrope	0.133		0.144		0.142		0.157		0.135		0.122		0.111		0.168		0.139		0.138		0.155		0.133		0.174	
X Spessartine	0.085		0.082		0.076		0.076		0.093		0.097		0.093		0.059		0.089		0.089		0.077		0.085		0.056	
X Grossular	0.133		0.101		0.131		0.090		0.116		0.155		0.157		0.099		0.100		0.101		0.098		0.133		0.119	

Units in () represent one standard deviation of replicate analyses in terms of least units cited

n.d. = not detected; less than 0.03%

All Fe calculated as FeO

Table A-2. Garnet analyses from sample GL-2.

	gA.10.8.i avg core	gA10.8.n rim	gA10.22.f rim	gA10.22.b core	gA10.22.p rim	gA10.15.x rim	gA10.15.aa rim	gA10.22.dd rim	gA10.22.gg rim	gA10.22.ii core	gA10.22.jj core	gA10.22.ll core
# of analyses	11	10	3	4	5	2	2	2	2	4	2	6
SiO ₂	37.0 (2)	37.0 (2)	37.9 (1)	37.9 (6)	36.9 (4)	37.4	37.0	37.3	37.0	37.2 (5)	36.9	37.0 (5)
TiO ₂	0.04 (1)	0.04 (1)	nd	nd	0.08 (1)	0.05	0.06	0.05	0.06	nd	0.04	0.04 (2)
Al ₂ O ₃	21.4 (1)	21.2 (2)	21.6 (3)	21.4 (1)	21.0 (4)	21.4	21.3	21.2	21.3	21.5 (2)	21.5	21.3 (11)
Cr ₂ O ₃	0.03 (1)	nd	nd	nd	nd	nd	0.04	nd	0.04	0.03 (1)	0.05	0.04 (2)
Y ₂ O ₃	0.07 (3)	0.07 (2)	0.04 (3)	0.05 (2)	0.03 (1)	0.06	0.08	0.08	0.08	0.03 (1)	0.09	nd
MgO	5.42 (7)	4.45 (16)	3.74 (5)	3.76 (2)	2.97 (3)	2.83	4.87	4.82	4.87	5.53 (7)	5.44	5.33 (8)
CaO	3.97 (7)	3.39 (7)	4.50 (11)	4.43 (5)	5.16 (7)	5.91	3.79	3.51	3.79	3.98 (3)	3.95	4.05 (1)
MnO	2.36 (6)	2.87 (12)	3.53 (5)	3.27 (2)	4.52 (5)	4.36	2.36	2.55	2.36	2.36 (2)	2.39	2.28 (4)
FeO	29.4 (1)	31.0 (4)	29.7 (2)	29.6 (7)	29.3 (1)	28.5	30.3	30.8	30.3	29.1 (1)	29.5	29.3 (3)
Na ₂ O	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Σ	99.69	100.0	101.0	100.4	99.97	100.5	99.9	100.3	99.9	99.778	99.7	99.4
Cations based on 12 oxygens												
Si	2.994	2.958	2.992	2.995	2.964	2.977	2.951	2.963	2.951	2.951	2.931	2.953
Ti	0.002	0.002	-	-	0.005	0.003	0.004	0.003	0.004	-	0.002	0.002
Al	2.003	1.993	2.004	2.007	1.986	2.004	2.001	1.984	2.001	2.008	2.012	1.999
Cr	0.002	-	-	-	-	-	0.002	-	0.002	0.002	0.003	0.002
Y	0.003	0.003	0.001	0.002	0.001	0.002	0.003	0.004	0.003	0.001	0.004	-
Mg	0.642	0.530	0.439	0.443	0.356	0.336	0.578	0.570	0.578	0.653	0.645	0.634
Ca	0.339	0.290	0.380	0.375	0.444	0.504	0.323	0.299	0.323	0.338	0.337	0.346
Mn	0.159	0.194	0.224	0.219	0.308	0.294	0.160	0.172	0.160	0.158	0.161	0.154
Fe ²⁺	1.956	2.068	1.960	1.957	1.970	1.894	2.021	2.045	2.021	1.929	1.961	1.952
Na	-	-	-	-	-	-	-	-	-	-	-	-
Σ	8.049	8.039	8.000	7.997	8.037	8.016	8.043	8.041	8.043	8.042	8.057	8.043
Fe/(Fe+Mg)	0.753	0.796	0.817	0.815	0.847	0.849	0.778	0.782	0.778	0.747	0.752	0.755
X Almandine	0.632	0.671	0.653	0.654	0.640	0.625	0.656	0.663	0.656	0.627	0.632	0.633
X Pyrope	0.207	0.172	0.146	0.148	0.116	0.111	0.188	0.185	0.188	0.212	0.208	0.205
X Spessartine	0.051	0.063	0.075	0.073	0.100	0.097	0.052	0.056	0.052	0.051	0.052	0.050
X Grossular	0.109	0.094	0.127	0.125	0.144	0.166	0.105	0.097	0.105	0.110	0.109	0.112

Units in () represent one standard deviation of replicate analyses in terms of least units cited

n.d. = not detected; less than 0.03%

All Fe calculated as FeO

Table A-3. Biotite analyses from samples GL-1 and GL-2.

	10.22.n mat.bt.c	10.22.n mat.bt.r	10.8.a bt.inc	10.15.b mat.bt	10.22.e mat.bt.r	10.15.e bt.inc	10.15.n bt.inc	10.8.k bt.inc
# of analyses	2	2	5	5	4	1	1	3
SiO ₂	35.8	36.2	36.6 (1)	36.4 (2)	36.5 (3)	36.8	36.7	37.1 (8)
TiO ₂	2.50	2.41	1.52 (7)	2.94 (10)	2.70 (4)	6.06	6.08	3.93 (3)
Al ₂ O ₃	16.4	16.4	16.7 (1)	16.5 (2)	16.4 (1)	16.7	16.6	17.8 (4)
MgO	11.1	10.9	13.8 (1)	10.8 (1)	10.7 (1)	12.9	12.9	12.3 (20)
CaO	nd	nd	nd	nd	nd	0.03	nd	0.05 (1)
MnO	0.10	0.12	0.08 (4)	0.13 (3)	0.11 (7)	0.11	0.10	nd
FeO	19.4	19.3	16.9 (2)	19.4 (2)	19.3 (2)	14.1	14.1	13.8 (2)
Na ₂ O	0.12	0.11	0.20 (11)	0.18 (6)	0.15 (10)	0.48	0.51	0.33 (2)
K ₂ O	9.66	9.53	9.49 (10)	9.38 (6)	9.46 (17)	9.05	9.02	9.45 (8)
H ₂ O	3.91	3.92	3.98 (1)	3.95 (3)	3.94 (3)	4.08	4.07	4.02 (4)
Σ	99.0	98.9	99.3	99.7	99.3	100.3	100.1	99.1
Cations based on 22 oxygens								
Si	5.501	5.534	5.515	5.523	5.557	5.409	5.000	5.517
Ti	0.288	0.278	0.172	0.336	0.309	0.671	0.674	0.440
Al	2.957	2.956	2.961	2.948	2.945	2.900	2.880	3.120
Mg	2.525	2.486	3.106	2.445	2.438	2.820	2.841	2.726
Ca	-	-	-	-	-	0.005	-	0.009
Mn	0.013	0.016	0.010	0.017	0.014	0.013	0.013	-
Fe ²⁺	2.487	2.495	2.124	2.458	2.455	1.732	1.741	1.717
Na	0.036	0.033	0.059	0.054	0.044	0.138	0.146	0.095
K	1.889	1.859	1.823	1.817	1.839	1.699	1.696	1.792
H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Σ	15.694	15.656	15.771	15.600	15.601	15.387	15.398	15.415
Fe/(Fe+Mg)	0.496	0.501	0.406	0.501	0.502	0.380	0.380	0.386

Units in () represent one standard deviation of replicate analyses in terms of least units cited

n.d. = not detected; less than 0.03%

All Fe calculated as FeO

Table A-4. Feldspar analyses from samples GL-1 and GL-2.

	10.22.c mat.pl.c		10.22.c2 mat.pl.c		10.22.c3 mat.pl.r		10.22.s mat.pl.r		10.22.i mat.pl.r		10.22.m mat.pl.r		10.22.n mat.pl.r		10.8.g pl.inc		10.8.h pl.inc		10.15.h pl.inc		10.15.g pl.inc		10.15.h pl.inc		10.22.f pl.inc		10.22.g pl.inc		10.22.h pl.inc	
# of analyses	5		6		1		1		1		1		1		3		3		4		4		2		2		2		2	
SiO ₂	55.3	(4)	54.8	(3)	54.7		54.1		55.8		54.5		54.7		52.5	(4)	54.7	(1)	56.2	(7)	55.8	(3)	53.4		55.6		56.0		56.3	
Al ₂ O ₃	28.1	(2)	28.3	(10)	28.5		28.7		28.6		28.3		28.3		29.8	(3)	28.2	(2)	27.5	(3)	27.5	(1)	28.9		27.7		27.9		27.7	
CaO	10.7	(11)	10.6	(5)	11.1		11.1		10.8		10.8		10.5		12.5	(3)	10.5	(2)	9.60	(32)	9.56	(17)	11.6		9.94		10.3		9.95	
FeO	nd		0.08	(6)	0.04		nd		nd		0.05		nd		0.42	(6)	0.21	(9)	0.41	(12)	0.17	(9)	0.33		0.08		0.23		0.21	
Na ₂ O	5.62	(4)	5.29	(12)	5.50		5.36		5.35		5.38		5.51		4.55	(21)	5.72	(11)	6.28	(12)	6.22	(11)	4.97		5.88		5.79		5.97	
K ₂ O	0.10	(1)	0.12	(2)	0.11		0.07		0.07		0.08		0.09		0.05	(1)	0.10	(6)	0.03	(1)	0.05	(2)	nd		0.06		0.08		0.06	
Σ	99.8		99.3		99.9		99.3		100.6		99.1		99.1		99.8		99.4		100.0		99.3		99.2		99.3		100.3		100.2	
Cations based on 8 oxygens																														
Si	2.497		2.483		2.473		2.495		2.495		2.478		2.486		2.389		2.481		2.531		2.527		2.436		2.519		2.514		2.528	
Al	1.495		1.517		1.516		1.506		1.506		1.517		1.513		1.597		1.510		1.457		1.467		1.554		1.477		1.477		1.465	
Ca	0.516		0.519		0.535		0.517		0.517		0.527		0.513		0.609		0.510		0.463		0.463		0.567		0.494		0.494		0.479	
Fe ²⁺	-		0.003		0.002		-		-		0.002		-		0.016		0.008		0.016		0.016		0.013		0.009		0.009		0.008	
Na	0.491		0.466		0.480		0.464		0.464		0.474		0.485		0.402		0.504		0.548		0.548		0.440		0.504		0.504		0.520	
K	0.006		0.007		0.007		0.004		0.004		0.005		0.005		0.003		0.006		0.002		0.002		-		0.005		0.005		0.004	
Σ	5.005		4.995		5.013		4.986		4.986		5.003		5.002		5.016		5.019		5.016		5.015		5.008		5.002		5.002		5.003	
X Anorthite	50.9		52.3		52.3		52.5		52.5		52.4		51.1		60.1		50.0		45.7		45.7		56.3		49.3		49.3		47.8	
X Albite	48.5		47.0		47.0		47.1		47.1		47.1		48.4		39.6		49.4		54.1		54.1		43.7		50.2		50.2		51.8	
X K-feldspar	0.6		0.7		0.7		0.4		0.4		0.5		0.5		0.3		0.6		0.2		0.2		0.0		0.5		0.5		0.4	

Units in () represent one standard deviation of replicate analyses in terms of least units cited

n.d. = not detected; less than 0.03%

All Fe calculated as FeO

Appendix B:
Structural and Lithologic Data for the
Moravian Falls and Taylorsville Quadrangles

Note: Stations correspond to locations shown in Plate 2. Lithologic abbreviations are notations made in the field and do not correspond to specific units.

FIELD LITHOLOGIES	
abbreviations	lithologies/textures
am	amphibolite
bgn	biotite gneiss
bi gtd	biotite granitoid
bs	biotite schist
cs	calc silicate
ggd	granodiorite
ggn	granite gneiss
gms	garnet-muscovite schist
hbl ggd	hornblende granodiorite
pclastic	porphyroclastic
mgw	metagraywacke
mig	mylonitic
ms	muscovite schist
myl	mylonitic
ogn	orthogneiss
peg	pegmatite
qtzite	quartzite
sap	saprolite
ss	sillimanite schists
ultmyl	ultramylonitic

MAP UNITS	
abbreviations	unit
am	amphibolite
Ctf	Cambrian Tallulah Falls-Ashe Fm.
Dmwt	Devonian Walker Top granite (mylonitic)
Dtg	Devonian Toluca granite
gms	garnet-muscovite schist
hm	hibriten mylonite
Oh	Ordovician Henderson gneiss
Opma	Ordovician poor mountain amphibolite
Sbc	Silurian Brooks Crossroads granite
SDcs	Silurian-Devonian calc silicate
SDmgw	Silurian-Devonian metagraywacke
SDss	Silurian-Devonian sillimanite schist

Table B-1. Structural and lithologic data for the Moravian Falls and Taylorsville quadrangles.

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lineation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	1	MV	bgn/bgn-grt sch	039 45 SE							341 90		hm
I	2	MV	am/bgn	061 54 SE									Opma
I	3	MV	pclastic myl ogn	070 64 SE									hm
I	4	MV	pclastic ult myl ogn	050 58 SE									hm
I	5	MV	mgm am	051 18 SE									Opma
I	6	MV	mgm am	059 48 SE	12 241								Opma
I	7	MV	mgm am	066 28 SE									Opma
I	8	MV	ms bs	057 76 SE									gms
I	9	MV	myl wt	050 32 SE									Dwt
I	10	MV	myl wt	093 49 NW									Dwt
I	11	MV	ss	060 29 SE									SDss
I	12	MV	ss	064 74 SE									SDss
I	13	MV	pclastic myl ogn	031 31 SE									Dwt
I	14	MV	bgn/mgw	046 68 SE									SDmgw
I	15	MV	bgn/mgw	068 33 SE									SDmgw
III	16	TV	bgn/mgw			21 052	305 34 NE	65	NW				SDmgw
III	17	TV	bgn/mgw/peg	049 49 NW									SDmgw
I	18	MV	bgn/mgw	305 26 NE									SDmgw
I	19	MV	pclastic myl ogn	060 72 SE									Dmwt
I	20	MV	ss	002 66 SE									SDss
I	21	MV	ss	279 37 SW									SDss
I	22	MV	ss	134 42 NE									SDss
I	23	MV	bgn/mgw	050 29 SE	16 049						039 64 NW	309 90	SDmgw
I	24	MV	ss	134 42 NE									SDss
I	25	MV	ss	081 44 NW									SDss
I	26	MV	ss	001 37 SE									SDss
I	27	MV	ss	043 38 SE									SDss
I	28	MV	bgn/mgw/ggn	016 39 SE									SDmgw
I	29	MV	bgn/cs/ggn	042 51 SE	17 071	17 071	042 51 SE	0-40	NW/SE		310 75 NE		SDmgw
I	30	MV	bgn/bn/ggn	055 34 SE							301 90		SDmgw
I	31	MV	ggn	055 43 SE	11 090						301 90		ggn
I	32	MV	myl wt/ggn	055 51 SE							325 71 NE	241 71 NW	Dmwt
I	33	MV	myl wt/bgn	059 54 SE							274 18 SW		Dmwt
I	34	MV	pclastic myl ogn	050 34 SE							309 90		Dmwt
I	35	MV	pclastic myl ogn	047 44 SE	8 047								SDmgw
I	36	MV	bgn/mgw/ggn	035 54 SE									SDmgw
I	37	MV	bgn/mgw/ggn	050 46 SE									SDmgw
I	38	MV	bgn/mgw/ggn	057 42 SE									SDmgw
I	39	MV	pclastic myl ogn	047 34 SE									Dmwt
I	40	MV	pclastic myl ogn	043 42 SE	10 043								Dmwt
I	41	MV	bgn/mgw	053 14 SE									SDmgw
I	42	MV	bgn/mgw	024 45 SE									SDmgw
I	43	MV	ss	124 62 NE									SDss
I	44	MV	ss	062 53 NW	4 050								SDss
I	45	MV	bgn/mgw	070 51 SE									SDmgw
I	46	MV	bgn/mgw	049 46 SE									SDmgw
I	47	MV	ggn	065 61 SE							321 81 SW	244 62 SE	ggn
I	48	MV	ss	060 52 SE									SDss
I	49	MV	ss sap	039 56 SE									SDss
III	50	MV	ss	084 52 NW									SDss
I	51	MV	pclastic myl ogn	330 32 NE									Dmwt
I	52	MV	pclastic myl ogn	009 32 SE									Dmwt
I	53	MV	ss	018 17 SE									SDss
I	54	MV	ggn/bgn	069 24 SE		13 099							ggn
I	55	MV	pclastic myl ogn	065 32 SE	8 065						316 90		Dmwt
I	56	MV	pclastic myl ogn	074 12 SE	2 074	2 074							Dmwt
I	57	MV	pclastic myl ogn	036 31 SE									Dmwt
I	58	MV	pclastic myl ogn	064 10 SE									Dmwt
I	59	MV	pclastic myl ogn	054 66 SE									Dmwt
I	60	MV	ggn/bgn	040 69 SE	9 066								Dtg
III	61	MV	ggn/bgn	093 19 SW									Dtg
III	62	MV	ggn/bgn	075 49 SE									Dtg
III	63	MV	ggn/bgn	083 61 NW		66 340	072 65 NW	15-30	SW				Dtg
III	64	MV	ggn/bgn	086 38 SE									Dtg
III	65	MV	ggn/bgn	065 52 SE									Dtg
III	66	MV	ggn/bgn	073 47 SE									Dtg
III	67	MV	ggn	294 25 NE									Dtg
III	68	MV	ggn/bgn	064 24 NW							075 47 NW	024 77 SE	Dtg
III	69	MV	ggn	048 29 NW									Dtg
III	70	MV	ggn	051 53 NW									Dtg
III	71	MV	ggn	056 54 NW							340 76 NE	056 54 NW	Dtg
III	72	MV	ggn/bgn	081 22 NW							081 22 NW	034 57 SE	Dtg
III	73	MV	ggn	074 39 NW									Dtg
III	74	MV	ggn	065 24 NW									Dtg
III	75	MV	ggn	066 19 NW									Dtg
I	76	MV	ggn	054 41 NW	9 240								Dtg
III	77	MV	ggn	073 37 SE									Dtg
III	78	MV	ggn	086 37 SE									Dtg
III	79	MV	ggn	047 28 SE									Dtg
III	80	MV	bgn/cs	062 52 SE		3 238	064 61 SE	5 25	NW				SDmgw
III	81	MV	bgn/cs	055 56 SE									SDmgw
III	82	MV	bgn/mgw	045 41 SE									SDmgw
III	83	MV	bgn/mgw			33 268	084 74 SE	40-60	NW				SDmgw
III	84	MV	bgn/mgw			41 120	295 73 SW	5 20	NE				SDmgw
I	85	MV	pclastic myl ogn	048 41 SE		16 086	057 41 SE	5 30	NW				Dmwt
I	86	MV	ss	054 47 SE	23 071								SDss
I	87	MV	ss	052 34 SE	8 062								SDss
I	88	MV	ss	037 46 SE									SDss
I	89	MV	ss	047 43 SE									SDss
I	90	MV	pclastic myl ogn	054 66 SE	14 074						320 78 NE		Dmwt
I	91	MV	pclastic myl ogn	056 66 SE	4 059								Dmwt
I	92	MV	pclastic myl ogn	073 69 SE									Dmwt
I	93	MV	pclastic myl ogn	063 42 SE	4 067								Dmwt
I	94	MV	pclastic myl ogn	061 53 SE	2 237								Dmwt
I	95	MV	pclastic ult myl ogn	065 42 SE									hm
I	96	MV	pclastic ult myl ogn	064 76 SE									hm
I	97	MV	pclastic ult myl ogn	060 50 SE									hm
I	98	MV	pclastic ult myl ogn	080 68 SE		5 086	080 68 SE	15-35	NW		330 90	128 90	hm
III	99	MV	pclastic ult myl ogn	039 61 SE		2 302	116 54 NE	15-45	SW				hm
III	100	MV	bgn/mgw	114 44 NE									SDmgw
III	101	MV	bgn/mgw	139 28 NE									SDmgw
III	102	MV	ggn/bgn	096 26 NE									SDmgw
III	103	MV	ggn/bgn	081 64 NW									SDmgw
III	104	MV	ggn/bgn	088 58 NW									SDmgw
III	105	MV	bgn/mgw			11 040	080 36 NW	20-45	NW				SDmgw
I	106	MV	pclastic myl ogn	056 40 SE									hm

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lineation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	214	MV	ss	049 51 SE									SDss
I	215	MV	ss	060 76 SE									SDss
I	216	MV	ss	044 24 SE	7 232								SDss
I	217	MV	ss	040 29 SE									SDss
I	218	MV	ss	054 73 SE									SDss
I	219	MV	ss	083 67 SE									SDss
I	220	MV	ss	041 46 SE		28 190							SDss
I	221	MV	ss/pclastic myl ogn	080 24 NW									SDss
I	222	MV	ss	037 36 SE									SDss
I	223	MV	ss	072 65 NW									SDss
I	224	MV	mgw	073 64 SE									SDss
I	225	MV	ss	071 64 SE									SDss
I	226	MV	ss	048 19 SE									SDss
I	227	MV	ggn	040 22 SE									ggn
I	228	MV	ggn	044 70 SE									ggn
I	229	MV	bgn/ggn	066 66 SE									ggn
I	230	MV	ggn	049 51 SE									ggn
I	231	MV	mgw	045 72 SE									SDmgw
I	232	MV	pclastic myl ogn	045 32 SE							300 90		SDmgw
I	233	MV	pclastic myl ogn	043 65 SE	2 221								SDmgw
I	234	MV	ggn	041 41 SE									SDmgw
I	235	MV	ggn/bgn	039 30 SE									SDmgw
I	236	MV	ggn/bgn	044 34 SE									SDmgw
I	237	MV	ggn/bgn	039 34 SE									SDmgw
I	238	MV	ggn/bgn	023 31 SE									SDmgw
I	239	MV	bgn/bs	003 40 NW									SDmgw
III	240	MV	ggn	302 24 NE	7 071								ggn
I	241	MV	ggn/mgw	315 28 NE									SDmgw
I	242	MV	ggn/ss	058 27 SE									SDss
I	243	MV	ss	049 44 SE									SDss
I	244	MV	ss	046 39 SE									SDss
I	245	MV	ss	040 44 SE									SDss
I	246	MV	pclastic myl ogn	049 49 NW									Dmwt
I	247	MV	pclastic myl ogn	055 49 NW							056 55 NW	319 74 SW	Dmwt
I	248	MV	pclastic myl ogn	080 56 NW									Dmwt
I	249	MV	pclastic myl ogn	059 35 SE	4 064								Dmwt
I	250	MV	pclastic myl ogn	059 32 SE	6 245								Dmwt
I	251	MV	pclastic myl ogn	061 26 SE	7 074								Dmwt
I	252	MV	pclastic myl ogn	043 23 NW	9 056								Dmwt
I	253	MV	pclastic myl ogn	063 39 NW	13 251								Dmwt
I	254	MV	pclastic myl ogn	050 35 SE	1 074								Dmwt
I	255	BM	pclastic myl ogn	061 52 SE	4 066								Dmwt
I	256	MV	pclastic myl ogn	071 30 SE	1 074						154 90		Dmwt
I	257	MV	pclastic myl ogn	36 54 NW	11 221						339 90		Dmwt
I	258	MV	pclastic myl ogn	058 43 SE	6 061								Dmwt
I	259	MV	pclastic myl ogn	063 48 SE	9 249								Dmwt
I	260	MV	pclastic myl ogn	061 25 NW									Dmwt
I	261	MV	ss	065 59 NW	22 231								SDss
I	262	MV	ss	060 55 SE									SDss
I	263	MV	pclastic myl ogn	073 40 NW	11 080								Dmwt
I	264	MV	pclastic myl ogn	079 25 NW	1 070								Dmwt
I	265	MV	mgw/pclastic myl ogn	041 28 SE									Dmwt
I	266	MV	ss	020 18 SE									SDss
I	267	MV	ss sap	016 25 SE									SDss
I	268	MV	mgw/bgn	321 26 SW									SDmgw
I	269	MV	pclastic myl ogn	057 43 SE									Dmwt
I	270	MV	BGN / MGW	067 39 SE									SDmgw
I	271	MV	pclastic myl ogn	058 44 NW									Dmwt
I	272	MV	pclastic myl ogn/ss	069 54 NW									Dmwt
I	273	MV	ss	054 31 SE									SDss
I	274	MV	ss	045 44 NW									SDss
I	275	MV	ggn	078 27 NW									Sbc
I	276	MV	ggn	071 66 NW									Sbc
I	277	MV	ggn	078 44 NW									Sbc
I	278	MV	pclastic myl ogn	076 39 NW	6 060						327 86 NE		Dmwt
I	279	MV	pclastic myl ogn/bgn	062 71 NW									SDmgw
I	280	MV	pclastic myl ogn/bgn	047 24 NW									SDmgw
I	281	MV	pclastic myl ogn	061 71 SE	2 064						319 74 NE	044 74 NW	Dmwt
I	282	MV	pclastic myl ogn	044 25 SE	1 049						304 66 NE	305 16 NE	Dmwt
I	283	MV	pclastic myl ogn	035 44 SE							069 67 NW		Dmwt
I	284	MV	ss	073 66 NW									SDss
I	285	MV	ss	066 30 SE	16 226								SDss
I	286	MV	ss	070 54 SE									SDss
I	287	MV	ss	056 32 SE									SDss
I	288	MV	ss	068 24 NW									SDss
I	289	MV	ss	043 57 SE									SDss
I	290	MV	ss	064 33 SE	12 076								SDss
I	291	MV	pclastic myl ogn/ss	049 38 SE									Dmwt
I	292	MV	pclastic myl ogn	056 41 SE	8 061								Dmwt
I	293	MV	ss	071 34 SE									SDss
I	294	MV	ss	074 55 SE									SDss
I	295	MV	ss	073 53 SE									SDss
I	296	MV	pclastic myl ogn	064 46 SE									Dmwt
I	297	MV	pclastic myl ogn	064 46 SE									Dmwt
I	298	MV	pclastic myl ogn	058 64 SE									Dmwt
I	299	MV	bgn/mgw	071 31 SE									SDmgw
I	300	MV	ss	065 58 SE									SDss
I	301	MV	ss	079 67 NW									SDss
III	302	MV	mgw/cs	061 15 SE									SDmgw
III	303	MV	mgw/bs	049 44 SE									SDmgw
III	304	MV	mgw	060 55 SE									SDmgw
III	305	MV	mgw	057 42 SE									SDmgw
III	306	MV	mgw	066 40 SE	16 056	18 045	041 21 SE	13	NW				SDmgw
III	307	MV	mgw	069 31 SE									SDmgw
III	308	MV	mgw	061 20 SE									SDmgw
I	309	MV	mgw	079 45 NW		22 094	349 28 NE	70-90	NNW				SDmgw
I	310	MV	pclastic myl ogn	072 47 NW							337 82 SW	044 57 SE	Dmwt
I	311	MV	pclastic myl ogn	046 53 SE	10 203						315 80 SW		Dmwt
I	312	MV	pclastic myl ogn	059 58 SE									Dmwt
I	313	MV	pclastic myl ogn sap	037 47 SE		12 226	034 71 SE	60-80	NW				Dmwt
I	314	MV	pclastic myl ogn/mgw	071 54 SE									SDmgw
I	315	MV	ss	060 49 SE	26 220								SDss
I	316	MV	ss	046 44 SE	14 057								SDss
I	317	MV	pclastic myl ogn/mgw	053 56 SE							336 88 NE		SDmgw
II	318	MV	pclastic myl ogn	036 34 SE									Dmwt
II	319	MV	pclastic myl ogn/mgw	039 32 SE	6 059						319 90		SDmgw
I	320	MV	pclastic ultmyl ogn	071 47 SE									hm

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lincation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	321	MV	ss	063 51 SE									SDss
I	322	MV	ss	075 46 SE									SDss
I	323	MV	pclastic myl ogn/ss	044 39 SE									Dmwt
I	324	MV	ss	042 36 SE									SDss
I	325	MV	ss	069 60 SE		6 124	126 70 SW	20-40	NE				SDss
I	326	MV	ss	069 51 SE									SDss
I	327	MV	ss			7 060	063 78 NW	120-145	SE	7 060			SDss
I	328	GL	mgw/cs	047 44 SE									SDmgw
I	329	GL	mgw/cs	054 54 SE									SDmgw
I	330	GL	mgw/cs	061 50 SE									SDmgw
I	331	GL	mgw/cs	054 46 SE									SDmgw
I	332	GL	mgw/cs	030 40 SE	6 052								SDmgw
III	333	MV	ggn	047 46 SE							336 90		Sbc
III	334	MV	ggn	040 72 SE							059 78 NW		Sbc
III	335	MV	mgw	061 76 SE		39 054	319 40 NE	15-50	SE		335 72 SW	076 77 SE	SDmgw
III	336	MV	mgw	063 86 SE		16 071	332 18 NE	20-60	NW		075 56 SE	335 64 NE	SDmgw
III	337	MV	mgw										SDmgw
III	338	MV	ggn	340 40 NE									Sbc
III	339	MV	ggn	034 46 SE		2 039	034 24 SE	0-30	SW / SE		346 80 NE	071 74 NW	Sbc
III	340	MV	ggn	074 41 NW		15 044	074 41 NW	15-35	NW / ENE		338 26 NE	060 32 NW	Sbc
III	341	MV	ggn	079 64 SE							028 56 SE	319 11 NE	Sbc
III	342	MV	ggn	291 26 NE							343 80 SW	328 25 NE	Sbc
III	343	MV	ggn	081 43 SE									Sbc
III	344	MV	ggn	081 23 SE							330 66 SW	062 46 SE	Sbc
III	345	MV	ggn	066 10 SE							284 84 SW	046 79 NW	Sbc
III	346	MV	ggn	273 34 SW							300 70 NE	056 12 NW	Sbc
III	347	MV	ggn	082 33 SE	229								Sbc
III	348	MV	ggn	042 45 SE									Sbc
III	349	MV	ggn/mgw			13 015	055 24 NW	20-65	SE / NW				SDmgw
III	350	MV	ggn	031 36 SE									Sbc
III	351	MV	ggn	059 45 SE									Sbc
III	352	MV	ggn	057 32 NW							334 71 NE		Sbc
III	353	MV	ggn/mgw	306 10 NE									SDmgw
III	354	MV	mgw	066 17 SE							275 68 SW	326 64 NE	SDmgw
III	355	MV	mgw	064 29 NW									SDmgw
III	356	MV	mgw	069 20 NW									SDmgw
III	357	MV	mgw	059 36 NW							269 85 NW	346 76 NE	SDmgw
III	358	MV	mgw	056 41 NW							331 88 NE		SDmgw
II	359	MV	ggn	356 15 NE	11 108						316 83 SW	002 84 NW	Sbc
II	360	MV	ggn/mgw	024 29 SE		13 051	009 37 SE	15-40	NW		026 62 NW	074 76 SE	SDmgw
II	361	MV	ggn	005 27 SE	14 062								Sbc
II	362	MV	ggn	039 57 SE	4 049						324 88 NE	049 56 SE	Sbc
I	363	MV	hbl ggd	044 38 SE									OPMA
I	364	MV	hbl ggd	040 43 SE							311 80 SW	051 74 SE	OPMA
I	365	MV	ss	060 64 SE							348 90		SDss
I	366	MV	ss	071 57 SE									SDss
I	367	MV	ss	036 46 SE	6 051						336 72 NE	064 59 SE	SDss
I	368	MV	ss	051 11 SE	3 056						338 78 SW		SDss
I	369	MV	ss	057 33 SE							326 79 SW		SDss
I	370	MV	ss	066 46 SE									SDss
I	371	MV	pclastic myl ogn	059 37 NW									Dmwt
I	372	MV	pclastic myl ogn	065 49 NW	7 229	12 058	071 61 NW	0-30	SE				Dmwt
I	373	MV	pclastic myl ogn	051 74 SE									Dmwt
III	374	MV	mgw/cs			7 073	069 20 SE	40-80	NW				SDmgw
III	375	MV	bgm/mgw	065 62 NW									SDmgw
III	376	MV	mgw/cs			36 045	066 20 NW	100-160	SE				SDmgw
III	377	MV	mgw	051 50 NW									SDmgw
III	378	TV	bgm/mgw	273 66 SW									SDmgw
III	379	MV	ss	062 42 NW									SDss
III	380	MV	ss			16 091	068 36 SE	30-70	NNE				SDss
I	381	MV	ss sap			16 091	066 36 SE	30-70	NNE				SDss
III	382	MV	ggn		22 035								Sbc
III	383	MV	mgw	063 46 NW									SDss
III	384	MV	mgw	273 40 NE									SDmgw
III	385	MV	mgw			18 303	276 52 NE	0-20	SW				SDmgw
I	386	MV	mgw	053 69 SE	12 063								Dmwt
III	387	MV	ggn sap			6 079	080 51 SE	70-130	NW				Sbc
III	388	MV	ggn sap	062 21 NW	15 044								Sbc
III	389	MV	ggn	080 39 NW	12 066								Sbc
I	390	MV	ss	081 62 SE									SDss
I	391	MV	ss	081 62 SE									SDss
III	392	MV	mgw	074 71 NW									SDmgw
I	393	MV	ss	073 67 SE									SDss
I	394	MV	pclastic myl ogn	061 63 SE									Dmwt
I	395	MV	pclastic myl ogn	063 59 SE									Dmwt
I	396	MV	ss	059 70 SE	2 060								SDss
I	397	MV	ggn sap	060 42 SE	15 216								Opma
I	398	MV	hbl ggd	057 46 SE	18 222								Opma
I	399	MV	hbl ggd	059 44 SE	8 230								Opma
I	400	MV	ms/bs	070 28 SE	16 224								gms
I	401	MV	ms/bs	065 45 SE									gms
I	402	MV	myl pclastic ogn	051 52 SE									Oh
I	403	MV	myl pclastic ogn	051 71 SE		1 226	056 66 SE	10-20	NW		301 71 SW	056 59 SE	Oh
I	404	MV	myl pclastic ogn			7 226	046 45 SE	60	NW		041 57 NW	046 45 SE	Oh
III	405	MV	mgw	064 56 SE	22 071	29 084	311 54 NE	20-50	SW				SDmgw
III	406	MV	mgw			16 056							SDmgw
I	407	MV	mgw	005 37 SE							300 90		SDmgw
I	408	MV	pclastic myl ogn	045 27 SE	24 054								Dmwt
I	409	MV	pclastic myl ogn	069 46 SE	4 071								Dmwt
I	410	MV	pclastic myl ogn	049 64 SE	10 071	9 064	064 72 SE	17075	NW				Dmwt
I	411	MV	pclastic myl ogn	062 36 SE	2 064	22 010	130-190	NW					Dmwt
I	412	MV	pclastic myl ogn	064 57 SE		15 064	067 54 SE	40-80	NW				Dmwt
I	413	MV	pclastic myl ogn	076 28 SE	11 081						346 74 NE		Dmwt
I	414	MV	ggn	043 31 SE	16 049						039 64 NW	309 90	Sbc
I	415	MV	ggn	041 14 SE									Sbc
I	416	MV	ggn	049 16 SE						289 90			Sbc
I	417	MV	ggn	076 11 SE							066 74 NW		Sbc
I	418	MV	pclastic myl ogn/ss	026 46 SE	26 056								SDss
I	419	MV	ss	055 46 SE	7 059						349 86 SW		SDss
I	420	MV	ss	051 62 SE							345 72 SW		SDss
I	421	MV	ss	079 46 NW						17 079	343 90		SDss
I	422	MV	ss	041 41 SE							301 90		SDss
I	423	MV	hbl ggd	045 52 SE	2 047						325 90		Opma
I	424	MV	ss	074 73 SE	2 079						309 76 NE		SDss
I	425	MV	hbl ggd	064 63 SE									Opma
I	426	MV	hbl ggd	071 57 SE	12 240						335 90		Opma
I	427	MV	pclasticult myl ogn	081 62 SE							351 90		hm

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lineation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	428	MV	pelastic myl ogn	061 48 SE		22 074	074 54 NW	120-150	SE				hm
I	429	MV	ss	039 56 SE							322 51 SW		SDss
I	430	MV	ss	034 57 SE	7 039						323 90		SDss
I	431	MV	ss	046 25 SE	14 050						316 90		SDss
II	432	MV	ss	069 44 SE	7 241						335 90		SDss
II	433	MV	ss	042 21 SE	16 081						331 84 SW		SDss
II	434	MV	ggn	078 38 SE							345 90		Sbc
II	435	MV	ggn	046 49 SE	9 054						298 73 NE		Sbc
II	436	MV	pelastic myl ogn	057 42 SE	4 061						331 72 NE		Dmwt
II	437	MV	ggn	061 33 SE									Sbc
II	438	MV	ss	044 35 SE							310 90		SDss
II	439	MV	ss	054 56 SE							319 64 SW		SDss
II	440	MV	mgw	066 44 SE	14 072						324 90		SDmgw
II	441	MV	ss	036 64 SE	11 209								SDss
II	442	MV	ss	022 44 SE							296 90		SDss
II	443	MV	ss/mgw	058 51 SE	12 224								SDss
I	444	MV	hbl ggd	054 52 SE							356 81 SW		Opma
I	445	MV	hbl ggd	052 72 SE							326 90		Opma
I	446	MV	ss	056 26 SE	16 216						336 69 SW		SDss
I	447	MV	pelastic myl ogn	056 72 NW	2 046						329 64 NW	066 69 NW	Dmwt
I	448	MV	pelastic myl ogn	040 37 SE	7 055								Dmwt
I	449	MV	ss	054 41 SE	11 220						286 76 SW		SDss
III	450	MV	ggn/mgw	067 44 NW	22 044								SDmgw
III	451	MV	ggn	066 45 SE							336 54 SW		Sbc
III	452	MV	ggn	291 62 NE							009 83 SE		Sbc
III	453	MV	ggn	076 54 SE							326 31 NE		Sbc
III	454	MV	ggn	072 62 SE									Sbc
III	455	MV	ggn	067 70 SE									Sbc
III	456	MV	ggn	070 66 SE	17 217								Sbc
III	457	MV	ggn	049 31 SE		2 030	027 67 NW	0-35	SE		336 90	051 90	Sbc
III	458	MV	mgw/ggn	046 42 NW									Sbc
III	459	MV	mgw/ggn			23 239	059 90	0-10	NW				Sbc
III	460	MV	mgw/ggn	014 57 SE									Sbc
III	461	MV	mgw/ggn	061 39 SE									Sbc
III	462	MV	mgw/ggn	071 41 NW									Sbc
III	463	MV	ggn	065 66 NW							059 78 NW		Sbc
III	464	MV	ggn	067 64 NW							018 42 NW	076 90	Sbc
III	465	MV	mgw/ggn	047 66 SE									Sbc
III	466	MV	mgw/ggn	051 39 NW									Sbc
III	467	MV	ggn	076 25 NW	11 056						285 84 NE		Sbc
I	468	MV	ss	029 64 NW							344 90		SDss
I	469	MV	ggn	330 46 NE							070 59 SE		Sbc
I	470	MV	mgw	083 36 NW	9 066						309 77 NE		SDmgw
I	471	MV	ggn	071 44 NW	23 032						326 90		Sbc
II	472	MV	mgw	026 19 SE	13 064						004 81 NW		SDmgw
II	473	MV	ggn	044 24 SE							296 64 NE	004 56 NW	Sbc
I	474	MV	pelastic myl ogn	066 28 SE	6 073						282 90	330 90	Dmwt
I	475	MV	mgw	051 46 SE	6 071						309 90		SDmgw
I	476	MV	mgw/ss	044 34 SE							229 74 NE		SDss
I	477	MV	ss	044 59 SE	2 049								SDss
III	478	MV	mgw	078 39 NW		40 041	070 28 NW	0-15	SW		300 54 SW	031 88 NW	SDmgw
I	479	MV	ss	065 35 SE						069	294 84 SW		SDss
I	480	MV	ss	081 40 NW									SDss
I	481	MV	ss	071 24 NW									SDss
I	482	MV	ggn	281 32 NE							351 80 SW	281 90	Sbc
I	483	MV	ss	073 31 SE									SDss
I	484	MV	ggn	071 21 SE									Sbc
I	485	MV	pelastic myl ogn	051 45 SE	23 214						284 54 NE		Dmwt
I	486	MV	pelastic myl ogn	065 46 SE							336 90	086 54 NW	Dmwt
I	487	MV	mgw	046 40 SE							306 79 NE		SDmgw
I	488	MV	mgw	049 48 NW									SDmgw
I	489	MV	mgw	051 35 SE							310 88 SW	047 39 SE	SDmgw
I	490	MV	ss			19 064	056 69 SE	50-100	SE				SDss
I	491	MV	ss	034 35 SE	18 055								SDss
II	492	MV	ggn	015 32 SE							270 72 S		Sbc
III	493	MV	ggn/mgw	084 36 NW							344 80 SW		SDmgw
III	494	MV	ggn	076 45 SE							344 26 SW	318 83 SW	Sbc
III	495	MV	mgw	081 22 SE									SDmgw
III	496	MV	mgw		19 075	7 076	024 41 SE	50-70	NW		024 68 SE	324 90	SDmgw
II	497	MV	ggn	273 43 NE							006 52 NW	295 90	Sbc
II	498	MV	ggn	044 26 SE							049 51 NW	316 79 NE	Sbc
II	499	MV	mgw	041 12 SE							034 59 NW	302 72 NE	SDmgw
II	500	MV	pelastic myl ogn	036 26 SE	10 201						316 77 NE	018 82 SE	Dmwt
II	501	MV	ggn	046 22 SE									Sbc
II	502	MV	ss	059 45 SE							316 82 NE		SDss
II	503	MV	pelastic myl ogn	048 20 SE	24 221						321 65 NE		Dmwt
II	504	MV	ggn	039 18 NW							321 81 NE		Sbc
II	505	MV	ss	059 36 SE									SDss
II	506	MV	mgw	051 41 SE	9 073						311 69 SW	060 72 SE	SDmgw
II	507	MV	ggn	074 42 SE									Sbc
II	508	MV	pelastic myl ogn	078 24 SE									Dmwt
II	509	MV	ggn	042 20 SE	9 197						326 90	061 62 SE	Sbc
II	510	MV	ggn	039 29 SE							331 61 SW		Sbc
II	511	MV	pelastic myl ogn	064 43 SE							331 80 NE		Dmwt
II	512	MV	ss	044 47 SE	14 210								SDss
I	513	MV	hbl ggd	039 32 SE							029 87 NW		Opma
I	514	MV	HBL GGD	036 36 SE							351 74 SW	041 77 NW	Opma
I	515	MV	HBL GGD	054 52 SE							334 73 NE		hm
I	516	MV	hgn	044 39 SE									SDmgw
I	517	MV	hbl ggd	057 36 SE							319 66 NE	054 60 SE	Opma
I	518	MV	ss/mgw	036 47 SE		18 246	061 49 SE	0-20	NW		301 86 SW	086 31 SE	SDss
I	519	MV	mgw	046 12 SE							324 79 NW	034 83 SE	SDmgw
I	520	MV	mgw	074 58 NW							330 76 SW	081 58 NW	SDmgw
I	521	MV	mgw	019 27 SE	9 059	9 059		160-180	NW		329 90	066 72 SE	SDmgw
I	522	MV	ggn	284 34 NE							306 85 SW	334 73 SW	Sbc
I	523	MV	ggn nap	059 69 SE									Sbc
III	524	MV	mgw	046 39 NW							329 64 SW		Sbc
III	525	MV	ggn/mgw	076 79 NW							346 82 SW	061 90	SDmgw
III	526	MV	ggn	060 44 NW							339 86 SW	061 66 NW	Sbc
III	527	MV	mgw	071 44 NW							339 88 SW		SDmgw
III	528	MV	mgw	067 78 NW									SDmgw
III	529	MV	mgw	300 41 NE							324 23 NE		SDmgw
III	530	MV	ggn	078 22 NW							326 69 NE	046 18 NW	Sbc
III	531	MV	mgw	076 32 NW									SDmgw
III	532	MV	mgw	068 52 NW		10 055	071 53 NW	40-60	SE		330 82 SW	094 56 NW	SDmgw
III	533	MV	mgw	081 44 NW							337 84 SW		SDmgw
III	534	MV	mgw	049 28 NW									SDmgw

Domain	Station	Quad	Lithology	Foliation (S)		Lineation		Fold Axis		Axial Surface		IL Angle	Fold Verg.	Crenulation Axis		Joint		Joint		Map Unit
				Strike	Dip	Plunge	Trend	Plunge	Trend	Strike	Dip			Plunge	Trend	Strike	Dip	Strike	Dip	
III	535	MV	mgw	070	67 NW															SDmgw
III	536	MV	ggn	096	41 NE											044	57 SE	311	79 SW	Sbc
III	537	MV	ggn	066	60 SE															Sbc
I	538	MV	plastic myl ogn	059	36 SE											278	52 NE			Dmwt
I	539	MV	mgw	061	64 NW											334	76 SW			SDmgw
I	540	MV	plastic myl ogn	064	22 SE															Dmwt
I	541	MV	mgw	056	61 SE											320	66 SW	029	79 SE	SDmgw
I	542	MV	mgw	067	71 SE											332	61 SW			SDmgw
I	543	MV	plastic myl ogn	043	41 SE											034	68 SE	283	53 NE	Dmwt
I	544	MV	mgw	054	43 NW											324	55 SW			SDmgw
I	545	MV	mgw	059	64 SE											316	51 SW			SDmgw
I	546	MV	mgw	042	61 SE											271	79 SW	321	62 NE	SDmgw
I	547	MV	ss	056	34 NW															SDss
I	548	MV	ss	077	57 NW											344	87 SW			SDss
I	549	MV	ss	061	56 NW											335	66 SW			SDss
I	550	MV	mgw	014	54 SE															SDmgw
I	551	MV	ggn	059	61 NW											344	78 SW			Sbc
I	552	MV	mgw	065	45 NW											333	84 SW			SDmgw
III	553	MV	ggn	046	23 SE											300	84 NE	041	33 SE	Sbc
III	554	MV	mgw	067	30 SE											066	61 SE	304	56 NE	SDmgw
III	555	MV	mgw	074	66 NW			30	056	015	56 SE	90-110	NW			338	59 NE	066	34 SE	SDmgw
III	556	MV	mgw	068	28 SE											349	83 NE	071	76 SE	SDmgw
III	557	MV	mgw	038	24 SE											309	82 NE	042	29 SE	SDmgw
III	558	MV	mgw	061	76 NW											061	76 NW	274	71 SW	SDmgw
III	559	MV	mgw	056	43 NW											319	84 NE	048	47 NW	SDmgw
III	560	MV	mgw/cs	049	51 NW											274	72 SW			SDmgw
III	561	MV	mgw	066	37 NW	1	066													SDmgw
I	562	MV	ss	060	51 SE											324	84 SW			SDss
I	563	MV	am	061	44 SE											329	87 NE			Opma
I	564	MV	plastic myl ogn	069	57 SE											330	81 SW	071	71 NW	Opma
I	565	MV	plastic myl ogn	036	41 SE			146	50 SE			150-180	SW							Opma
I	566	MV	ss	061	52 SE											326	74 SW	054	52 SE	SDss
I	567	MV	ggn	091	56 SW											009	67 NW			Sbc
I	568	MV	plastic myl ogn	054	39 SE											319	36 SW			Dmwt
I	569	MV	plastic myl ogn	066	64 SE											014	57 NW	298	76 SW	Dmwt
I	570	MV	plastic myl ogn	044	36 SE											047	35 SE	321	84 SW	Dmwt
I	571	MV	mgw	056	80 SW											336	80 SW			SDmgw
I	572	MV	mgw	068	47 SE											070	29 SE	331	90	SDmgw
I	573	MV	ss/qtzite	064	41 SE											071	56 NW	344	79 SW	SDss
I	574	MV	ss	041	51 SE											334	70 SW	045	47 SE	SDss
I	575	MV	ss	074	39 SE											324	72 NE			SDss
I	576	MV	ss	044	30 SE	18	070													SDss
I	577	MV	ss	064	55 SE											319	82 NE	054	52 SE	SDss
I	578	MV	ss	071	64 SE											026	68 NW			SDss
I	579	MV	plastic myl ogn	036	21 SE											319	84 NE	054	36 SE	Dmwt
I	580	MV	plastic myl ogn	061	22 SE											326	86 SW	054	14 SE	Dmwt
I	581	MV	plastic myl ogn	057	36 SE											329	74 SW	096	82 NE	Dmwt
I	582	MV	mgw	046	28 SE											326	71 NE	329	30 SW	SDmgw
I	583	MV	ss	291	27 NE											339	55 SW			SDss
I	584	MV	ss	031	68 NW											311	66 NE			SDss
I	585	MV	ss	036	46 SE															SDss
I	586	MV	plastic myl ogn	066	37 NW											316	80 NE	068	21 NW	Dmwt
I	587	MV	plastic myl ogn	285	14 NE											285	14 NE	329	79 NE	Dmwt
I	588	MV	ss	009	54 SE	31	054									321	84 SW			SDss
I	589	MV	plastic myl ogn	021	59 SE											274	89 SE			Dmwt
I	590	MV	mgw sap	030	52 SE															SDmgw
I	591	MV	mgw	031	42 SE											056	69 NW	064	64 SE	SDmgw
I	592	MV	ss	031	51 SE	29	062													SDss
III	593	MV	mgw	058	54 NW											278	74 NE	082	76 SE	SDmgw
III	594	MV	ss sap	068	49 SE											354	88 NE			SDss
I	595	MV	plastic myl ogn	038	49 SE			12	036	051	18 NW	60-100	SE			309	75 NE	016	37 NW	Dmwt
I	596	MV	mgw/cs	299	15 NE	30	034	26	064	352	47 NE	0-20	NNW			311	86 NE	029	47 SE	SDmgw
I	597	MV	mgw/ss	020	54 SE											331	32 SE			SDss
I	598	MV	mgw	036	72 SE											293	78 SW	035	30 SE	SDmgw
I	599	MV	mgw	055												280	84 SE	054	74 SE	SDmgw
I	600	MV	mgw/ggn	056	49 SE											359	49 NE	061	76 SE	SDmgw
I	601	MV	mgw	064	48 NW	1	235	31	041	050	46 SE	30-90	NW			066	41 SE	284	76 NE	Dmwt
I	602	MV	plastic myl ogn	064	38 SE											085	90			SDss
I	603	MV	ss	039	51 NW											324	79 NE			SDss
I	604	MV	ss	056	35 SE															SDss
I	605	MV	ss	088	56 SE															SDss
I	606	MV	mgw/ss	074	46 NW											338	79 NE	035	74 SE	SDss
I	607	MV	ggn/am					16	231	080	36 SE	20-30	NW			331	73 NE			Sbc
I	608	MV	am	051	26	SE										328	90	066	27 SE	Opma
I	609	MV	am	045	61 SE											048	36 NW	315	71 SW	Opma
I	610	MV	hbl ggd	041	44 SE	21	086									306	84 NE	046	39 SE	Opma
I	611	MV	hbl ggd	054	52 SE											051	54 SE	311	88 SW	Opma
I	612	MV	hbl ggd	050	54 SE	18	080									316	42 NE	051	50 NE	Opma
I	613	MV	hbl ggd	036	38 SE	13	053									316	90	041	33 SE	Opma
I	614	MV	hbl ggd	049	54 SE	16	064									309	82 SW	044	61 SE	Opma
I	615	MV	hbl ggd	035	52 SE											035	52 SE	054	46 NW	Opma
I	616	MV	mgw	059	58 SE											064	48 NW	066	54 SE	SDmgw
I	617	MV	plastic mwt	048	67 SE											048	67 SE	320	89 NE	hm
I	618	MV	hbl ggd	049	35 SE															Opma
I	619	MV	hbl ggd	054	56 SE											301	59 NE	055	60 SE	Opma
I	620	MV	ms	051	61 SE											321	78 SW	060	48 SE	gms
I	621	MV	hbl ggd	056	26 SE	21	097									354	71 SW	070	66 NW	Opma
I	622	MV	hbl ggd	058	58 SE											066	84 NW	326	80 SW	Opma
I	623	MV	hbl ggd	057	44 SE											321	74 SW	060	61 NW	Opma
I	624	MV	bgn	080	46 SE											335	76 NE	075	50 SE	Ctf
I	625	MV	bgn	074	52 SE											330	76 NE	069	68 NW	Ctf
I	626	MV	bgn	090	61 S											336	68 NE			Ctf
I	627	MV	bgn	078	57 SE											340	90			Ctf
I	628	MV	bgn	057	51 SE											349	77 SW			Ctf
I	629	MV	bgn	044	59 NW															Ctf
I	630	MV	bgn	065	34 SE											359	86 SW	067	36 SE	Ctf
I</																				

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lineation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
III	642	MV	mgw			6 050	041 36 SE	50-90	NW		054 88 SE	079 16 SE	SDmgw
III	643	MV	mgw	076 57 SE							329 86 SW	076 57 SE	SDmgw
III	644	MV	mgw	068 48 SE							068 48 SE	329 88 SW	SDmgw
III	645	MV	ggn	074 42 NW							074 42 NW	349 82 NE	Sbc
III	646	MV	mgw	067 65 SE							067 65 SE	064 58 NW	SDmgw
III	647	MV	mgw	071 76 NW									SDmgw
III	648	MV	mgw	059 41 NW							337 90	059 43 NW	SDmgw
III	649	MV	mgw	057 51 SE							057 51 SE	287 80 NE	SDmgw
III	650	MV	mgw	051 41 NW							051 41 NW	044 61 SE	SDmgw
III	651	MV	mgw	060 44 NW									SDmgw
III	652	MV	ggn	068 51 NW							68 51 NW	057 61 SE	Sbc
III	653	MV	mgw	079 39 NW							079 39 NW	351 88 NE	SDmgw
I	654	MV	myl plastic ogn	049 38 SE							049 66 SE	323 82 SW	Oh
I	655	MV	am/myl plastic ogn	076 59 SE	15 246						076 59 SE	081 34 NW	Oh
I	656	MV	myl plastic ogn	063 46 SE							046 46 SE		Oh
I	657	MV	myl plastic ogn	066 51 SE							066 51 SE	346 90	Oh
I	658	MV	myl plastic ogn	059 52 SE							059 52 SE		Oh
I	659	MV	myl plastic ogn	071 40 SE							071 40 SE		Oh
I	660	MV	myl plastic ogn	078 36 SE							078 36 SE	076 42 NW	Oh
I	661	MV	myl plastic ogn	059 31 SE							059 31 SE	057 82 NW	Oh
I	662	MV	hgn	064 36 SE							64 36 SE	57 26 NW	Ctf
I	663	MV	myl plastic ogn	049 42 SE							049 42 SE	036 60 NW	Oh
I	664	MV	myl plastic ogn	076 40 SE									Oh
I	665	MV	am/ggd	056 40 SE							068 82 SE	316 86 NE	Opma
I	666	MV	plastic myl ogn	055 44 SE							055 44 SE	020 22 NW	Dmwt
I	667	MV	ss	051 39 SE							028 66 SE	312 81 NE	SDas
I	668	MV	ss	047 57 SE							328 78 SW	047 57 SE	SDas
I	669	MV	ss	047 54 SE									SDas
I	670	MV	ss	024 38 SE							024 38 SE	015 52 NW	SDas
I	671	MV	hbl ggd	051 51 SE							051 51 SE	014 39 NW	Opma
I	672	MV	hbl ggd	056 50 SE							056 50 SE	068 26 NW	Opma
I	673	MV	hbl ggd	058 74 SE							058 74 SE	344 90	Opma
I	674	MV	hbl ggd	086 71 NW	24 067						086 71 NW	348 76 SW	Opma
I	675	MV	hbl ggd	047 66 SE									Opma
III	676	MV	mgw	055 43 SE	26 086						311 54 NE		SDmgw
III	677	MV	mgw	071 53 SE							071 53 SE	332 90	SDmgw
III	678	MV	mgw	071 38 SE							306 90		SDmgw
III	679	MV	mgw	051 61 SE							051 61 SE	326 67 SW	SDmgw
III	680	MV	mgw	085 23 SE							005 23 SE		SDmgw
III	681	MV	mgw	336 69 SW							336 69 SW	071 82 SE	SDmgw
III	682	MV	mgw	040 24 SE							040 24 SE	321 90	SDmgw
III	683	MV	mgw	057 39 SE							057 39 SE	350 87 NE	SDmgw
III	684	MV	mgw	071 66 SE							341 87 SW	071 66 SE	SDmgw
III	685	MV	mgw	077 52 SE									SDmgw
III	686	MV	mgw	052 71 SE							052 71 SE	082 45 SE	SDmgw
III	687	MV	cs	022 34 SE	28 084						022 34 SE	358 90	SDcs
III	688	MV	cs	055 47 SE							339 81 SW	018 77 NW	SDcs
III	689	MV	ss	346 66 NE	44 061						346 66 NE	301 61 SW	SDss
I	690	MV	ggn/mgw	032 36 SE							032 36 SE	336 64 SW	SDmgw
I	691	MV	ss	029 44 SE							358 55 SW	319 82 SW	SDas
I	692	MV	ss	028 54 SE							344 82 SW	324 37 NE	SDas
I	693	MV	ss	028 38 SE	24 052						324 71 SW		SDss
III	694	MV	ggn	069 54 NW							306 69 NE	299 30 NE	Sbc
III	695	MV	ggn	072 19 SE							021 43 SE	269 68 NW	Sbc
III	696	MV	ggn	076 37 SE							296 56 NE		Sbc
III	697	MV	ggn	086 29 NW							296 90	045 78 NE	Sbc
III	698	MV	mgw	076 21 NW							036 57 NW	316 20 NE	SDmgw
III	699	MV	mgw	084 49 NW							334 74 NE		SDmgw
I	700	MV	ggn/mgw	084 36 NW							286 54 SW	083 76 NW	SDmgw
I	701	MV	ss	083 76 NW							329 49 SW	345 29 NE	SDss
I	702	MV	ss			24 086	349 32 NE	40-60	NW		330 84 SW	051 60 SE	SDss
I	703	MV	ss	076 39 NW							021 900		SDss
I	704	MV	ggn/mgw	061 40 NW							336 88 SW	307 71 SW	SDmgw
I	705	MV	ss	034 33 SE							326 71 SW		SDss
I	706	MV	ss	040 29 SE							342 88 SW		SDss
I	707	MV	cs/mgw	020 42 SE	9 041						014 83 NW	320 67 SW	SDcs
I	708	MV	mgw	048 59 SE							329 75 SW		SDmgw
I	709	MV	plastic myl ogn	042 24 SE							334 79 SW	017 62 NW	Dmwt
I	710	MV	plastic myl ogn	034 28 SE							340 88 SW	037 66 SE	Dmwt
I	711	MV	plastic myl ogn	027 33 SE									Dmwt
I	712	MV	mgw	041 49 SE							327 88 SW	011 72 NW	SDmgw
I	713	MV	plastic myl ogn	039 34 SE							043 72 NW	326 67 SW	Dmwt
I	714	MV	mgw	045 37 SE							322 74 SW	040 66 NW	SDmgw
I	715	MV	mgw/ggn	036 37 SE							011 46 SE		SDmgw
I	716	MV	plastic myl ogn	036 31 SE							326 66 SW		Dmwt
I	717	MV	plastic myl ogn	020 31 SE							311 22 NE	009 79 NW	Dmwt
I	718	MV	plastic myl ogn	044 32 SE							064 72 SE		Dmwt
I	719	MV	plastic myl ogn	040 46 SE							333 69 SW		Dmwt
I	720	MV	plastic myl ogn	038 52 SE							079 67 SE		Dmwt
I	721	MV	plastic myl ogn	047 39 SE							087 80 SE	340 67 SW	Dmwt
I	722	MV	plastic myl ogn	044 42 SE							321 72 SW		Dmwt
I	723	MV	plastic myl ogn	039 28 SE							336 88 SW	094 77 NE	Dmwt
I	724	MV	plastic myl ogn	052 36 SE									Dmwt
I	725	MV	plastic myl ogn	043 31 SE							341 62 NE	11 82 NW	Dmwt
I	726	MV	plastic myl ogn	036 38 SE							077 62 NW		Dmwt
I	727	MV	plastic myl ogn	030 44 SE							019 80 NW		Dmwt
I	728	MV	ss	020 16 SE							360 77 SW	078 73 NW	SDss
I	729	MV	mgw	039							326 74 SW		SDmgw
I	730	MV	ss	074 65 SE							342 82 NE		SDss
I	731	MV	mgw	064 59 SE							334 69 SW		SDmgw
I	732	MV	plastic myl ogn	073 58 SE							324 56 NE		Dmwt
I	733	MV	ss	051 46 SE							321 59 SW		SDas
I	734	MV	plastic myl ogn	046 44 SE							309 73 SW		Dmwt
I	735	MV	ss	061 70 SE							336 87 NE		SDas
I	736	MV	mgw	034 51 SE									SDmgw
I	737	MV	mgw	074 49 SE							056 64 SE	316 88 NE	SDmgw
I	738	MV	mgw	039 16 SE									SDmgw
I	739	MV	mgw	056 34 SE							326 55 SW	64 52 NW	SDmgw
I	740	MV	plastic myl ogn	045 62 SE		12 080	060 36 SE	30	NW		336 90	069 61 NW	Dmwt
I	741	MV	ss	062 67 NW							065 82 NW	327 84 SW	SDas
I	742	MV	mgw	067 62 NW									SDmgw
I	743	MV	plastic myl ogn	038 33 SE							324 77 SW		Dmwt
I	744	MV	plastic myl ogn	041 49 SE							084 74 NW		Dmwt
I	745	MV	plastic myl ogn	050 39 SE							020 84 NW		Dmwt
I	746	MV	mgw/cs	044 35 SE							046 37 SE		SDcs
I	747	MV	mgw	039 42 SE							329 77 SW	77 81 SE	SDmgw
I	748	MV	cs	030 40 SE	6 052						030 40 SE		SDcs

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lineation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	856	MV	mgw	049 46 SE									SDmgw
I	857	MV	mgw/pclastic myl ogn	069 34 SE									Dmwt
I	858	MV	pclastic myl ogn	062 29 SE							334 88 NE		Dmwt
I	859	MV	mgw	054 50 SE							009 74 NW		SDmgw
I	860	MV	mgw	039 46 SE									SDmgw
I	861	MV	pclastic myl ogn	072 52 SE							339 84 NE	079 62 SE	Dmwt
I	862	MV	pclastic myl ogn	067 46 SE									SDmgw
I	863	MV	mgw/pclastic myl ogn	065 49 SE									SDmgw
I	864	MV	mgw	048 37 SE							330 76 SW	067 68 SE	SDmgw
I	865	MV	mgw	057 42 SE									SDmgw
I	866	MV	mgw	051 48 SE									SDmgw
I	867	MV	mgw	062 60 SE							019 86 NW		SDmgw
I	868	MV	mgw	054 37 SE									SDmgw
I	869	MV	mgw	063 58 SE							031 71 SE	347 67 SW	SDmgw
I	870	MV	ss	048 20 NW							011 77 NW		SDss
I	871	MV	pclastic myl ogn	060 52 SE							351 73 NE		Dmwt
I	872	MV	pclastic myl ogn	064 41 SE							001 83 NW		Dmwt
I	873	MV	mgw	071 59 NW									SDmgw
I	874	MV	mgw	058 48 SE							012 82 NW	062 56 SE	SDmgw
I	875	MV	mgw	062 56 NW									SDmgw
I	876	MV	mgw	041 59 NW							332 79 SW		SDmgw
I	877	MV	mgw	054 63 NW									SDmgw
I	878	MV	mgw	315 37 SW									SDmgw
I	879	MV	mgw	326 29 NE							334 84 NE		SDmgw
I	880	MV	mgw	292 34 NE									SDmgw
I	881	MV	mgw	273 51 NE									SDmgw
I	882	MV	mgw	060 37 NW							321 77 SW	064 52 NW	SDmgw
I	883	MV	mgw	066 57 NW							340 81 SW		SDmgw
I	884	MV	ss	072 46 NW							329 74 NE	084 69 NW	SDss
I	885	MV	ss	055 49 NW						10 040			SDss
I	886	MV	ss	039 47 SE	21 059						320 71 NE		SDss
I	887	MV	ss	044 39 SE							354 74 SW		SDss
I	888	MV	mgw	054 62 NW							321 66 SW		SDmgw
I	889	MV	mgw	058 48 NW									SDmgw
I	890	MV	pclastic myl ogn	062 49 SE									Dmwt
I	891	MV	pclastic myl ogn	051 44 SE							316 74 SW		Dmwt
I	892	MV	mgw	060 52 NW							351 71 NE		SDmgw
I	893	MV	mgw	064 55 NW									SDmgw
I	894	MV	mgw	059 63 NW									SDmgw
I	895	MV	mgw	062 66 NW									SDmgw
I	896	MV	mgw	065 59 NW							305 74 SW		SDmgw
I	897	MV	mgw	061 51 SE									SDmgw
I	898	MV	mgw	063 58 NW									SDmgw
I	899	MV	mgw	058 64 NW									SDmgw
I	900	MV	mgw	063 61 NW									SDmgw
I	901	MV	mgw	059 63 NW									SDmgw
I	902	MV	mgw	066 57 NW									SDmgw
I	903	MV	mgw	069 71 NW							328 76 NW		SDmgw
I	904	MV	pclastic myl ogn	063 54 SE									Dmwt
I	905	MV	mgw	061 44 SE									SDmgw
I	906	MV	mgw	064 51 NW									SDmgw
I	907	MV	mgw	065 42 SE							347 81 NE		SDmgw
I	908	MV	mgw	068 50 SE									SDmgw
I	909	MV	mgw	054 39 SE							352 74 NE		SDmgw
I	910	MV	mgw	048 41 SE									SDmgw
I	911	MV	mgw	042 49 SE									SDmgw
I	912	MV	pclastic myl ogn	039 36 SE							074 89 SE		Dmwt
I	913	MV	ss	042 41 SE									SDss
I	914	MV	mgw	054 56 SE									SDmgw
I	915	MV	mgw	059 48 NW									SDmgw
I	916	MV	ss	061 57 NW							082 56 SE		SDss
I	917	MV	mgw	056 49 NW									SDmgw
I	918	MV	mgw	059 53 NW									SDmgw
I	919	MV	mgw	066 54 NW							318 67 SW		SDmgw
I	920	MV	mgw	054 50 SE									SDmgw
I	921	MV	mgw	050 42 SE									SDmgw
I	922	MV	pclastic myl ogn	041 38 SE									Dmwt
I	923	MV	pclastic myl ogn	037 46 SE									Dmwt
I	924	MV	pclastic myl ogn	046 49 SE									Dmwt
I	925	MV	mgw/ss	047 57 SE									SDmgw
I	926	MV	ss	037 50 SE									SDss
I	927	MV	mgw	058 47 SE									SDmgw
I	928	MV	ss	061 41 SE	7 230						311 72 SW		SDss
I	929	MV	ss	057 54 SE							300 73 SW	079 60 SE	SDss
I	930	MV	mgw	039 59 SE							046 72 NW		SDmgw
I	931	MV	ss	048 57 SE									SDss
I	932	MV	ss	042 39 SE									SDss
I	933	MV	mgw	044 52 SE									SDmgw
I	934	MV	mgw	298 63 NE							326 79 NE	075 63 NW	SDmgw
I	935	MV	mgw	079 57 NW									SDmgw
I	936	MV	mgw	083 47 NW									SDmgw
I	937	MV	mgw	021 18 SE									SDmgw
I	938	MV	mgw	061 48 SE		18 071 057 53 SE	11596 NW				321 87 NE	296 83 SW	SDmgw
I	939	MV	mgw	054 36 SE									SDmgw
I	940	MV	mgw	050 63 SE									SDmgw
I	941	MV	ss	044 48 SE							306 68 SW		SDss
I	942	MV	ss	038 56 SE	2 216								SDss
III	943	MV	mgw	069 72 SE									SDmgw
III	944	MV	mgw	274 58 SE									SDmgw
III	945	MV	mgw	081 26 NW									SDmgw
III	946	MV	bgn	281 21 SW									SDmgw
II	947	MV	ggn	049 42 SE									Sbc
II	948	MV	ggn	306 39 SW		27 225 306 39 SW	20-45 NW						Sbc
II	949	MV	ggn	342 59 NE									Sbc
II	950	MV	ggn	047 63 NW									Sbc
II	951	MV	ggn	053 49 SE	7 064								Sbc
II	952	MV	ggn-bgn	019 62 SE									Sbc
II	953	MV	ggn	346 69 NE	47 063								Sbc
I	954	MV	ggn	293 51 NE									Sbc
III	955	MV	ggn	076 25 NW	11 061								Sbc
III	956	MV	ggn	057 83 SE									Sbc
III	957	MV	ggn	071 72 SE									Sbc
II	958	MV	ggn	012 27 SE									Sbc
II	959	MV	ggn	344 49 NE									Sbc
II	960	MV	ggn	029 52 SE									Sbc
II	961	MV	ggn	029 49 SE									Sbc
II	962	MV	ggn	011 29 SE									Sbc

Domain	Station	Quad	Lithology	Foliation (S)		Lineation		Fold Axis		Axial Surface		IL Angle	Fold Verg.	Crenulation Axis		Joint		Joint		Map Unit
				Strike	Dip	Plunge	Trend	Plunge	Trend	Strike	Dip			Plunge	Trend	Strike	Dip	Strike	Dip	
II	963	MV	ggn	033	37 SE															Sbc
II	964	MV	ggn	352	32 NE															Sbc
II	965	MV	ggn	037	76 SE															Sbc
II	966	MV	ggn	331	36 NE															Sbc
II	967	MV	ggn	283	42 NE	27	049													Sbc
II	968	MV	MWT/GGN	046	66 SE															Dmwt
II	969	MV	ggn/pclastic myl ogn	067	71 SE															Dmwt
II	970	MV	ggn/pclastic myl ogn	073	59 SE															Sbc
III	971	MV	ggn	081	41 SE															Sbc
III	972	MV	ggn	074	37 SE															Sbc
III	973	MV	ggn	063	71 SE															Sbc
III	974	MV	ggn	051	67 SE															Sbc
III	975	MV	mgw/pclastic ult myl ogn	069	67 SE															hm
III	976	MV	mgw	077	57 NW															SDmgw
III	977	MV	mgw	064	36 NW															SDmgw
III	978	MV	mgw	073	38 NW															SDmgw
III	979	MV	mgw	067	54 NW															SDmgw
III	980	MV	mgw/pclastic ult myl ogn	054	76 SE															hm
III	981	MV	mgw/pclastic ult myl ogn	067	64 SE															hm
III	982	MV	ggn	064	73 SE															Sbc
III	983	MV	ggn	062	29 NW															Sbc
III	984	MV	ggn	068	49 NW															Sbc
III	985	MV	ggn	059	46 NW															Sbc
III	986	MV	mgw	070	56 SE															SDmgw
III	987	MV	mgw	064	72 NW															SDmgw
III	988	MV	mgw	073	66 NW															SDmgw
III	989	MV	mgw	058	51 NW															SDmgw
III	990	MV	mgw	066	37 NW															SDmgw
III	991	MV	mgw/pclastic myl ogn	081	71 NW															SDmgw
III	992	MV	ggn	290	59 NW															Sbc
III	993	MV	ggn	068	50 NW															Sbc
III	994	MV	ggn	037	31 NW															Sbc
III	995	MV	ggn	049	26 NW															Sbc
III	996	MV	ggn	076	47 NW															Sbc
III	997	MV	mgw/pclastic ult myl ogn	074	80 SE															SDmgw
III	998	MV	mgw	066	41 NW															SDmgw
III	999	MV	mgw	070	49 SE															SDmgw
III	1000	MV	mgw	054	41 SE															SDmgw
III	1001	MV	mgw	056	41 NW															SDmgw
III	1002	MV	mgw	059	55 NW															SDmgw
III	1003	MV	mgw	067	58 NW															SDmgw
III	1004	MV	mgw	048	54 SE															SDmgw
III	1005	MV	mgw	055	47 SE															SDmgw
III	1006	MV	mgw	069	58 SE															SDmgw
III	1007	MV	mgw	073	48 SE															SDmgw
III	1008	MV	mgw	059	57 SE															SDmgw
III	1009	MV	mgw	047	51 SE															SDmgw
III	1010	MV	ggn	026	66 SE															Dtg
III	1011	MV	ggn	071	26 NW															Dtg
III	1012	MV	ggn	033	29 SE															Dtg
III	1013	MV	ggn	084	57 NW															Dtg
III	1014	MV	ggn	060	41 NW															Dtg
III	1015	MV	ggn	032	39 SE															Dtg
III	1016	MV	ggn	047	32 SE	7	208													Dtg
III	1017	MV	ggn	084	66 SE															Dtg
III	1018	MV	ggn	317	82 SW															Dtg
III	1019	MV	mgw	082	63 NW															SDmgw
III	1020	MV	mgw	072	59 NW															SDmgw
III	1021	MV	mgw	057	43 SE															SDmgw
III	1022	MV	mgw	049	54 SE															SDmgw
III	1023	MV	mgw	031	47 SE															SDmgw
III	1024	MV	mgw	068	36 SE															SDmgw
III	1025	MV	mgw	053	59 SE															SDmgw
III	1026	MV	mgw	061	55 SE															SDmgw
III	1027	MV	mgw	068	69 SE															SDmgw
III	1028	MV	mgw	003	59 SE															SDmgw
III	1029	MV	mgw	351	81 NE															SDmgw
III	1030	MV	mgw	343	67 NE															SDmgw
III	1031	MV	mgw	353	74 NE															SDmgw
III	1032	MV	mgw	039	46 SE															SDmgw
III	1033	MV	ggn	312	51 NE	47	051													Dtg
III	1034	MV	ggn	279	19 SW															Dtg
III	1035	MV	ggn	277	59 SW															Dtg
III	1036	MV	ggn	076	68 SE															Dtg
III	1037	MV	ggn	031	32 SE															Dtg
III	1038	MV	mgw	348	77 NE															SDmgw
III	1039	MV	mgw	341	87 NE															SDmgw
III	1040	MV	mgw	301	70 NE															SDmgw
III	1041	MV	mgw	336	38 NE	12	034	336	38 NE	30-60	NW									SDmgw
III	1042	MV	mgw	009	48 SE															SDmgw
III	1043	MV	mgw	336	51 NW															SDmgw
III	1044	MV	mgw	026	44 SE															SDmgw
III	1045	MV	ggn	348	68 NE															Dtg
III	1046	MV	ggn	078	49 NW															Dtg
III	1047	MV	ggn	291	73 SW															Dtg
III	1048	MV	mgw	066	39 NW															SDmgw
III	1049	MV	mgw	049	46 NW															SDmgw
III	1050	MV	ggn	082	52 SE															Dtg
III	1051	MV	ggn	341	44 SW															Dtg
III	1052	MV	ggn	074	52 SE															Dtg
III	1053	MV	ggn	067	67 SE	14	073													Dtg
III	1054	MV	ggn	078	52 SE															Dtg
III	1055	MV	mgw	071	60 SE															SDmgw
III	1056	MV	mgw	059	47 NW	6	047	059	47 NW	0-40	SE									SDmgw
III	1057	MV	mgw	052	57 NW															SDmgw
I	1058	MV	mgw	049	30 NW															SDmgw
I	1059	MV	ss	050	58 SE															SDss
I	1060	MV	ss	057	66 SE															SDss
I	1061	MV	mgw	044	51 SE															SDmgw
I	1062	MV	mgw	051	55 NW															SDmgw
III	1063	MV	mgw	070	66 NW															SDmgw
III	1064	MV	mgw	065	59 NW															SDmgw
III	1065	MV	mgw	069	52 NW															SDmgw
III	1066	MV	mgw	066	47 NW															SDmgw
III	1067	MV	mgw	054	56 NW															SDmgw
III	1068	MV	mgw	349	68 NE			</												

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lineation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	1177	MV	pclastic myl ogn	063 54 SE									SDmgw
I	1178	MV	ss	061 59 SE									SDss
I	1179	MV	pclastic myl ogn	051 62 SE									Dmwt
I	1180	MV	mgw	048 56 SE									SDmgw
I	1181	MV	mgw	066 52 SE									SDmgw
I	1182	MV	ss	041 46 SE	12 055								SDss
I	1183	MV	ss	046 38 SE									SDss
I	1184	MV	ss	049 36 SE									SDss
I	1185	MV	ss	055 26 SE									SDss
I	1186	MV	ss	048 41 SE									SDss
I	1187	MV	ss	053 48 SE	1 052								SDss
I	1188	MV	ss	039 47 SE									SDss
II	1189	MV	ss	026 41 SE									SDss
II	1190	MV	ss	033 51 SE									SDss
II	1191	MV	ss	022 44 SE	16 041								SDss
II	1192	MV	ss	019 37 SE									SDss
I	1193	MV	ss	057 41 SE									SDss
I	1194	MV	mgw	052 55 SE									SDmgw
I	1195	MV	pclastic myl ogn	059 46 SE									Dmwt
I	1196	MV	pclastic myl ogn	067 61 SE									Dmwt
II	1197	MV	pclastic myl ogn	016 32 SE									Dmwt
II	1198	MV	mgw	031 43 SE									SDmgw
II	1199	MV	pclastic myl ogn	016 46 SE	3 016								Dmwt
II	1200	MV	pclastic myl ogn	029 36 SE									Dmwt
II	1201	MV	pclastic myl ogn	034 62 SE	7 037								Dmwt
I	1202	MV	ss	044 33 SE									SDss
I	1203	MV	pclastic myl ogn	056 42 SE									Dmwt
I	1204	MV	pclastic myl ogn	049 37 SE									Dmwt
I	1205	MV	pclastic myl ogn	055 46 SE									Dmwt
I	1206	MV	pclastic myl ogn	042 39 SE									Dmwt
I	1207	MV	ss	058 49 SE									SDss
I	1208	MV	ss	059 37 SE									SDss
I	1209	MV	ss	047 44 SE	16 059								SDss
I	1210	MV	pclastic myl ogn	050 46 SE									hm
I	1211	MV	ss	055 49 SE									SDss
I	1212	MV	ss	059 52 SE									SDss
I	1213	MV	ss	040 42 SE	5 046								SDss
I	1214	MV	pclastic myl ogn	046 51 SE									Dmwt
I	1215	MV	ss	067 49 SE									SDss
I	1216	MV	ss	049 56 SE									SDss
I	1217	MV	ss	044 53 SE	21 062								SDss
I	1218	MV	ss	056 59 SE									SDss
I	1219	MV	ss	057 46 SE									SDss
I	1220	MV	ss	055 49 SE									SDss
I	1221	MV	ss	052 56 SE									SDss
I	1222	MV	pclastic myl ogn	057 35 SE									Dmwt
I	1223	MV	pclastic myl ogn	049 42 SE									Dmwt
I	1224	MV	ss	056 52 SE									SDss
I	1225	MV	ss	059 61 SE									SDss
I	1226	MV	ss	049 52 SE									SDss
I	1227	MV	ss	057 46 SE	21 226								SDss
I	1228	MV	ss	052 41 SE									SDss
I	1229	MV	ss/pclastic myl ogn	056 51 SE									Dmwt
I	1230	MV	ss	062 57 SE	6 067								SDss
I	1231	MV	ss	055 49 SE									SDss
I	1232	MV	pclastic ultmyl ogn	066 52 SE	2 070								hm
I	1233	MV	pclastic ultmyl ogn	051 61 SE									hm
I	1234	MV	ss	056 47 SE									SDss
I	1235	MV	pclastic ultmyl ogn	044 52 SE		24 054	044 52 SE	0-35	NW				hm
I	1236	MV	pclastic ultmyl ogn	054 61 SE									hm
I	1237	MV	ss	067 49 SE									SDss
I	1238	MV	ss	051 55 SE									SDss
I	1239	MV	ss/pclastic myl ogn	040 51 SE	12 213								Dmwt
I	1240	MV	ss/pclastic myl ogn	043 42 SE									Dmwt
I	1241	MV	mgw	052 46 SE									SDmgw
I	1242	MV	ss	057 49 SE	13 062								SDss
I	1243	MV	ss	046 61 SE									SDss
III	1244	MV	mgw	051 66 SE									SDmgw
III	1245	MV	mgw	060 67 SE									SDmgw
III	1246	MV	mgw	072 61 SE									SDmgw
III	1247	MV	mgw	085 63 SE									SDmgw
III	1248	MV	mgw	082 54 SE		6 072	082 54 SE	50-70	NW				SDmgw
I	1249	MV	ss	047 61 SE	8 057								SDss
I	1250	MV	ss	056 44 SE									SDss
I	1251	MV	ss	048 52 SE									SDss
I	1252	MV	ss	056 49 SE									SDss
I	1253	MV	ss	051 63 SE									SDss
I	1254	MV	mgw	060 59 SE									SDmgw
I	1255	MV	mgw	049 55 SE									SDmgw
I	1256	MV	mgw	052 48 SE									SDmgw
I	1257	MV	mgw	041 52 SE									SDmgw
I	1258	MV	mgw	039 58 SE									SDmgw
I	1259	MV	mgw	044 49 SE									SDmgw
I	1260	MV	mgw	036 54 SE									SDmgw
I	1261	MV	mgw	050 61 SE									SDmgw
III	1262	MV	mgw	059 46 SE									SDmgw
III	1263	MV	mgw	067 29 SE									SDmgw
I	1264	MV	ss	049 60 SE									SDss
I	1265	MV	ss	046 49 SE									SDss
I	1266	MV	ss	052 41 SE	18 061								SDss
I	1267	MV	ss	033 44 SE									SDss
I	1268	MV	mgw	029 50 SE									SDmgw
I	1269	MV	mgw	051 46 SE		21 216	051 46 SE	60-70	NW				SDmgw
I	1270	MV	pclastic myl ogn	059 69 SE									Dmwt
I	1271	MV	pclastic myl ogn	041 52 SE									Dmwt
I	1272	MV	pclastic myl ogn	045 49 SE									Dmwt
I	1273	MV	mgw	056 58 SE									SDmgw
I	1274	MV	ss	040 51 SE									SDss
I	1275	MV	pclastic myl ogn	056 60 SE									Dmwt
I	1276	MV	pclastic myl ogn	066 55 SE									Dmwt
I	1277	MV	pclastic myl ogn	044 58 SE									Dmwt
I	1278	MV	pclastic myl ogn	067 53 SE									Dmwt
I	1279	MV	mgw	057 49 SE									SDmgw
I	1280	MV	mgw	041 57 SE									SDmgw
I	1281	MV	pclastic myl ogn	051 36 SE									Dmwt
I	1282	MV	pclastic myl ogn	047 29 SE									Dmwt
I	1283	MV	pclastic myl ogn	056 59 SE									Dmwt

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lineation Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	1284	MV	mgw	040 32 SE									SDmgw
I	1285	MV	mgw	046 41 SE									SDmgw
I	1286	MV	ss	055 47 SE	19 217								SDss
I	1287	MV	ss	049 51 SE									SDss
I	1288	MV	ss	044 46 SE									SDss
I	1289	MV	ss	051 41 SE									SDss
I	1290	MV	ss	032 36 SE									SDss
I	1291	MV	ss	036 40 SE	7 059								SDss
I	1292	MV	ss	051 62 NW									SDss
I	1293	MV	ss	064 36 NW									SDss
I	1294	MV	ss	056 42 SE									SDss
I	1295	MV	ss	061 49 SE									SDss
I	1296	MV	ss	067 51 SE									SDss
I	1297	MV	ss	069 36 SE									SDss
I	1298	MV	mgw	038 34 SE									SDmgw
I	1299	MV	mgw/pclastic myl ogn	042 39 SE									SDmgw
I	1300	MV	mgw	051 56 SE									SDmgw
I	1301	MV	ss	048 51 SE									SDss
I	1302	MV	ss	055 47 SE	23 199								SDss
I	1303	MV	ss	057 41 SE									SDss
I	1304	MV	ss	046 57 SE									SDss
I	1305	MV	ss	055 59 SE									SDss
I	1306	MV	ss	063 60 SE									SDss
I	1307	MV	ss	032 58 SE						17 071			SDss
I	1308	MV	ss	059 65 SE	16 063								SDss
I	1309	MV	ss	045 55 SE									SDss
I	1310	MV	ss	049 62 SE						6 057			SDss
I	1311	MV	ss	066 62 SE									SDss
I	1312	MV	ss	044 49 SE									SDss
I	1313	MV	mgw	048 61 SE									SDmgw
I	1314	MV	mgw	038 55 SE									SDmgw
I	1315	MV	mgw	042 58 SE									SDmgw
I	1316	MV	ss	041 66 SE	8 052								SDss
I	1317	MV	ss	049 55 SE									SDss
I	1318	MV	ss	042 53 SE									SDss
I	1319	MV	ss	044 66 SE	3 046								SDss
I	1320	MV	ss	041 50 SE		16 216	041 50 SE	40-60 NW					SDss
I	1321	MV	ss	076 61 SE									SDss
I	1322	MV	ss	071 51 SE									SDss
I	1323	MV	ss	052 59 SE	6 059								SDss
I	1324	MV	ss	071 67 SE									SDss
I	1325	MV	ss	056 62 SE									SDss
I	1326	MV	ss	059 44 SE									SDss
I	1327	MV	ss	055 51 SE	10 066								SDss
I	1328	MV	ss	064 51 SE									SDss
I	1329	MV	ss	060 47 SE	6 063								SDss
I	1330	MV	ss	077 57 SE									SDss
I	1331	MV	ss	064 52 SE									SDss
I	1332	MV	ss	067 46 SE									SDss
I	1333	MV	ss	070 48 SE									SDss
I	1334	MV	ss	056 48 SE		19 063	056 48 SE	20-50 SE					SDss
I	1335	MV	ss	078 55 SE									SDss
I	1336	MV	ss	049 51 SE	12 057								SDss
I	1337	MV	pclastic ultmyl ogn	067 42 SE									hm
I	1338	MV	pclastic ultmyl ogn	052 61 SE									hm
I	1339	MV	pclastic ultmyl ogn	051 54 SE		16 059	051 54 SE	35-45 NW					hm
I	1340	MV	hbl ggd	037 49 SE									Opma
I	1341	MV	hbl ggd	058 42 SE	13 220								Opma
I	1342	MV	hbl ggd	059 56 SE									Opma
I	1343	MV	hbl ggd	064 51 SE									Opma
I	1344	MV	ss	074 69 SE									SDss
I	1345	MV	ss	079 50 SE									SDss
I	1346	MV	pclastic myl ogn	061 53 SE									Dmwt
I	1347	MV	pclastic myl ogn	059 57 SE									Dmwt
I	1348	MV	ss	063 67 SE	21 228								SDss
I	1349	MV	ss	055 52 SE									SDss
I	1350	MV	pclastic ultmyl ogn	043 55 SE		14 239	043 55 SE	20-45 NW					hm
I	1351	MV	ss	061 65 SE									SDss
I	1352	MV	pclastic ultmyl ogn	041 49 SE		16 203	041 49 SE	25-35 NW					hm
I	1353	MV	am	061 61 SE									Opma
I	1354	MV	ss	068 56 SE						3 073			SDss
I	1355	MV	pclastic myl ogn	044 51 SE									Dmwt
I	1356	MV	ss	059 66 SE	1 061								SDss
I	1357	MV	ss	073 59 SE									SDss
I	1358	MV	pclastic ultmyl ogn	064 58 SE									hm
I	1359	MV	pclastic ultmyl ogn	056 59 SE		21 236	056 59 SE	25-35 NW					hm
I	1360	MV	pclastic ultmyl ogn	067 64 SE									hm
I	1361	MV	pclastic ultmyl ogn	070 58 SE									hm
I	1362	MV	hbl ggd	063 61 SE									Opma
I	1363	MV	hbl ggd	059 57 SE	18 072								Opma
I	1364	MV	hbl ggd	060 55 SE									Opma
I	1365	MV	pclastic ultmyl ogn	075 51 SE									hm
I	1366	MV	pclastic ultmyl ogn	070 59 SE									hm
I	1367	MV	pclastic ultmyl ogn	072 59 SE									hm
I	1368	MV	pclastic ultmyl ogn	062 61 SE									hm
I	1369	MV	ss	060 57 SE	13 226								SDss
I	1370	MV	pclastic ultmyl ogn	055 40 SE									hm
I	1371	MV	pclastic ultmyl ogn	062 45 SE									hm
I	1372	MV	hbl ggd	074 49 SE	11 243								Opma
I	1373	MV	pclastic ultmyl ogn	075 77 SE									hm
I	1374	MV	pclastic ultmyl ogn	057 54 SE									hm
I	1375	MV	pclastic ultmyl ogn	050 58 SE									hm
I	1376	MV	pclastic ultmyl ogn	059 52 SE									hm
I	1377	MV	hbl ggd	055 44 SE									Opma
I	1378	MV	hbl ggd	040 41 SE									Opma
I	1379	MV	hbl ggd	058 55 SE	5 236								Opma
I	1380	MV	ss	047 42 SE									SDss
I	1381	MV	ss	035 41 SE	19 208								SDss
I	1382	MV	ss	080 46 SE									SDss
I	1383	MV	ss	054 45 SE									SDss
I	1384	MV	ss	056 35 SE									SDss
I	1385	MV	ss	069 39 SE									SDss
I	1386	MV	hbl ggd	066 41 SE									Opma
I	1387	MV	hbl ggd	064 39 SE									Opma
I	1388	MV	hbl ggd	058 44 SE									Opma
I	1389	MV	hbl ggd	051 41 SE									Opma
I	1390	MV	hbl ggd	069 53 SE	10 234								Opma

Domain	Station	Quad	Lithology	Foliation (S) Strike Dip	Lination Plunge Trend	Fold Axis Plunge Trend	Axial Surface Strike Dip	IL Angle	Fold Verg.	Crenulation Axis Plunge Trend	Joint Strike Dip	Joint Strike Dip	Map Unit
I	1498	MV	hbl ggd	064 53 SE	20 231								Opma
I	1499	MV	hbl ggd	049 60 SE									Opma
I	1500	MV	hbl ggd	052 57 SE									Opma
I	1501	MV	hbl ggd	059 51 SE	16 228								Opma
I	1502	MV	hbl ggd	058 47 SE									Opma
I	1503	MV	hbl ggd	051 55 SE									Opma
I	1504	MV	hbl ggd	053 49 SE	4 230								Opma
I	1505	MV	hbl ggd	047 37 SE									Opma
I	1506	MV	hbl ggd	055 42 SE									Opma
I	1507	MV	hbl ggd	061 56 SE									Opma
I	1508	BM	hbl ggd	050 49 SE									Opma
I	1509	MV	hbl ggd	059 52 SE									Opma
I	1510	MV	hbl ggd	046 61 SE	11 056								Opma
I	1511	MV	hbl ggd	049 57 SE									Opma
I	1512	MV	hbl ggd	055 59 SE									Opma
I	1513	MV	hbl ggd	061 52 SE	1 062								Opma
I	1514	MV	hbl ggd	049 57 SE									Opma
I	1515	MV	hbl ggd	053 66 SE									Opma
I	1516	MV	hbl ggd	051 55 SE									Opma
I	1517	MV	hbl ggd	066 49 SE	1 238								Opma
I	1518	MV	ms	067 51 SE									gms
I	1519	MV	ms	058 44 SE	6 061								gms
I	1520	MV	ms	071 55 SE	18 245								gms
I	1521	MV	pclastic mgw	059 47 SE									Ctf
I	1522	MV	ms	068 49 SE	16 239								gms
I	1523	MV	pclastic mgw	065 57 SE									Ctf
I	1524	MV	pclastic mgw	061 52 SE	10 070								Ctf
I	1525	MV	pclastic mgw	066 45 SE									Ctf
I	1526	MV	pclastic mgw	063 39 SE									Ctf
I	1527	MV	pclastic mgw	078 48 SE									Ctf
I	1528	MV	pclastic mgw	056 39 SE	2 056								Ctf
I	1529	MV	pclastic mgw	064 43 SE									Ctf
I	1530	MV	pclastic mgw	073 55 SE									Ctf
I	1531	MV	pclastic mgw	071 59 SE									Ctf
I	1532	MV	pclastic mgw	060 64 SE									Ctf
I	1533	MV	ms	057 63 SE									gms
I	1534	MV	pclastic mgw	065 57 SE									Ctf
I	1535	MV	pclastic mgw	063 49 SE									Ctf
I	1536	MV	pclastic mgw	056 66 SE									Ctf
I	1537	MV	pclastic mgw	049 54 SE									Ctf
I	1538	MV	pclastic mgw	067 61 SE									Ctf
I	1539	MV	pclastic mgw	069 53 SE									Ctf
I	1540	MV	ms	064 48 SE	16 073								gms
I	1541	MV	ms	061 52 SE	7 065								gms
I	1542	MV	pclastic mgw	056 51 SE									Ctf
I	1543	MV	pclastic mgw	062 60 SE									Ctf
I	1544	MV	pclastic mgw	057 59 SE									Ctf
I	1545	MV	pclastic mgw/ms	069 51 SE	12 077								Ctf
I	1546	MV	pclastic mgw	059 66 SE									Ctf
I	1547	MV	pclastic mgw	046 55 SE	10 060								Ctf
I	1548	MV	pclastic mgw	049 58 SE									Ctf
I	1549	MV	pclastic mgw	046 44 SE									Ctf
I	1550	MV	pclastic mgw	051 49 SE									Ctf
I	1551	MV	pclastic mgw	066 61 SE									Ctf
I	1552	MV	pclastic mgw	074 59 SE									Ctf
I	1553	MV	pclastic mgw	068 66 SE	9 240								Ctf
III	1554	MV	bi gtd	070 35 SE									Oh
III	1555	MV	bi gtd	069 29 SE									Oh
III	1556	MV	bi gtd	071 23 SE									Oh
III	1557	MV	ss	068 52 SE									SDss
III	1558	MV	myl pclastic ogn	064 47 SE									Dmwt
III	1559	MV	myl pclastic ogn	066 52 SE									Dmwt
III	1560	MV	ss	073 61 SE									SDss
III	1561	MV	ss	077 59 SE									SDss
III	1562	MV	ss	082 31 SE									SDss
III	1563	MV	bi gtd	080 36 SE									Oh
III	1564	MV	bi gtd	077 41 SE									Oh
III	1565	MV	bi gtd	066 42 SE									Oh
III	1566	MV	bi gtd	049 56 SE									Oh
III	1567	MV	bgn/mgw	072 52 NW		8 237	050 59 NW	5 25	SE				SDmgw
III	1568	MV	bgn/mgw	060 41 NW									SDmgw
III	1569	MV	bgn/mgw	074 37 NW									SDmgw
III	1570	MV	bgn/mgw	066 52 NW									SDmgw
III	1571	MV	bgn/mgw	069 61 NW									SDmgw
III	1572	MV	bgn/mgw	074 57 NW									SDmgw
III	1573	MV	bgn/mgw	057 66 NW									SDmgw
III	1574	MV	bgn/mgw	064 44 NW									SDmgw
III	1575	MV	bgn/mgw	081 54 NW									SDmgw
III	1576	MV	ggw	055 46 NW	12 243								Sbc
III	1577	MV	ggw	072 39 NW									Sbc
III	1578	MV	ggw	306 18 NE									Sbc
III	1579	MV	ggw	057 50 SE									Sbc
III	1580	MV	ggw	068 55 SE									Sbc
I	1581	MV	ggw	049 39 SE	3 220								Sbc
I	1582	MV	ggw	038 36 SE									Sbc
I	1583	MV	ggw	052 57 SE									Sbc
I	1584	MV	ggw	057 51 SE	7 225								Sbc
III	1585	MV	ggw	072 49 NW	2 057								Sbc
III	1586	MV	ggw	088 33 NW									Sbc
III	1587	MV	ggw	335 21 NE									Sbc
III	1588	MV	bgn/mgw	279 44 NE									SDmgw
III	1589	MV	bgn/mgw	077 50 SE	9 240								SDmgw
I	1590	MV	bgn/mgw	049 31 SE	1 227								Dmwt
I	1591	MV	bgn/mgw	055 39 SE	1 235								Dmwt
I	1592	MV	bgn/mgw	057 42 SE	1 057								Dmwt
I	1593	MV	bgn/mgw	060 36 SE	3 060								Dmwt
I	1594	MV	bgn/mgw	040 40 SE									Dmwt
I	1595	MV	bgn/mgw	044 49 SE	4 214								Dmwt
I	1596	MV	ss	049 52 SE									SDss
I	1597	MV	ss	041 66 SE									SDss
I	1598	MV	mgw	046 51 SE									SDmgw
I	1599	MV	ss	039 42 SE									SDss
I	1600	MV	myl pclastic ogn	051 55 SE	1 053								Dmwt
I	1601	MV	bgn/mgw	048 39 SE									SDmgw
I	1602	MV	ss	042 46 SE									SDss
I	1603	MV	hbl ggd	051 40 SE							068 60 SE		Opma
I	1604	MV	hbl ggd	062 59 SE							355 84 NE	049 66 SE	Opma

Domain	Station	Quad	Lithology	Foliation (S)		Lineation		Fold Axis		Axial Surface		IL	Fold	Crenulation Axis		Joint		Joint		Map
				Strike	Dip	Plunge	Trend	Plunge	Trend	Strike	Dip	Angle	Verg.	Plunge	Trend	Strike	Dip	Strike	Dip	Unit
I	1712	MV	gms	077	70 SE															gms
I	1713	MV	gms	061	66 SE	4	068													gms
I	1714	MV	gms	066	54 SE	19	229													gms
I	1715	MV	gms	064	68 SE	34	236													gms
I	1716	MV	myl pelastic ogn					15	234	046	64 SE	0-30	NW							Oh
I	1717	WK	gms	044	66 SE			22	046				NW			276	74 NE			gms
I	1718	WK	myl pelastic ogn	060	49 SE															Oh
I	1719	MV	myl pelastic ogn	054	41 SE															Oh
I	1720	WK	myl pelastic ogn	048	51 SE											321	86 SW			Oh
I	1721	WK	myl pelastic ogn	061	58 SE											326	77 SW			Oh

Vita

Matt Gatewood was born and raised in north Mobile, Alabama. A love of natural science, engineering, and the outdoors was manifested in the early years by hobbies including camping, fishing, playing guitar, and the study of marine and wildlife biology. After graduating from Satsuma High School in 1996, Matt attended the University of South Alabama. A career in geology was begun upon the realization that the earth sciences offered the potential for field-based research in the natural sciences. Matt graduated from the University of South Alabama in 2002 and subsequently entered the University of Tennessee to begin graduate work in tectonics and structural geology. In Fall, 2006 Matt moved to Tuscaloosa, AL to begin work on a Ph.D. in geology. His dissertation will focus on the process of garnet nucleation and its tectonic implications.