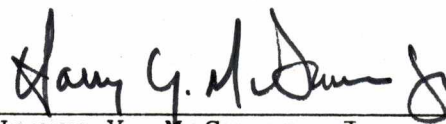


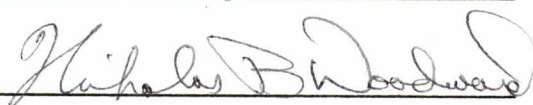
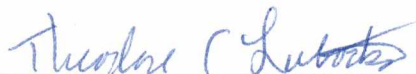
To the Graduate Council:

I am submitting herewith a thesis written by Bobby Steven Absher entitled "Petrogenesis of Granulite Facies Rocks at Winding Stair Gap, North Carolina Blue Ridge." I have examined the final 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.



Harry Y. McSween, Jr.
Major Professor

We have read this thesis and
recommend its acceptance:



Accepted for the Council:



The Graduate School

PETROGENESIS OF GRANULITE FACIES ROCKS
AT WINDING STAIR GAP, NORTH CAROLINA
BLUE RIDGE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Bobby Steven Absher

March 1984

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ABSTRACT

Granulite facies rocks in the thermal core of Paleozoic (Taconic) metamorphism are exposed in southwestern North Carolina in a 370 m long road cut at Winding Stair Gap. Lithologic units are primarily composed of metasedimentary and metavolcanic rocks. Prograde conditions of $T = 750^{\circ}\text{--}775^{\circ}\text{C}$; $P = 6.5\text{--}7.0\text{ kb}$ were determined from mineral stability fields and exchange geothermometry/geobarometry. Plutons emplaced within the Hayesville thrust sheet during the Taconic orogeny are the inferred heat source. Partitioning of water into anatectic melts of quartzo-feldspathic gneiss and garnet-sillimanite schist units resulted in $P_{\text{H}_2\text{O}} < P_{\text{total}}$ during the prograde event. An isobaric cooling path, from metamorphic peak to 600°C , may be related to extrusion of partial melts from Winding Stair Gap in the form of pegmatites and trondhjemite dikes emplaced at higher structural levels. Limited retrograde effects were facilitated by the release of water from crystallization of remaining in situ melts at $T < 700^{\circ}\text{C}$.

Structural mapping of Winding Stair Gap and the surrounding area indicates three periods of deformation occurred before, during, and after peak metamorphism. Reconstruction of the predeformation stratigraphy suggests five of the six lithologic units belong to the Tallulah Falls Formation or the upper part of the Coweeta Group. The

sixth unit, an orthopyroxenite, may be related to structurally emplaced ophiolitic slices occurring elsewhere in the Hayesville thrust sheet. Mineral assemblages in the mafic granulites suggest the granulite facies rocks at Winding Stair Gap are different from Precambrian granulite facies rocks.

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1. Geology of the Winding Stair Gap Area . . . In Pocket

I. INTRODUCTION

Significance of Study

Granulite facies rocks represent the high temperature extreme of regional metamorphism. The widespread occurrence of granulite facies terranes in Precambrian shield areas may be related to presumably higher geothermal gradients. The presence of granulite facies rocks in younger metamorphic belts is relatively uncommon. Estimated pressures for many granulite and amphibolite facies terranes are similar (Bohlen, 1983), suggesting the higher temperatures necessary for granulite facies metamorphism are derived from additional heat sources rather than increased burial depth. In addition to an increase in temperature, most granulite facies rocks show evidence of low P_{H_2O} . Two mechanisms for lowering P_{H_2O} which have been the subject of much debate are the influx of CO_2 (Wendlandt, 1981; Janardhan and others, 1982; Newton and Hansen, 1983) and the removal of water during metamorphism (Phillips, 1980; Wells, 1980; Valley, 1983). Convincing examples of each mechanism have been described for individual granulite localities.

One of the post-Precambrian granulite terranes, heretofore undescribed, occurs in the Blue Ridge Province of the southern Appalachians. The most accessible and best exposed examples of these rocks are at Winding Stair Gap in

southwestern North Carolina. Six different lithologic units contained in a continuous, 370 m long road cut provide critical information necessary to determine the conditions of granulite facies metamorphism and to construct prograde and retrograde paths in P - T - X_{H_2O} space. This information has been used to specify the nature of the additional heat source and to determine the most likely mechanism for lowering P_{H_2O} .

The Paleozoic metamorphic rocks in the Blue Ridge of the southern Appalachians have been described as a classic Barrovian sequence by Carpenter (1970), Hadley and Nelson (1971), Hatcher (1972), and Hurst (1973). Winding Stair Gap is located at the southwestern edge of the Hyp* (hypersthene) isograd (fig. 1) mapped by Force (1976) within the thermal core of the Taconic metamorphism. The only other granulite facies rocks in the Blue Ridge are the Precambrian (Grenville) basement in North Carolina and Virginia (Morgan, 1972; Hatcher and others, 1980; Gulley and Monrad, 1983). The presence of granulite facies rocks formed during the Taconic orogeny is an additional factor to consider in modeling the tectonic history of the southern Appalachians.

*Mineral abbreviations used throughout the text are presented in Appendix A.

Figure 1. Regional geology of southwestern North Carolina and northeastern Georgia. Isograd locations are from Hadley and Nelson (1971) above 35°N and Hurst (1973) below 35°N, except for the Hyp isograd from Force (1976). Fault locations and unit contacts are from Hatcher and Butler (1979).

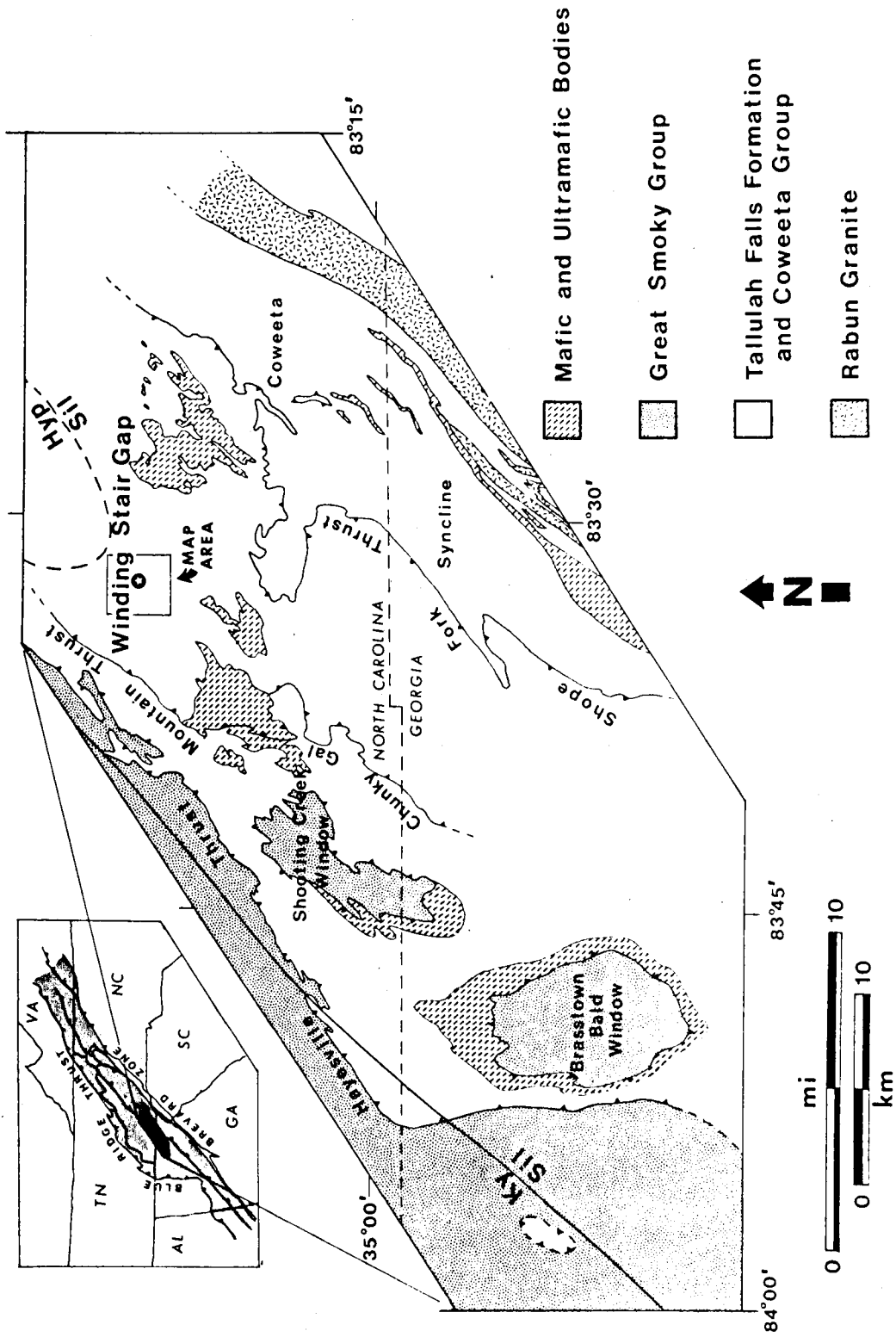


Figure 1.

Field and Analytical Methods

The Winding Stair Gap exposure, opened in 1978, is on U.S. Hwy. 64 eleven miles south of Franklin, North Carolina. The north side of the Winding Stair Gap exposure was mapped (scale = 1:4000) using a photomosaic to show detailed structural and stratigraphic relationships. Photographs were taken at 10 m intervals from a distance of 30 m. The distorted image was divided into a system of equal area grids (Bonne projection), and the information was transferred to orthogonal coordinates in which original angular and linear relationships are preserved. The south side of the exposure was studied but not mapped in detail. Field mapping of the Winding Stair Gap area utilized topographic base maps of the Rainbow Springs and Wayah Bald 7.5' quadrangles.

Over 100 thin sections from samples collected at Winding Stair Gap, cut perpendicular to foliation, were examined in transmitted light. Twenty polished thin sections were examined in both transmitted and reflected light. Sample locations and petrographic descriptions for the thin sections are presented in Appendix B. Compositions for the major minerals in representative samples of the six lithologies were determined using an automated MAC 400S electron microprobe with an accelerating voltage of 15 kV. Correction procedures were those of Bence and Albee (1968)

utilizing the data of Albee and Ray (1970). Grt and Fe-Ti oxide samples were analyzed using a beam current of 0.05 μA and a beam diameter of 1 μm . Fsp, Scp, Bt, Hbl, and Opx were analyzed using a slightly defocused beam and a beam current of 0.03 μA . Multiple analyses of the same grain to assess instrument precision and analysis of cores and rims of grains to document zonation were standard procedures. Ferric iron in Grt, Hbl, Cum, and Fe-Ti oxide analyses were determined from stoichiometry and charge balance.

II. GEOLOGIC SETTING

Regional Geology

The Blue Ridge Belt of southwestern North Carolina and northeastern Georgia is composed of meta-igneous and meta-sedimentary units separated from the Valley and Ridge Province to the west by the Great Smoky-Cartersville Fault and from the Inner Piedmont to the east by the Brevard Fault Zone. Numerous windows, such as Grandfather Mountain (Bryant and Reed, 1970), Wear, Tuckaleechee, and Cades Coves (King and others, 1968), Brasstown Bald and Shooting Creek (Hatcher and Butler, 1979), exposing low-grade metamorphic rocks overlain by higher grade rocks attest to the allochthonous nature of the southern Blue Ridge. COCORP seismic reflection data suggest a master decollement beneath the southern Blue Ridge extending eastward at least to the Kings Mountain Belt (Williams, 1980; Iverson and Smithson, 1983) and possibly as far as the Coastal Plain (Cook and others, 1979; Harris and Bayer, 1979). Westward movement of the Blue Ridge sheet has been estimated at between 56 km (Harris and Bayer, 1979) and 260 km (Cook and others, 1979). Blue Ridge rocks overlying Mississippian-age rocks indicates thrusting along the decollement was active at least until the Late Paleozoic (King and others, 1968).

Within the southern Blue Ridge sheet, the premeta-morphic Hayesville Fault (Hatcher and others, 1979) (fig. 1)

signifies a major break between continental crust/shelf metasedimentary rocks to the west and continental slope/ocean basin metasedimentary rocks containing possible ophiolitic material to the east (Hatcher, 1978; Hatcher and Butler, 1979; Hatcher and others, 1979). Grenville-age basement rocks (Long and others, 1959; Hurst, 1973; Fullagar and others, 1979) are absent east of the Hayesville Fault except within the Tallulah Falls Dome (Hatcher, 1973) and Toxaway Dome (Fullagar and others, 1979). Metasedimentary rocks of the Great Smoky Group are confined west of the Hayesville Fault except for occurrences within the Brasstown Bald and Shooting Creek Windows (Hatcher and Butler, 1979; Hatcher and others, 1979). The Tallulah Falls Formation and Coweeta Group occur east of the Hayesville Fault (fig. 1) along with most of the mafic and ultramafic rocks and Paleozoic granitic plutons of northeastern Georgia and southwestern North Carolina (Rankin, 1975; Hatcher, 1978; Misra and Keller, 1978). The Hayesville Fault may be a thrust rooted in the master decollement (Hatcher, 1978; Cook and others, 1980; Hatcher and Zietz, 1980; Furman and Mancuso, 1982). Other major faults in this area (fig. 1) include the pre- to synmetamorphic Shope Fork Thrust (Hatcher, 1976; 1978; 1981) and the syn- to postmetamorphic Chunky Gal Mountain Thrust (Hatcher, 1978; Hatcher and Butler, 1979; Kuntz and Hedge, 1981; McElhaney and McSween, 1983).

The area in which the Winding Stair Gap exposure occurs was originally mapped as Carolina Gneiss (mica gneiss) and Roan Gneiss (Hbl gneiss) by Keith (1907). Hadley and Nelson (1971) mapped the area as Bt-Qtz-Pl schist and gneiss with thin interlayers of metasandstone and amphibolite. Larger mafic and ultramafic bodies surrounding the Winding Stair Gap area (fig. 1, p. 3) were mapped as amphibolite, ultramafic intrusive rocks, and mafic intrusive rocks. More recently the region between the Chunky Gal Mountain and Shope Fork Faults has been assigned to the Tallulah Falls Formation and Coweeta Group (Hatcher and Butler, 1979).

The Tallulah Falls Formation is an assemblage of meta-sedimentary and mafic metavolcanic rocks of Late Precambrian age equivalent to the Sandy Springs Formation to the southwest (Higgins, 1966) and the Ashe Formation to the northeast (Rankin, 1970; Rankin and others, 1973). The stratigraphic sequence is composed of a lowermost amphibolite-Bt gneiss member successively overlain by pelitic schist and Bt gneiss members (Hatcher, 1971; 1973; 1976).

Stratigraphically above the Tallulah Falls Formation is a sequence of cleaner, Upper Precambrian or Lower Paleozoic metasedimentary and possibly metavolcanic rocks classified as Coweeta Group and described by Hatcher (1980; 1981). The Coweeta Group may be time-equivalent to the Chilhowee Group and Murphy belt sedimentary rocks to the west and the

Alligator Back Formation to the northeast (Hatcher, 1981). The Persimmon Creek Gneiss, the lowest member of the Coweeta Group, is a Bt gneiss with interlayered metasandstone and pelitic schist. The Coleman River Formation, consisting of metasandstone and meta-arkose with minor calc-silicate quartzite and pelitic schist, overlies the Persimmon Creek Gneiss. The uppermost member, the Ridgepole Mountain Formation, contains a highly variable assemblage of pelitic schist, garnetiferous metasandstone, quartzite, and Bt schist. Amphibolite and Hbl gneiss occur as interlayers in the Coweeta Group and probably represent mafic dikes and sills (Hatcher, 1980).

Description and Distribution of Lithologies

Metasedimentary units at Winding Stair Gap include Bt-Grt granulite, calc-silicate gneiss, Sil schist, and quartzo-feldspathic gneiss. Grt-bearing quartzo-feldspathic gneiss has been migmatized and locally mobilized into small felsic intrusive bodies. Meta-igneous units include Bt-Hbl granulite and orthopyroxenite.

Mapping of the Winding Stair Gap exposure (fig. 2) places Sil schist and Bt-Hbl granulite in intimate association at the northeastern end of the exposure. Bt-Grt granulite and calc-silicate gneiss occur at the southwestern end of the exposure. Orthopyroxenite occurs with the Bt-Grt

Winding Stair Gap

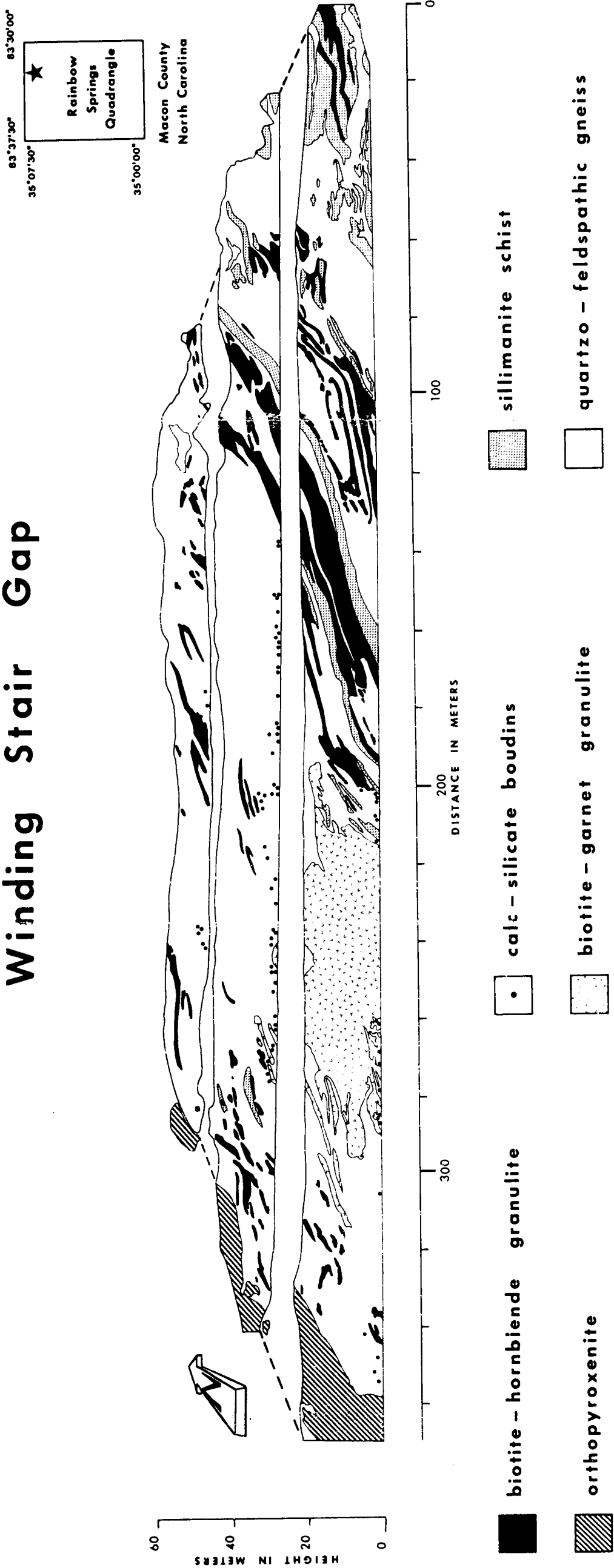


Figure 2. Sketch map of the north side of the Winding Stair Gap exposure showing the distribution of lithologic units. The exposure occurs as three tiers, each recessed from the one below by approximately 5 m.

granulite and calc-silicate gneiss units, but its relationship to the original stratigraphic sequence, if any, is unclear. Quartzo-feldspathic gneiss, volumetrically the most important unit at Winding Stair Gap, occurs throughout the exposure.

A 10 km² area in the Rainbow Springs and Wayah Bald quadrangles (plate 1), with the Winding Stair Gap exposure near the center, was mapped to determine the larger-scale structural and stratigraphic setting for the road cut. Exposure in the field area is too poor to allow mapping of boundaries between individual stratigraphic units. However, locations of outcrops other than the quartzo-feldspathic gneiss, in the field and along logging road excavations, allow a possible contact between two stratigraphic packages to be traced laterally. Sil schist and Bt-Hbl granulite are confined to the northeast of a line trending W-NW through the Winding Stair Gap exposure. Bt-Grt granulite, calc-silicate gneiss, and orthopyroxenite units are confined to the southwest (plate 1).

The Sil schist unit, composed chiefly of Bt, Grt, Sil, Pl, and Kfs, is generally confined to the northeastern half of the Winding Stair Gap exposure, although isolated blocks (1-10 m length) in the quartzo-feldspathic gneiss occur in the southwestern half. The strong planar fabric produced by Bt and coarse-grained Sil needles (fig. 3a) is interrupted

Figure 3. Photomicrographs of representative samples of Winding Stair Gap units. The scale bar at bottom center is the same for a-f.

a. Sil schist with Bt, Grt, and Sil adjacent to Kfs and Qtz segregations. The strong foliation formed by Bt and Sil orientation, approximately horizontal in the photomicrograph, represents S_2 . X-nicols.

b. Bt-Hbl granulite with Bt, Hbl, Pl, Qtz, and abundant Ilm.

c. Weakly-foliated quartzo-feldspathic gneiss showing mortar texture of large Fsp porphyroclasts mantled by smaller Qtz and Fsp grains. X-nicols.

d. Bt-Grt granulite showing Hbl, Bt, Pl, Qtz, and Opx.

e. Calc-silicate gneiss adjacent to quartzo-feldspathic gneiss. Minerals include Grt, Cal, Qtz, Scp, and Hbl.

f. Orthopyroxenite with large Opx and smaller Bt and Pl. Opaque phases are Po, Py, and Ccp.

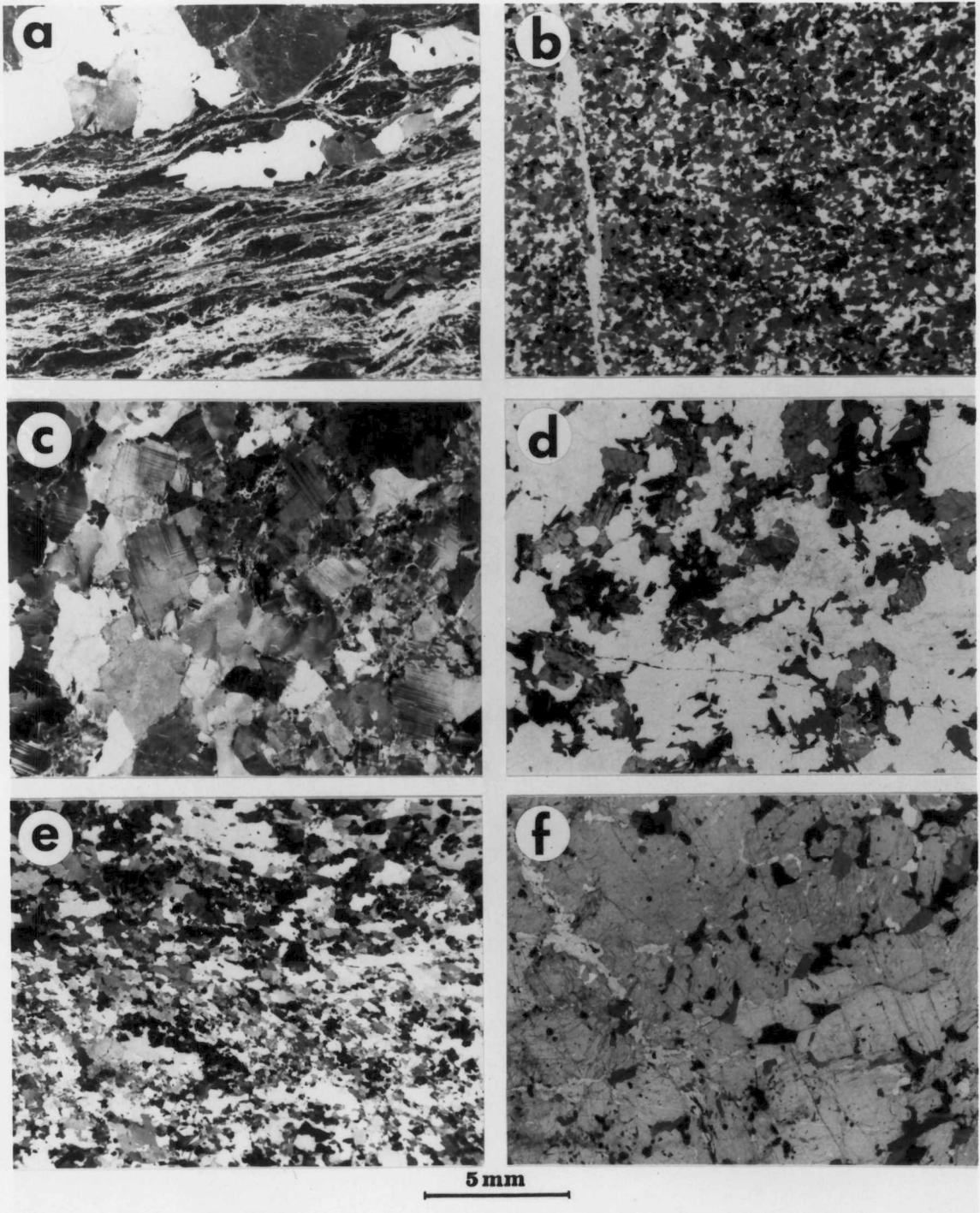


Figure 3.

by monomineralic segregations of Grt. The froth-textured Grt zones, composed of monomineralic segregations of very small Grt (less than 0.5 mm dia.) which give the appearance of froth, are commonly confined to the hinges of isoclinal recumbent folds. Elongate lenses of microperthitic Kfs, generally sigmoidally-shaped, occur within the Sil schist near contacts with nonfoliated quartzo-feldspathic gneiss. The irregular, lenticular bodies of Kfs form a macroscopic texture like that of the protometatexite stage of migmatization, characterized by irregular podiform to lensoid leucosome segregations which have not coalesced into continuous, foliation-controlled layers (Breaks and Bond, 1982). Field exposures of Sil schist outside of Winding Stair Gap are uncommon and are generally preserved only where sandwiched between more resistant quartzo-feldspathic layers.

Bt-Hbl granulite is a greenish-gray, fine- to medium-grained granoblastic rock occurring as 1-5 m thick bands closely associated in isoclinal recumbent folds with Sil schist and as enclaves (1-40 m long; 0.5-2 m wide) surrounded by quartzo-feldspathic gneiss. The enclaves occur as discontinuous segments probably representing an originally continuous layer disaggregated during deformation. The enclaves are generally confined to the southwestern half and upper two tiers of the Winding Stair Gap

exposure. Outside of the Winding Stair Gap exposure, Bt-Hbl granulite is rarely exposed, but flattened, palm-sized fragments are occasionally preserved as float. Bt-Hbl granulite (fig. 3b) is composed of equigranular Hbl, Bt, Pl, and Qtz. Opx, Grt, and Cum are commonly present, with minor amounts of Mag, Po, and Py. Ilm is a common opaque phase, occasionally comprising as much as 5 volume % of the rock.

The quartzo-feldspathic gneiss is the most resistant unit in the Winding Stair Gap area, supporting all of the topographic highs. The quartzo-feldspathic gneiss is composed of Qtz, Kfs, Pl, Bt, and Grt and exhibits wide variability in textures, type and amount of accessory minerals, and field relationships. One textural end-member of the unit is a well-foliated metatexite migmatite (Mehnert, 1968) characterized by a conspicuous gneissic appearance of leucosome segregations (0.5-2.0 cm wide) and thinner Bt-Grt bands (0.2-0.5 mm wide). The prominent light- and dark-colored bands are often continuous and parallel for a distance of several meters before culminating in chaotic swirls. Gneissic banding and Bt foliation are parallel to the dominant schistosity at Winding Stair Gap, S_2 (a more detailed discussion of structural features follows). Intrafolial folds probably represent a transposed S-surface. Sil is the only alumino-silicate mineral in the migmatite, occurring as coarse-grained Sil in the Bt-Grt

restite but more commonly as fibrolite along smoothly-curved, Fsp grain boundaries. Coarse-grained Ms is absent, although sericite alteration of Fsp occurs sporadically. Mag and Ilm are the common opaque phases. The metatexite migmatite probably formed as a part of the prograde event because of the presence of coarse-grained Sil, absence of primary Ms, and the well-developed gneissic banding.

Weakly-foliated Bt- and Grt-bearing quartzo-feldspathic gneiss of granitic to granodioritic composition occur as discordant bands of variable thickness. Mortar texture, in which large, deformed Pl and Kfs porphyroclasts are wrapped by a finer-grained matrix of Fsp, Qtz, and phyllosilicate minerals, is common in the weakly-foliated granofels (fig. 3c). Mortar texture and deformed Fsp grains may indicate an early stage of cataclasis in the quartzo-feldspathic gneiss. Alternatively, cores of grains mantled by subgrains may be indicative of incipient schistosity development (Borradaile, 1982). Fsp grains not exhibiting mortar texture have smoothly-curved boundaries, but associated Qtz generally has embayed or amoeboid boundaries. Fibrolitic Sil is often present along Pl and Kfs grain boundaries, but coarse-grained Sil is absent. Ms occurs as alteration bands along cleavage planes in Fsp and along Fsp grain boundaries. Mag and Ilm are commonly present.

Nonfoliated granofels of granitic to granodioritic composition, sometimes Ky-bearing, appears to be the

youngest quartzo-feldspathic gneiss member, cutting across migmatitic gneiss, weakly-foliated granofels, and other lithologic units. Coarse-grained Ms is common, often comprising 5 volume % of the rock. Rounded inclusions of Pl, Kfs, and Qtz are common within larger Pl and Kfs grains. Ilmeno-hematite and hemo-ilmenite are the iron-titanium oxide minerals. The nonfoliated quartzo-feldspathic rocks at Winding Stair Gap appear to be in situ melts (neosome) rather than intrusive bodies injected from an outside source area. Contacts between different generations of quartzo-feldspathic gneiss are commonly difficult to distinguish and are commonly gradational, suggesting little or no difference in temperature between the melt and the surrounding rock. Those granitic bodies that can be distinguished from the surrounding quartzo-feldspathic gneiss are small (less than 10 m length) and are completely enclosed within the surface exposed by the road cut.

The Bt-Grt granulite, a dark greenish-gray, composite unit containing a Hbl-Bt-Opx assemblage (fig. 3d, p. 13) and a Bt-Grt-Hbl assemblage, is exposed at the southwestern end of the Winding Stair Gap outcrop. The Bt-Grt granulite unit appears only at the lowermost level and base of the second tier. Coarse-grained Bt and large, poikiloblastic Grt (1-5 cm dia.) are diagnostic of the unit. The Bt-Grt granulite is readily distinguished in the field by the salt

and pepper weathering surface produced by Pl and Bt and by the presence of large Grt grains. Bt-Grt granulite is exposed outside Winding Stair Gap along a logging road northeast of Rattlesnake Gap and along the Appalachian Trail southeast of Rocky Cove Knob.

The calc-silicate gneiss occurs as zoned boudins rarely over 1 m long and 10 cm wide within quartzo-feldspathic gneiss. Calc-silicates represent a thin, boudinaged layer completely enclosing the Bt-Grt granulite unit. Some of the calc-silicate boudins have been folded and appear to have been rotated as much as 90° from the bedding orientation. Exposures of calc-silicate gneiss at Rattlesnake Gap and south of Panther Knob confirm the relationship between calc-silicate gneiss and Bt-Grt granulite observed at the Winding Stair Gap exposure. Scp, Grs, and Spn are diagnostic minerals in the Qtz- and Cal-rich gneiss (fig. 3e, p. 13).

Concentric mineral zonation superimposed on mineralogical layering complicates the petrographic relationships in the calc-silicate boudins. Layering occurs as rod-like segregations of dark-colored minerals, usually Grt and Hbl, which form gneissic bands separated by Cal, Qtz, and Scp parallel to the long axes of the boudins. Other mafic minerals, such as Di and Czo, form mineralogical layers highly variable both within a particular boudin and between

lateral exposures of the same layer. The presence of abundant Grt produces boudins with yellow color; Hbl- and Czo-rich boudins are light green. The complexity of the layering patterns may be related to original inhomogeneities of the impure carbonate protolith rather than to metasomatic processes. The concentric zonation is a regular, sharp pattern which occurs at boundaries between quartzo-feldspathic gneiss and calc-silicate gneiss and may be related to metasomatism.

At the edge of the calc-silicate boudin, Cal, present only as a minor accessory in the quartzo-feldspathic gneiss, is abundant. Pl becomes more calcic toward the calc-silicate unit, changing to Scp + Pl less than 2 cm from the outer boundary of the boudin. Grt composition changes from Alm in the quartzo-feldspathic gneiss to an Alm-Grs mixture in the calc-silicate. Spn is present in the calc-silicate gneiss; Ilm is the Ti-oxide mineral present in the quartzo-feldspathic gneiss.

The orthopyroxenite is a 15-20 m thick, dark brown, nonfoliated unit. Lenses (1-2 m long) composed almost entirely of Bt and Grt occurring near the edges of the orthopyroxenite unit probably represent alteration zones. Relict Opx grains surrounded by Pl are present in the Bt-Grt lenses. Minor Bt and Pl occur as interstitial phases between Opx grains (2-4 mm dia.) in unaltered samples (fig. 3f,

p. 13). Pinkish-green Pl-Qtz veins (1-8 cm wide) form a reticulated pattern throughout the orthopyroxenite unit. An increased abundance of Hbl and coarse-grained Bt adjacent to the Pl-Qtz veins indicates retrograde hydration of Opx. The Pl-Qtz veins, also present in enclaves of Bt-Hbl granulite, may be filling fractures produced by extension of the orthopyroxenite and Bt-Hbl granulite layers during folding. Cum, occurring along cleavage planes and as coronas around Opx, is in turn rimmed by Hbl, indicating both amphiboles are retrograde products.

Deformational Styles

The deformational features observed at Winding Stair Gap and in the surrounding area can be categorized as those coinciding with peak metamorphism, relicts of deformational events occurring prior to peak metamorphism, and deformation following peak metamorphism. In the field area, the dominant schistosity, S_2 , is frequently the only structural element preserved. The structural elements in the Winding Stair Gap exposure give an indication of the structural complexity of the area and are hopefully representative of the surrounding area.

The earliest structural element is compositional layering, S_0 . Within the Grt-Bt granulite unit, Hbl-Bt-Opx and Bt-Grt-Hbl assemblages represent different compositions.

A regular succession of Hbl-Bt-Opx and Bt-Grt-Hbl assemblages occur at the base of the Winding Stair Gap exposure between 215 m and 260 m (fig. 4). Unfortunately, the two assemblages are not readily distinguishable from a distance of more than several meters, so the exact location within the Bt-Grt granulite unit is not known. The Bt-Grt granulite is completely surrounded by calc-silicate gneiss boudins (fig. 4), providing another S_0 marker bed. The association of Bt-Grt granulite and calc-silicate gneiss is also present in the field area (plate 1). Calc-silicate gneiss and Bt-Grt granulite are confined southwest of a line extending E-W from Panther Knob to the Winding Stair Gap exposure. Sil schist and Bt-Hbl granulite are confined to an area northeast of the line. Because exposures of rock units other than quartzo-feldspathic gneiss are uncommon, the boundary between calc-silicate gneiss/Bt-Grt granulite and Sil schist/Bt-Hbl granulite is only an approximation.

The regular succession of Hbl-Bt-Opx and Bt-Grt-Hbl assemblages in the Bt-Grt granulite and the band of calc-silicate boudins completely enclosing the Bt-Grt granulite indicate the presence of a fold, F_1 (fig. 4). Although F_1 is shown as a single fold axis in figure 4, the repetition of assemblages in the Bt-Grt granulite unit could as easily be explained by several minor isoclinal folds oriented parallel to the F_1 axis. Boudinage of the calc-silicate

gneiss is probably related to extension along the outer arc of the fold. F_1 is transected by the dominant schistosity, S_2 , indicating F_1 occurred prior to peak metamorphism. The trace of the axial plane of the tight, upright to steeply inclined fold trends $N36^\circ W$ and plunges to the NW at 8° . Asymmetry of the Bt-Grt granulite unit suggests the F_1 fold has been refolded about an axis parallel to S_2 .

No direct evidence for the development of schistosity accompanying F_1 has been identified, although there is evidence of an earlier S-surface (S_0 ?) transposed by S_2 . Intrafolial folds, common within the quartzo-feldspathic gneiss, could be S_0 or possibly S_1 .

The dominant schistosity at the Winding Stair Gap exposure and the surrounding field area is defined by the parallel alignment of platy and acicular minerals, particularly Bt, Sil, and Hbl, and the development of gneissic banding. S_2 schistosity and gneissic banding are shown by the alignment of mineral grains in figures 3a and 3e (p. 13), respectively. At the Winding Stair Gap exposure, S_2 is oriented approximately $N45^\circ W$; 20° - 40° SW. S_2 has been mapped in the field area, generally as gneissic banding of quartzo-feldspathic gneiss (plate 1). The general orientation of S_2 in the field area is to the NE, dipping 30° - 80° NW. The alignment of prograde minerals, such as Sil and Bt, into a pervasive schistosity indicates the

deformational event producing S_2 occurred contemporaneously with peak metamorphism.

Isoclinal recumbent folds, F_2 , are best expressed at the northeast end of the Winding Stair Gap exposure in the Sil schist and Bt-Hbl granulite units. The axial planes of the isoclinal recumbent folds are oriented $N44^\circ-57^\circ W$; $20^\circ-40^\circ SW$, parallel to S_2 and nearly perpendicular to the outcrop face. F_2 also occurs as refolding of the previously described F_1 in the Bt-Grt granulite unit, folding of calc-silicate boudins at 200 m on the middle tier (fig. 4), and folding of the orthopyroxenite unit. Only the lower limb of the orthopyroxenite is preserved as fresh rock; the upper limb location was determined by soil mapping. Isoclinal recumbent folds are not commonly observed in the field area, presumably because of inadequate exposure.

Deformation following peak metamorphism and S_2 development is neither widespread nor pervasive. In the Sil schist unit, crenulations of Bt and Sil defining S_2 have been observed in thin section and in hand-specimen. Kfs lenses within the Sil schist are sometimes deformed into S-shaped bodies. Retrograde Ky and Ms occur in the Kfs lenses. F_3 deformation of the Kfs lenses must have occurred during or after retrograde metamorphism. Crenulation of retrograde Bt replacing Opx, observed microscopically and in hand-specimen at 245 m on the lowermost tier (fig. 4), also indicates F_3 occurred during or following retrograde metamorphism.

Deformation of S_2 in the field area is suggested by the map pattern to the north and southwest of Rocky Cove Knob and north of Rattlesnake Gap (plate 1). The only fold hinge exposed, located north of Rattlesnake Gap, is oriented $N48^\circ E$; plunging $80^\circ NE$. The relationship between the F_3 crenulation and folding of S_2 in the field area has not been determined.

Postmetamorphic brittle faults, suggested by Hatcher and Butler (1979), have not been observed to offset lithologic units at the scale of 1:4000 for the Winding Stair Gap exposure. A Kfs-rich vein (10-50 cm wide) in the Bt-Grt granulite unit (lowermost tier at 240-250 m) trending $N34^\circ W$ and dipping $71^\circ N$ may have been emplaced along a brittle fault. The Kfs-rich vein is bordered by a band of comminuted Pl, Qtz, and Bt, suggesting emplacement along a small shear zone. Coarse-grained Ms and sericite alteration of Kfs in the vein is common. Protomylonitic textures in the quartzo-feldspathic gneiss unit adjacent to the hinge zones of isoclinal recumbent folds located at 20 m on the middle tier (fig. 4) may represent minor cataclastic deformation.

Timing of Deformation and Metamorphism

The relative timing of deformational events at Winding Stair Gap can be related to metamorphism by the changes in

styles of deformation and by the presence or absence of foliation in parts of the quartzo-feldspathic gneiss. The earliest events, F_1 (and S_1 ?) predate the development of the migmatite gneiss. F_2 and S_2 , developed during peak metamorphism, are contemporaneous with metatexite migmatization. The weakly-foliated granofels probably crystallized late in the prograde metamorphic event or immediately following the metamorphic peak. The last deformation, F_3 , is associated with nonfoliated granitic rocks and retrograde minerals. F_3 and the retrograde phases do not appear to represent a separate, unrelated metamorphic and deformational episode, however. The extent of retrograde metamorphism is very limited at Winding Stair Gap, with most retrograde effects confined to the outer edges of the orthopyroxenite, Bt-Grt granulite, and Bt-Hbl granulite units. Crenulations do not develop a penetrative fabric, either at the Winding Stair Gap exposure or in the surrounding area. The F_3 event probably represents a minor deformational feature produced as the rocks cooled from the metamorphic peak.

The folding events recognized in the Winding Stair Gap area are consistent with regional patterns (fig. 5). The earliest fold and S-surface development at Winding Stair Gap possibly coincides with F_1 of Hatcher and Butler (1979). The EW trend of F_1 at Winding Stair Gap follows the regional trend of Early Paleozoic folds (Hadley and Goldsmith, 1963);

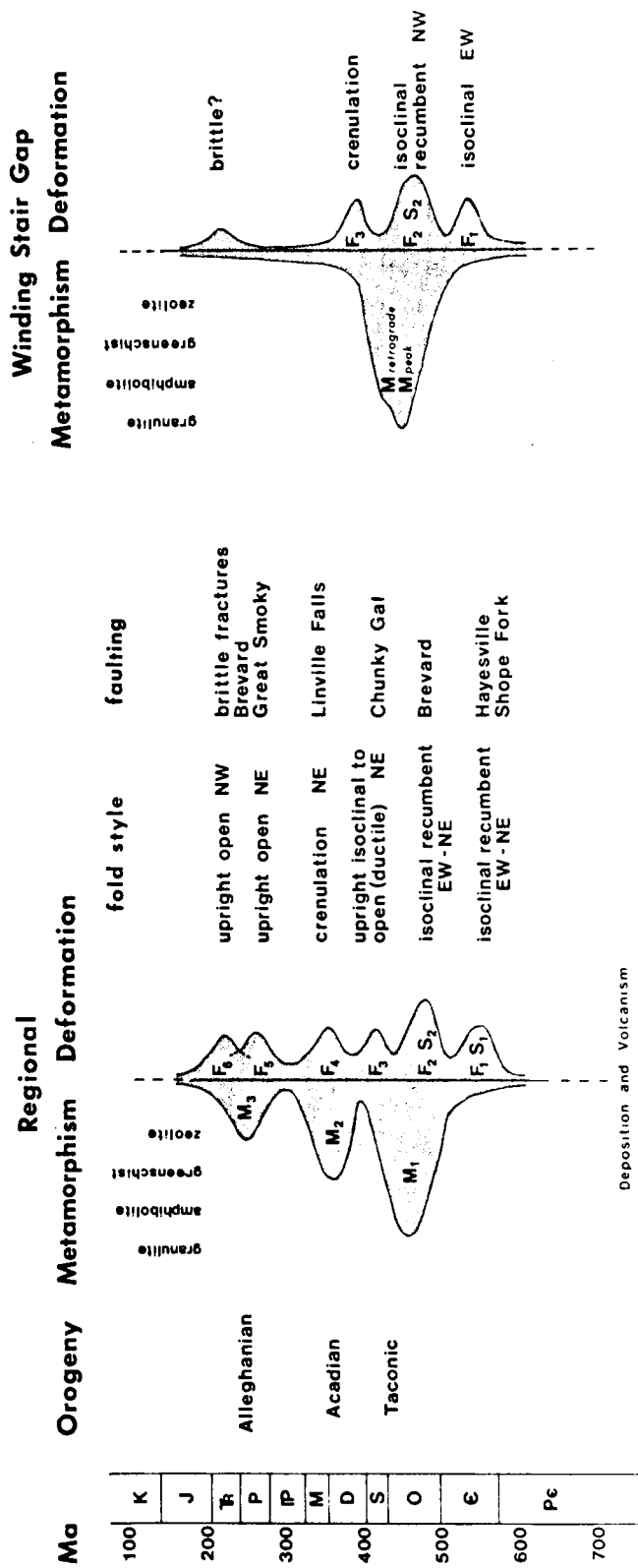


Figure 5. Comparison of regional metamorphic and deformational events with deformational and metamorphism interpreted for Winding Stair Gap. Data for regional deformational and metamorphic events has been synthesized from Hatcher and Butler (1979), Hatcher and others (1980), Butler and Fullagar (1982), and Glover and others (1983). Many of the regional events have been recognized only in localized areas of the Piedmont.

F_1 and S_1 have been interpreted as Taconic structures formed prior to peak metamorphism (Hatcher, 1976; Hatcher and Butler, 1979).

F_2 and S_2 at Winding Stair Gap may be equivalent to the F_2 folds and dominant S-surface of Hatcher and Butler (1979). The F_2 folds at Winding Stair Gap have EW to NW axial traces, whereas the regional F_2 orientation is EW to NE (fig. 5). The trend of S_2 is consistent with the mapped foliation orientation of Hadley and Nelson (1971). Hatcher and Butler (1979) interpreted F_2 and S_2 as Taconic features developed near the thermal peak of metamorphism.

The crenulation at Winding Stair Gap, F_3 , does not directly correlate with the regional F_3 event in either style of deformation or inferred timing (fig. 5). A regional F_4 crenulation, interpreted as Acadian by Hatcher and Butler (1979), may be related to F_3 at Winding Stair Gap, though a positive correlation is impossible based on the limited data available.

Absolute ages for metamorphism in the southern Appalachians indicate a Middle Ordovician (Taconic) event. Younger dates have been interpreted as an Acadian overprint by some authors, but the effect of Acadian metamorphism in the southern Blue Ridge, if any, is minor. Butler (1972) has suggested the major metamorphic event in the southern Appalachians occurred more than 430 m.y. ago based on K-Ar

and Rb-Sr dates of Bt, Ms, and Hbl. Kish (1982) has presented a 480 m.y. date based on whole rock K-Ar dating of slates. Younger whole rock K-Ar dates by Kish (1982) have been argued as the result of slow cooling or partial resetting by a younger metamorphic event. Dallmeyer (1975) and Sutter and Dallmeyer (1982), using incremental $^{40}\text{Ar}/^{39}\text{Ar}$ of Bt and Hbl, suggest a 480 m.y. date. Fullagar and Bottino (1970) argue the southern Blue Ridge metamorphism occurred prior to 475 m.y. ago. Metamorphism during the Taconic orogeny 450-500 m.y. ago (Rodgers, 1967) may be associated with a thick Middle Ordovician clastic wedge in east Tennessee derived from the east (Rodgers, 1967; Dallmeyer, 1975).

Later dates of Paleozoic metamorphism, 335-350 m.y. (Hadley, 1964), 350 m.y. (Long and others, 1959; Sutter and Dallmeyer, 1982), may be due to sustained high temperatures above the Ar^{40} , K-Ar, and Rb-Sr blocking temperatures for Bt, Hbl, and Ms (Hadley, 1964; Butler, 1972; Sutter, 1982; Kish, 1982). Devonian clastic rocks in east Tennessee, derived from a northern rather than an eastern source, and the absence of a local sedimentation source in the Carolinas (Rodgers, 1967) bring into question the importance of the Acadian Orogeny in the southern Appalachian Blue Ridge. The Winding Stair Gap area is near the western boundary of Acadian metamorphism proposed by Glover and others (1983).

Stratigraphic Correlation

An attempt was made to reconstruct the stratigraphic sequence at Winding Stair Gap using the location of lithologic units in figure 2 (p. 11), outcrop locations in the field mapping (plate 1), and interpretations of the predeformation lithologic relationships (fig. 4, p. 22). The Winding Stair Gap exposure lies within an area mapped as Coweeta Group and Tallulah Falls Formation by Hatcher and Butler (1979). A generalized stratigraphic sequence for the Winding Stair Gap exposure is compared with generalized stratigraphic columns for the Tallulah Falls Formation and Coweeta Group in figure 6. The Bt-Grt granulite and calc-silicate gneiss units appear to be a "package" at Winding Stair Gap, as do the Sil schist and Bt-Hbl granulite. Anatexis of the quartzo-feldspathic gneiss obscures its position relative to the other units in the stratigraphic column. No evidence is present at Winding Stair Gap to suggest which end of the column is up. Because of the structural complexity and overprint of granulite facies metamorphism, the exact character and orientation of premetamorphic units must be highly subjective.

Correlating the Winding Stair Gap units with intervals within either the Tallulah Falls Formation or the Coweeta Group is difficult because of the similarities between the metasedimentary sequences, complexity of the deformation,

Figure 6. Schematic diagram showing possible correlations of Winding Stair Gap lithologies with generalized stratigraphic sequences of the Tallulah Falls Formation and Coweeta Group. Tallulah Falls Formation stratigraphy is from Hatcher (1973); Coweeta Group stratigraphy is from Hatcher (1981). Note the difference in scales from the columns.

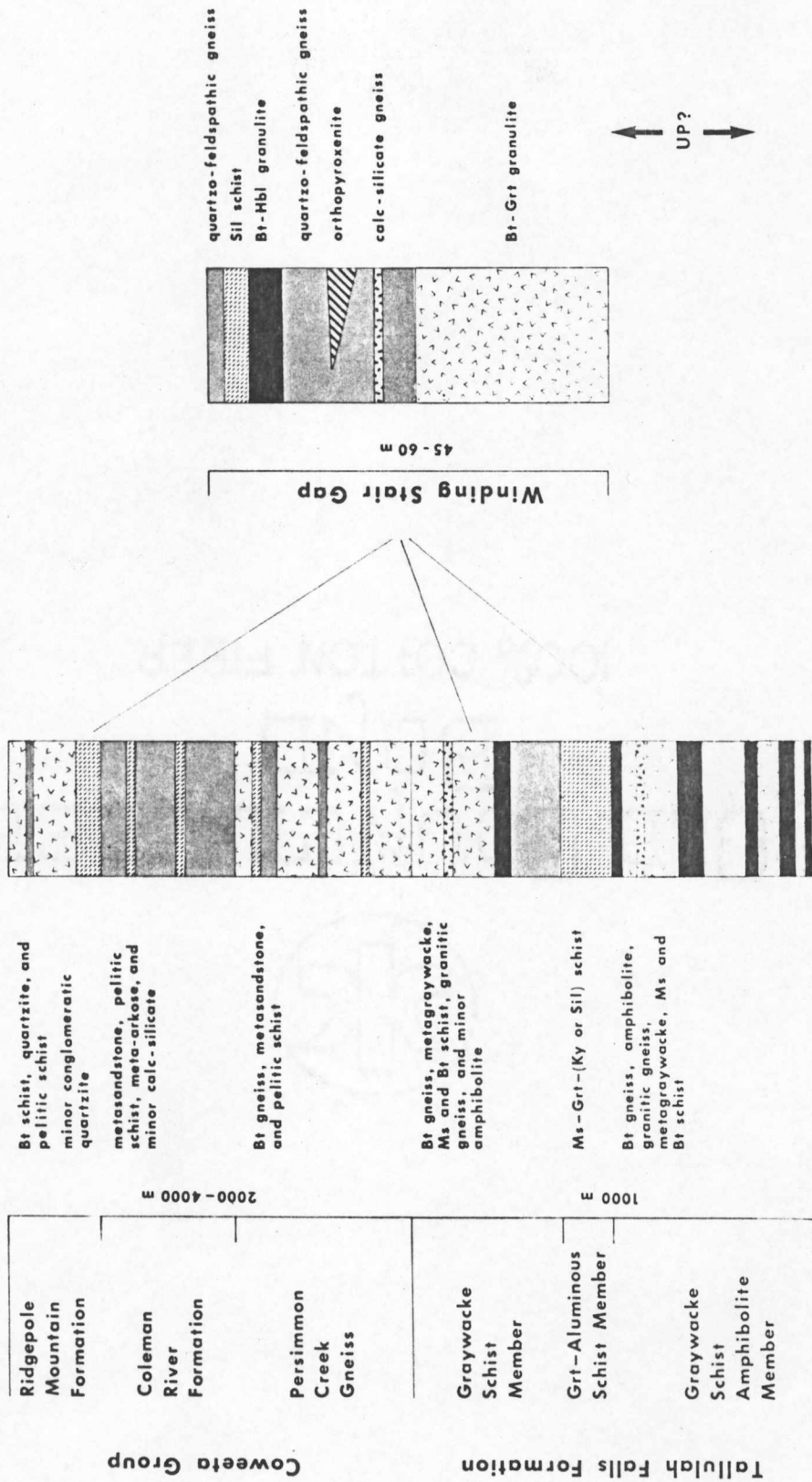


Figure 6.

and insufficient exposure in the field area. Hatcher and Butler (1979) have tentatively assigned Winding Stair Gap to the Ridgepole Mountain Formation of the Coweeta Group based on the diversity of assemblages present, the abundance of Bt-rich gneiss, and the presence of pelitic schist. Excluding the orthopyroxenite unit and Bt-Hbl granulite, the units at Winding Stair Gap are consistent with those of the Ridgepole Mountain Formation. The scarcity of mafic rocks (Bt-Hbl granulite) in the field mapping may indicate the mafic rocks are anomalously abundant at Winding Stair Gap or that they have been overlooked in areas of poorer exposure.

Placement of the Winding Stair Gap lithologies at certain intervals within the Tallulah Falls Formation also appears reasonable (fig. 6). Sil schist may correspond with Grt-aluminous schist and Bt-Grt granulite may correlate with either the upper or lower metagraywacke members. Both the upper and lower graywacke schist members contain minor calc-silicate quartzite. The mafic rocks at Winding Stair Gap may be analogous to amphibolite layers in the Tallulah Falls Formation. There is insufficient information to assign unequivocally the rocks at Winding Stair Gap to either the Coweeta Group or the Tallulah Falls Formation.

The stratigraphic position of the orthopyroxenite unit has not been considered in the above discussion. Higgins and others (1980) argued the orthopyroxenite may have been

structurally emplaced. Seismic evidence by Furman and Mancuso (1982) suggest the high amplitude reflectors associated with the Rainbow Springs gravity high (southwest of the Winding Stair Gap area) (Hatcher and Zietz, 1980) are mafic and ultramafic bodies thrust up along the Hayesville and Shope Fork Faults. The presence of other mafic-ultramafic bodies in the area, possibly of ophiolitic origin, such as Chunky Gal Mountain (McElhaney and McSween, 1983; Shaw and Wasserburg, 1984), is circumstantial evidence the orthopyroxenite at Winding Stair Gap may also be ophiolitic. An igneous origin for the orthopyroxenite can be interpreted from chemical evidence presented in the mineral chemistry section below. However, these data are also compatible with a granulite facies metamorphic assemblage, and emplacement of the orthopyroxenite was clearly premetamorphic. Like many of the mafic and ultramafic bodies in the southern Blue Ridge, the origin of the orthopyroxenite at Winding Stair Gap remains enigmatic.

III. MINERALOGY AND PHASE RELATIONS

Mineral Chemistry

Grt occurs in Sil schist, Bt-Grt granulite, Bt-Hbl granulite, quartzo-feldspathic gneiss, and calc-silicate gneiss units. The calc-silicate gneiss Grt is composed largely of Alm and Grs components with significant Sps; Grt in the other units is an Alm-Pyp mixture with lesser amounts of Grs and Sps (Table 1). Ternary plots of Fe^{2+} -Mg-Mn and Fe^{2+} -Mg-Ca (fig. 7) indicate limited variation within a single sample, though the variation between units of different bulk composition is quite large. Chemical variation of Grt in the calc-silicate gneiss reflects distance from the boudin interior, becoming less calcic in the exterior. Smaller grains also have more calcic compositions than larger grains, suggesting either disequilibrium or multiple generations of Grt in the calc-silicate gneiss.

Core and rim compositions of individual Grt (fig. 7) indicate very little change in Ca, no systematic change in Mn, and a decrease in $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ toward the rim. The zonation pattern is unlike the zonation pattern attributed to fractionation during growth of Ca- and Mn-rich cores and Fe- and Mg-rich rims typical of lower-grade Grt (Hollister, 1966; Tracy and others, 1976).

The depletion of Mg at Grt rims has been postulated as an essentially solid state diffusion process or a product of

Table 1. Representative Microprobe Analyses of Grt

	Bt-Granulite		Bt-Hbl Granulite		Sil Schist				Calc-Silicate Gneiss	
	FG-2		Q-54		P-9				FG-1A	
	core ³	rim ³	core ³	rim ³	core ³	rim ³	core ²	rim ⁴	core ³	rim ³
SiO ₂	38.37(7)	37.5(2)	35.7(4)	36.5(6)	34.2(1)	34. (1)	35.4(6)	35. (1)	39.37(4)	37.2(2)
TiO ₂	.05(1)	.05(1)	.07(1)	.06(2)	.04(1)	.05(1)	.05(2)	.04(1)	.09(1)	.08(1)
Al ₂ O ₃	21.89(4)	21.88(5)	21.8(2)	21.8(1)	22. (1)	21.5(6)	21.8(1)	22. (2)	21.13(6)	21.18(2)
FeO	25.9(2)	27. (3)	30.2(4)	31.3(3)	33.6(6)	34.5(3)	28.9(2)	30.5(7)	21.8(3)	22.4(2)
MnO	2.21(5)	1.84(4)	1.93(5)	2.01(8)	2.4(2)	2.7(1)	2.06(1)	2.12(9)	3.55(5)	3.5(2)
MgO	5.89(2)	5.50(6)	7.2(1)	6.7(1)	5.1(8)	5.4(1)	8.95(4)	8.72(8)	4.08(5)	3.9(2)
CaO	6.06(4)	6.13(8)	2.84(4)	2.91(2)	1.1(2)	1.31(2)	1.67(6)	1.8(1)	10.6(1)	11.1(6)
total	100.37	99.90	99.74	101.28	98.44	99.46	98.83	100.19	100.62	99.36
formula basis										
(oxygens)	12	12	12	12	12	12	12	12	12	12
Si	2.986	2.936	2.799	2.858	2.659	2.667	2.762	2.724	3.058	2.929
Al ^{IV}	.014	.064	.201	.142	.341	.333	.238	.276	-	.071
Al ^{VI}	1.988	1.954	1.811	1.832	1.673	1.680	1.770	1.736	1.932	1.896
Ti	.002	.002	.004	.002	.002	.002	.002	.002	.004	.004
Fe ³⁺⁺	.010	.044	.185	.167	.325	.318	.232	.262	-	.100
Fe ²⁺	1.673	1.726	1.797	1.844	1.990	2.021	1.685	1.707	1.418	1.373
Mn	.144	.122	.126	.132	.188	.180	.134	.138	.232	.234
Mg	.681	.640	.840	.778	.695	.674	1.038	1.004	.471	.460
Ca	.503	.512	.236	.246	.126	.124	.137	.152	.883	.934
total	8.001	8.000	7.999	8.000	7.999	7.999	7.998	8.001	7.998	8.001

*Number of replicate analyses.

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

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

†Fe³⁺ calculated from charge balance and stoichiometry.

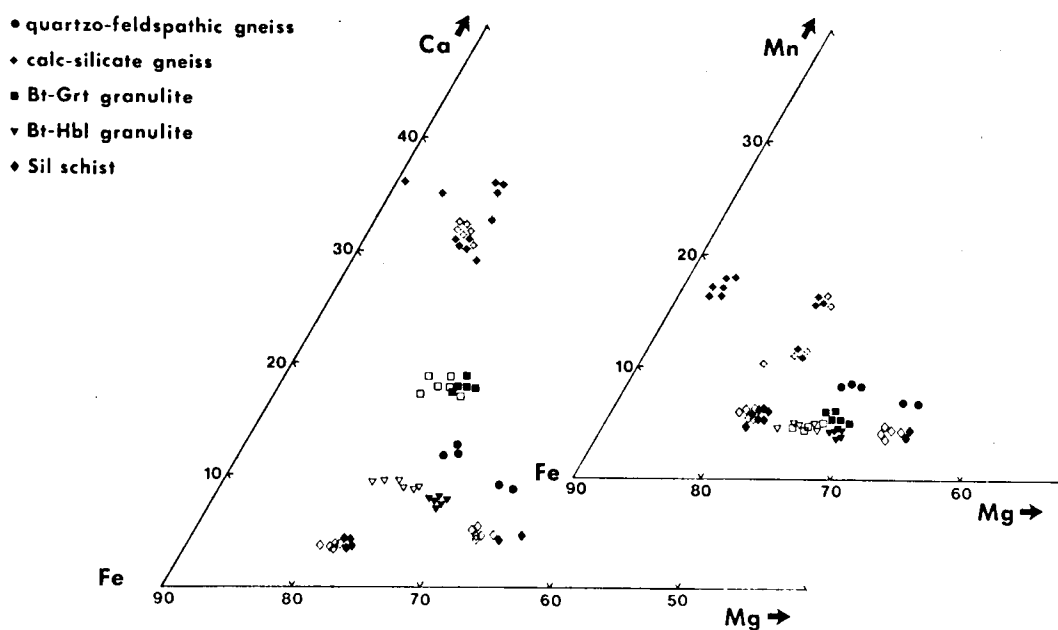


Figure 7. Molar Grt compositions shown on Fe^{2+} -Mg-Ca and Fe^{2+} -Mg-Mn ternary diagrams. Fe-enrichment of rims (open symbols) relative to cores (filled symbols) is the only consistent zonation pattern. No rim compositions for Grt in quartzo-feldspathic gneiss were measured because of the small grain size.

retrograde hydration reactions (Grant and Weiblen, 1971; Tracy and others, 1976; Amit, 1976). One proposed retrograde hydration reaction involves the breakdown of Grt to produce Chl (Amit, 1976). Mg, and to a lesser extent Fe^{2+} , leave the Grt structure to form Chl, with Mn diffusing back to form Grt rims enriched in Mn and depleted in $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ relative to the core compositions. Chl in Grt fractures and at Grt edges indicates retrograde hydration has occurred, but lack of Chl in the vicinity of many zoned Grt and absence of Mn-enriched Grt rims (fig. 7) suggests retrograde hydration is not the main zonation process. A second mechanism to produce the observed zonation patterns is solid state cation exchange between Grt and adjacent ferromagnesian minerals, particularly Bt (Tracy, 1982). Diffusion zoning would involve only Fe^{2+} and Mg because Ca and Mn are not readily assimilated by Bt. Zoning is absent in Bt adjacent to Grt, probably reflecting homogenization of Bt due to higher diffusion rates in that mineral. Retrograde hydration reactions have occurred in the Grt at Winding Stair Gap, although the retrograde process cannot account for zonation in all Grt samples nor the lack of consistent Mn-enrichment at Grt rims. Retrograde Grt growth and diffusion zoning are less easily demonstrated but may have been instrumental in creating the observed zonation patterns.

Bt is the most abundant and widespread ferro-magnesian mineral at Winding Stair Gap, occurring in every unit except the calc-silicate gneiss. Bt analyses (Table 2) are reported as cations per 22 oxygens. $Mg/(Mg+Fe)$ is lowest in Bt from the quartzo-feldspathic gneiss and highest from the orthopyroxenite, suggesting a direct relationship between $Mg/(Mg+Fe)$ and bulk composition. Al is less variable and apparently not directly controlled by bulk chemistry. Generally high Ti and $K/(K+Na)$ for the Bt are typical of high grade metamorphism (Tracy, 1978; Dymek, 1983).

Inclusion-free, greenish-brown Hbl with straight or smoothly-curved grain boundaries in the Bt-Hbl granulite and Bt-Grt granulite units is an apparent prograde mineral. Retrograde blue-green Hbl, present in the orthopyroxenite and mafic granulites, occurs as inclusion-riddled grains lacking smooth grain boundaries and as coronas surrounding relict Opx. Prograde and retrograde Hbl are chemically similar except for lower Ti contents in the retrograde Hbl (Table 3), a pattern observed in secondary Hbl from other granulite terranes (Sen and Oliver, 1981). As these authors note, lower Ti may simply reflect compositional differences of the reactants producing the secondary Hbl rather than a significant change in pressure or temperature.

Calcic amphiboles in the Bt-Hbl granulite and Bt-Grt granulite units are tschermakitic Hbl or tschermakite

Table 2. Representative Microprobe Analyses of Bt

	Bt-Grt Granulite		Bt-Hbl Granulite		Orthopyroxenite		Sil Schist		Q-F Gneiss	
	FG-2 ^{3*}	Q-18 ³	Q-54 ³		FM-3 ³		P-9 ³	FS-2 ⁴	Q-3 ⁵	
SiO ₂	35.2(7)	34.7(6)	36.0(4)		37.8(7)		34.8(7)	35.5(3)	35.6(2)	
TiO ₂	3.75(5)	3.7(1)	2.28(6)		2.79(4)		3.4(2)	3.04(6)	2.98(2)	
Al ₂ O ₃	15.9(1)	15.9(2)	18.4(2)		16.20(3)		18.2(2)	17.4(1)	17.32(7)	
FeO	17.4(2)	15.8(2)	13.73(7)		9.09(4)		15.8(1)	12.8(4)	16.8(2)	
MnO	.08(3)	.11(2)	n.d.		n.d.		n.d.	n.d.	.08(5)	
MgO	12.1(1)	14.0(3)	14.4(2)		19.5(2)		13.31(7)	16.01(5)	12.4(1)	
CaO	.08(1)	n.d.	.07(1)		n.d.		.06(2)	n.d.	n.d.	
Na ₂ O	.04(4)	.24(4)	.21(4)		.8(1)		.08(2)	.4(1)	.50(7)	
K ₂ O	9.2(1)	9.3(2)	8.96(3)		8.96(5)		9.39(6)	9.8(1)	9.57(5)	
total	93.75	93.75	94.05		95.14		95.05	94.95	95.25	
formula basis										
(oxygens) 22	22	22	22	22	22	22	22	22	22	
Si	5.428	5.325	5.397	5.489	5.244	5.297	5.386			
Al ^{IV}	2.572	2.675	2.603	2.511	2.756	2.703	2.614			
Al ^{VI}	.315	.199	.641	.200	.475	.354	.472			
Ti	.435	.427	.256	.304	.385	.341	.339			
Fe	2.240	2.026	1.718	1.102	1.988	1.594	2.123			
Mn	.009	.015	-	-	-	-	.010			
Mg	2.776	3.199	3.211	4.212	2.984	3.555	2.793			
Ca	.013	-	.011	-	.010	-	-			
Na	.011	.072	.061	.225	.024	.115	.147			
K	1.808	1.819	1.711	1.657	1.803	1.863	1.845			
total	15.607	15.757	15.609	15.702	15.669	15.822	15.729			

*Number of replicate analyses.

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

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

Table 3. Representative Microprobe Analyses of Hbl, Cum, and Opx

	Hbl						Cum			Opx		
	Bt-Hbl Granulite			Bt-Grt Granulite			C-s Gneiss			Ortho- Pyroxenite		
	Q-49 ^{4*}	Q-54 ⁴	Q-18 ³	Q-49 ^{4*}	Q-54 ⁴	Q-18 ³	FG-1A ³	FM-3 ³	FM-3 ³	FM-1 ³	Q-54 ³	Q-18 ³
SiO ₂	41.0(4)	42.3(3)	40.9(4)	41.41(5)	45.9(2)	53.7(4)				52.1(2)	51.2(6)	49.5(3)
TiO ₂	1.3(3)	1.43(3)	1.37(4)	.85(4)	.88(3)					n.d.	n.d.	n.d.
Al ₂ O ₃	13.9(5)	13.67(3)	13.6(3)	13.65(3)	12.17(5)	1.84(8)				2.12(4)	2.84(1)	1.96(3)
FeO	15.3(2)	11.4(2)	15.9(1)	15.8(3)	9.8(3)	14.5(2)				15.0(2)	20.6(8)	27.0(1)
MnO	.24(4)	.14(1)	.26(4)	.38(4)	.18(3)	.38(2)				.40(4)	.39(4)	.7(1)
MgO	11.0(2)	12.7(2)	11.1(2)	10.2(2)	16.75(8)	25.1(3)				29.72(9)	23.8(2)	19.66(5)
CaO	10.6(2)	11.12(3)	10.1(2)	11.40(4)	10.37(9)	.40(3)				.17(3)	.29(2)	.55(5)
Na ₂ O	1.3(1)	1.3(1)	1.2(2)	1.44(7)	2.04(7)	.61(6)				n.d.	n.d.	n.d.
K ₂ O	.8(1)	1.10(4)	1.3(2)	1.34(2)	.40(1)	n.d.				n.d.	n.d.	n.d.
total	95.44	95.16	95.73	96.47	98.49	96.57				99.61	99.12	99.60
formula basis (oxygens)	23	23	23	23	1	2	23	1	2	23	6	6
Si	6.205	6.073	6.362	6.256	6.212	6.046	6.271	6.210	6.336	6.541	6.336	6.336
Al IV	1.795	1.927	1.638	1.744	1.788	1.954	1.729	1.790	1.644	1.459	1.644	1.644
Al VI	.683	.498	.767	.621	.646	.415	.707	.622	.313	.582	.313	.313
Ti	.145	.142	.157	.154	.146	.142	.093	.092	.089	.092	.089	.089
Fe ³⁺ †	.294	1.270	-	.754	.378	1.597	.148	.593	1.134	.062	1.134	1.134
Mg	2.482	2.429	2.843	2.795	2.510	2.433	2.302	2.280	3.443	3.554	3.443	3.443
Fe ²⁺	1.652	.634	1.437	.659	1.639	.366	1.834	1.370	1.109	1.109	-	-
Mn	.027	.026	.017	.017	.037	.036	.043	.043	.020	.021	.020	.020
Ca	1.718	1.681	1.778	1.748	1.643	1.599	1.873	1.855	1.531	1.580	1.531	1.531
Na(H4)		.319252	-	.338	-	.145	-	.469	-	-	-	-
Na(1)	.381	.054	.368	.110	.347	-	.427	.278	.073	.560	.073	.073
K	.145	.142	.206	.203	.127	.124	.261	.258	.069	.071	.069	.069
total	15.527	15.195	15.573	15.313	15.473	15.060	15.688	15.536	15.141	15.631	15.141	15.141
										4.056	4.024	4.043

*Number of replicate analyses.

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

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

†Fe³⁺ calculated from charge balance and stoichiometry.

Normalization for Hbl assuming 15 cations exclusive of Na and K (column 1) and 13 cations exclusive of Ca, Na, and K (column 2).

according to the nomenclature of Leake (1978). Edenitic Hbl occurs in the calc-silicate gneiss and magnesio-hornblende is present in the orthopyroxenite. Fe-Mg amphibole in the orthopyroxenite is a magnesio-cummingtonite. Cation normalization of microprobe data for Hbl (Table 3) follows guidelines described by Robinson and others (1981), assuming 15 cations exclusive of Na and K (column 1) and 13 cations exclusive of Ca, Na, and K (column 2). The amount of ferric iron estimated for the Hbl samples depends upon the correction procedure followed. Normalization to 15 cations exclusive of Na and K approaches a minimum reasonable value for Fe^{3+} ; normalization to 13 cations exclusive of Ca, Na, and K approaches a maximum reasonable value for Fe^{3+} . The true value of Fe^{3+} probably lies between the reported estimates. The normalization procedure will also affect the estimates of Na in the M4 and A sites.

High values of K, Ti, and Al and low Si values indicate the Hbl formed at high metamorphic grade (Spear, 1981a; Laird and Albee, 1981). A plot of Al^{IV} versus Na + K (fig. 8) indicates the Winding Stair Gap Hbl, with the exception of retrograde Hbl in the orthopyroxenite, is enriched in the tschermakite component relative to Hbl from other granulite terranes (Engel and Engel, 1962; Corbett and Phillips, 1981).

Opx occurs as strongly pleochroic (X = pink; Z = green) hypersthene in the Bt-Grt granulite and Bt-Hbl granulite

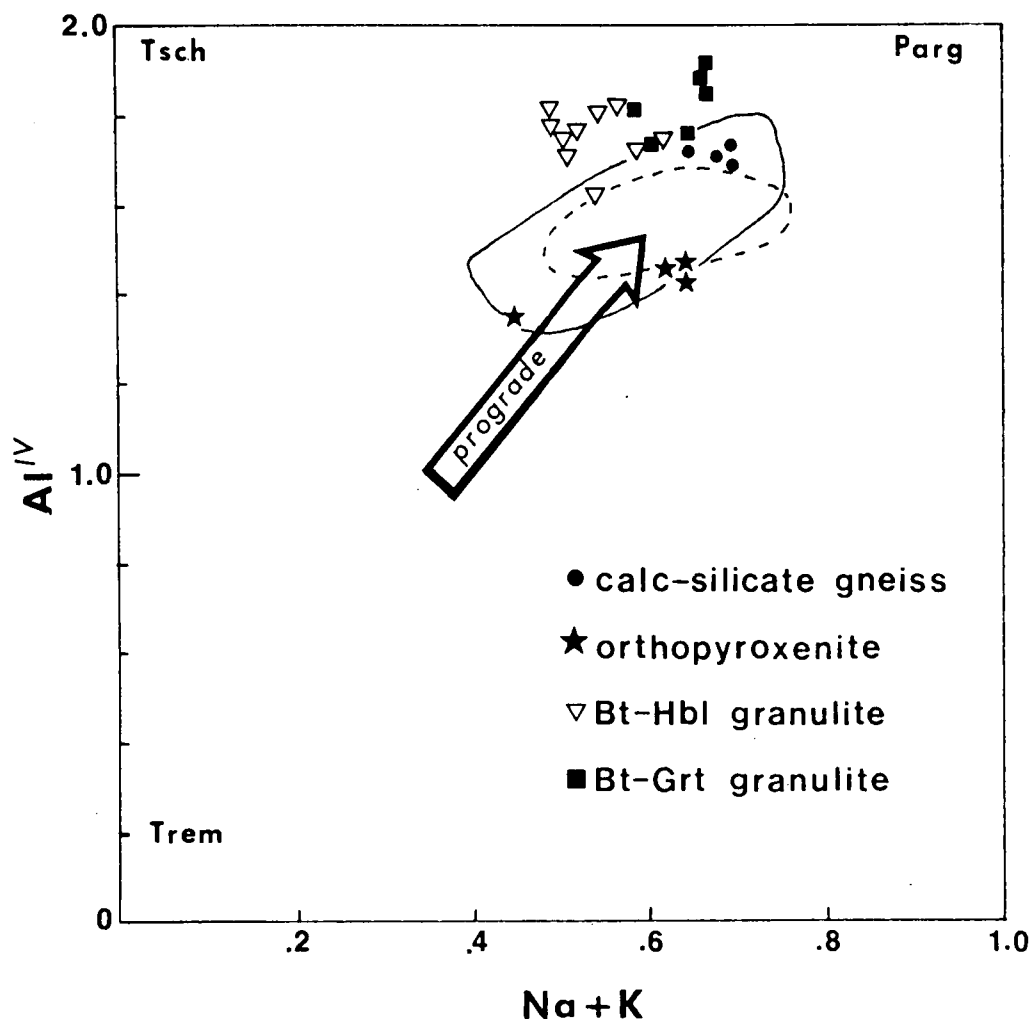


Figure 8. Al^{IV} versus $(Na+K)$ for Winding Stair Gap Hbl compared with compositional ranges from the Adirondacks and Broken Hill, Australia. The range of Adirondack Hbl compositions (Engel and Engel, 1962) is shown as a dashed line; the solid line indicates the compositional range for Hbl from Broken Hill (Corbett and Phillips, 1981). Arrow indicates the approximate prograde path transforming tremolite (Trem) to a composition enriched in pargasite (Parg) and tschermakite (Tsch) components (Corbett and Phillips, 1981). Hbl in the orthopyroxenite is retrograde.

units and as slightly pleochroic bronzite in the orthopyroxenite unit. Representative microprobe analyses (Table 3) indicate Na, Ca, and Fe^{3+} are low or absent. Unzoned Opx shows little chemical variation within a particular unit (fig. 9). $\text{Mg}/(\text{Mg}+\text{Fe})$ variation between units apparently reflects bulk composition. Bhattacharyya (1971) developed a plot of Al_2O_3 versus $\text{MgO}+\text{FeO}+\text{Fe}_2\text{O}_3$ to delineate the fields of igneous and metamorphic Opx (fig. 9). All Opx samples lie within the metamorphic field, although some Opx from the orthopyroxenite unit are within a transition zone where metamorphic and igneous compositions overlap (Rietmeijer, 1983), further complicating the relationship between the orthopyroxenite and other units at Winding Stair Gap.

Pl occurs in all units at Winding Stair Gap and is the most abundant mineral in the Bt-Grt granulite and quartzofeldspathic gneiss units. Pl composition ranges from andesine to bytownite (Table 4) with core to rim zonation absent except for slightly calcic cores in a few large grains in the Bt-Grt granulite. A plot of An-contents (fig. 10) indicates chemical variation within units other than the Bt-Hbl granulite and calc-silicate gneiss is limited. Pl from the Bt-Hbl granulite has a composition range of An_{76-89} with no apparent relationship to cores, rims, or size of grains. Two compositional peaks occur in

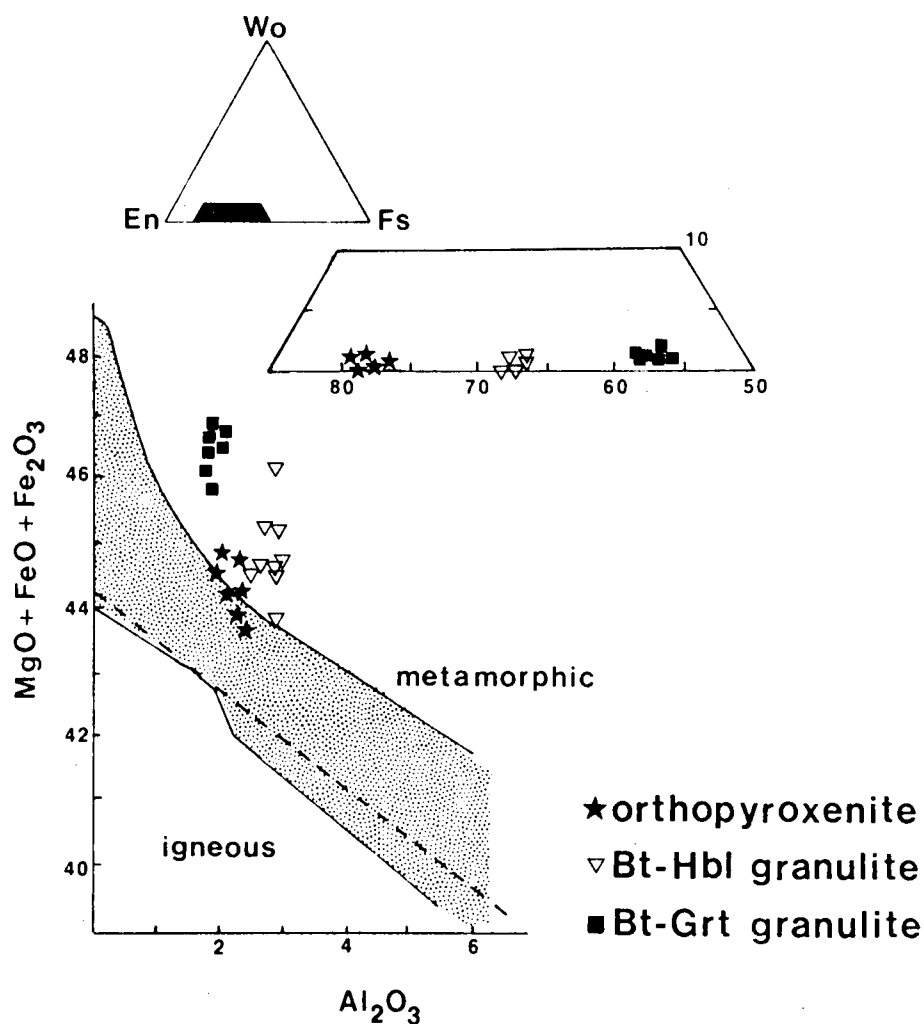


Figure 9. Opx compositions shown in a portion of the pyroxene quadrilateral. $\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3$ versus Al_2O_3 (wt. %) for Opx compositions (bottom) has been used to distinguish igneous and metamorphic Opx. The dashed line is the demarcation boundary of Bhattacharyya (1971). Shaded area defines a region where igneous and metamorphic Opx compositions overlap (Rietmeijer, 1983).

Table 4. Representative Microprobe Analyses of Pl, Kfs, and Scp

Pl														Kfs	Scp				
Bt-Hbl Granulite			Bt-Grt Granulite		Sil Schist		Q-F Gneiss	c-s Gneiss	ortho-pyroxenite	Sil Schist	c-s Gneiss								
Q-49 ^{3*}	Q-54 ³	Q-18 ³	FG-2 ⁵	FS-2 ⁴	Q-3 ⁴	FG-1A ³	FM-3 ³	P-9 ³	FG-1 ³										
SiO ₂	48.2(2)	48.1(3)	57.3(3)	56.9(5)	58.2(1)	56.4(2)	46.6(2)	57.6(3)	66.1(5)	45.4(2)									
Al ₂ O ₃	33.3(3)	34.2(3)	26.9(1)	27.2(1)	25.7(1)	27.1(1)	34.7(2)	26.82(5)	18.9(1)	27.94(8)									
CaO	15.77(7)	15.9(2)	8.93(9)	8.7(1)	7.4(1)	8.9(2)	17.7(2)	8.50(7)	.08(1)	18.31(1)									
Na ₂ O	2.44(8)	2.2(1)	5.7(3)	6.1(1)	7.5(3)	6.9(2)	1.50(5)	7.05(8)	1.3(1)	3.1(1)									
K ₂ O	n.d.	.06(3)	.10(2)	.19(2)	.19(2)	.14(2)	n.d.	.05(1)	13.5(4)	.08(1)									
total	99.76	100.46	99.46	99.09	98.99	99.44	99.50	100.02	99.88	94.83									
formula basis (oxygens)														8	8	8	8	8	24
Si	2.209	2.187	2.590	2.569	2.629	2.550	2.109	2.580	3.008	6.948									
Al	1.796	1.833	1.424	1.445	1.354	1.441	1.890	1.415	1.017	5.051									
Ca	.772	.773	.429	.421	.365	.432	.875	.407	.003	2.998									
Na	.216	.196	.499	.530	.671	.602	.133	.611	.112	.942									
K	-	.002	.005	.010	.009	.008	-	.002	.790	.012									
total	4.993	4.991	4.947	4.975	5.028	5.033	5.007	5.015	4.930	15.951									
Or	-	0.3	0.5	1.0	0.9	0.8	-	0.2	87.3										
Ab	21.9	19.8	53.5	55.2	64.2	57.8	13.2	59.9	12.4										
An	78.1	79.9	46.0	43.8	34.0	41.4	86.8	39.9	0.3										

*Number of replicate analyses.

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

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

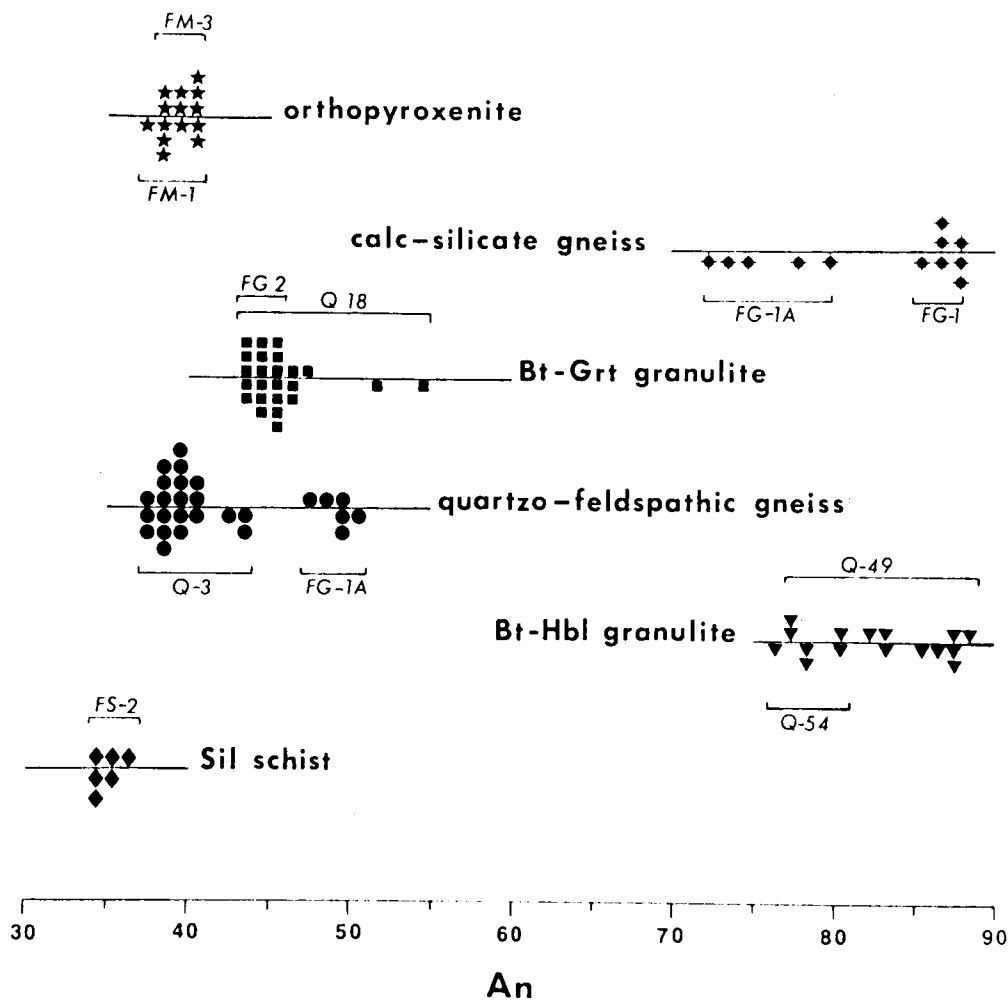


Figure 10. Molar An content of Pl cores (below line) and rims (above line). Brackets indicate composition range of analyses from the indicated sample.

the calc-silicate gneiss, with Pl at An_{73-79} restricted to Scp pseudomorphs in sample FG-1A. Kfs (Or_{87}) occurs as microperthite predominantly in the Sil schist and quartzofeldspathic gneiss units.

Scapolite in the calc-silicate gneiss occurs as stubby, unzoned grains with a composition near end-member mizzonite (Table 4). The equivalent An composition ($eqAn_x$; where $x = 100(Al-3)/3$) is $eqAn_{68}$, somewhat less calcic than the coexisting Pl. Energy dispersive scans indicate S and Cl are not present in detectable amounts, consistent with the findings of Evans and others (1969) and Oterdoom and Wenk (1983) that Scp of $eqAn_{65-100}$ contains no Cl in the anion site. The meionite content of Scp, determined by the ratio $Ca/(Ca+Na)$, ranges from Me_{73-80} . Experimental results at 750°C and 4 kb indicated Scp coexisting with Pl and Cal has a narrow composition range of Me_{74-77} (Orville, 1975), although Ellis (1978) suggested the composition range may be as great as Me_{65-87} . Scp with composition Me_{75} forms at the lowest temperature in the presence of Pl and Cal, suggesting it is a minimum on the Scp free energy surface (Aitken, 1983).

Fe-Ti oxides are minor but ubiquitous constituents of all units except the calc-silicate gneiss. Ilm and Mag occur as discrete grains lacking visible exsolution lamellae. Ilmeno-hematite (exsolved lamellae of Ilm in Hem)

and less commonly hemo-ilmenite (exsolved lamellae of Hem in Ilm) are restricted to nonfoliated quartzo-feldspathic gneiss and Ky-bearing Kfs segregations in the Sil schist. Microprobe analyses of Mag, Ilm, and ilmeno-hematite for two samples are presented in Table 5. As the exsolution lamellae in the ilmeno-hematite were too narrow (less than 3 μm) to analyze without contamination, analyses of several grains using a defocused beam were averaged to provide an estimate of the homogeneous composition.

Mineral Assemblages and Reactions

The Sil schist (Bt+Grt+Sil+Kfs+Pl+Qtz+Mag+ilmeno-hematite) occurs as Bt-Grt-Sil layers adjacent to discontinuous lenses of Kfs and Qtz and as froth-textured Grt with minor amounts of Bt, Sil, Qtz, and Pl in fold hinges. Differences in the modal amount of Bt, Grt, and Sil within the Sil schist may be due to differences in bulk composition. Coexisting Bt and Grt (fig. 11) are more magnesian in the Grt-rich assemblage (FS-2) than in the Bt-Sil-Grt assemblage (P-9), further suggesting compositional differences between fold hinge and fold limb. Interpretation of the Sil schist unit as a single layer repeated by isoclinal folding (fig. 2, p. 11), however, suggests the variation in mineral composition and Grt abundance between fold hinges and fold limbs may be due to an unidentified differentiation process rather than original inhomogeneity of the layer.

Table 5. Representative Microprobe Analyses of Fe-Ti Oxides

	Bt-Hbl Granulite		Sil Schist	
	Q-49 ^{3*}	Q-49 ³	P-9 ³	P-9 ¹²
	Mag	Ilm	Mag	Ilm-Hem
TiO ₂	.10 (1)	46.4 (2)	.05 (1)	27. (1)
Al ₂ O ₃	.45 (2)	.17 (2)	.32 (8)	.22 (1)
Cr ₂ O ₃	.04 (2)	n.d.	.28 (2)	.09 (2)
FeO	93.2 (8)	50.7 (2)	92.6 (7)	69.5 (9)
MnO	.06 (3)	.69 (4)	.08 (1)	.07 (4)
MgO	n.d.	.52 (4)	n.d.	.06 (5)
total	93.85	98.48	93.33	96.94
formula basis (oxygen)	12	12	12	12
Ti	.007	3.677	.003	2.045
Al	.057	.019	.044	.026
Cr	-	-	.023	.005
Fe ³⁺⁺	5.929	.013	5.927	3.873
Fe ²⁺	3.004	4.459	2.996	2.042
Mn	.003	.059	.007	.004
Mg	-	.080	-	.008
total	9.000	8.307	9.000	8.003

*Number of replicate analyses.

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

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

+Fe³⁺ calculated from charge balance and stoichiometry.

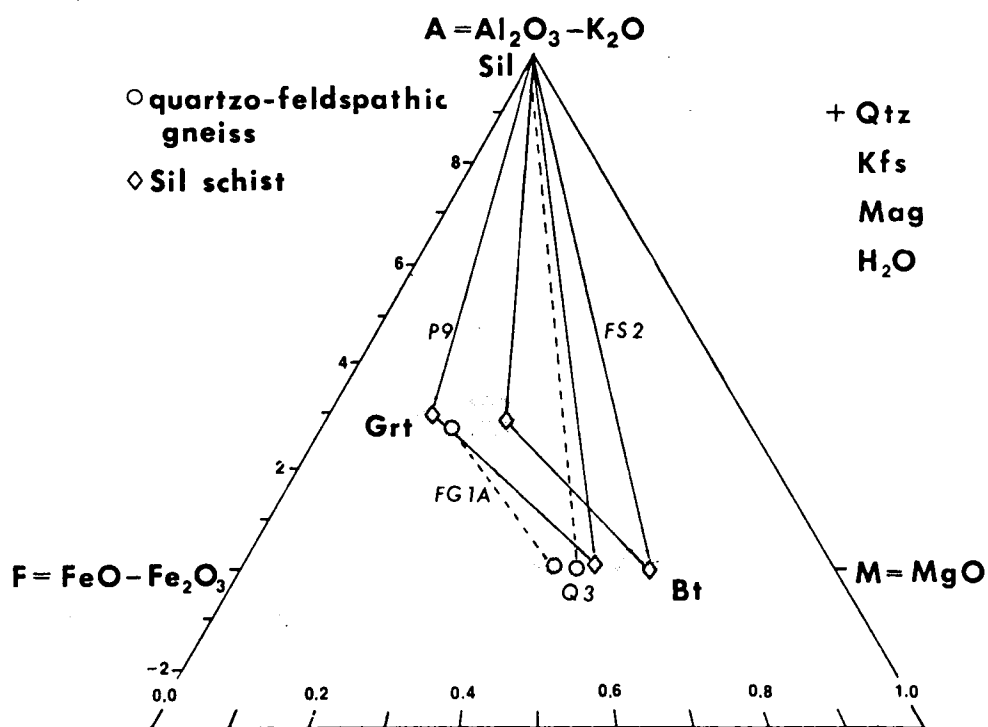


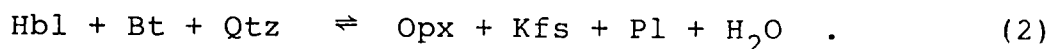
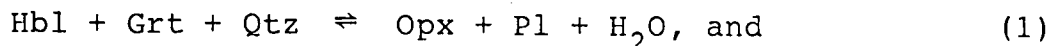
Figure 11. AFM projection through Qtz, Kfs, Mag, and water modified from Thompson (1957). Phase relations in the Sil schist and quartzo-feldspathic gneiss are shown. Sample numbers are in italics.

Kfs segregations within the Bt-Grt-Sil layers are concentrated near the edges of the Sil schist unit adjacent to nonfoliated quartzo-feldspathic gneiss and may indicate partial melting of the Sil schist. Ky and Ms are commonly present in the undeformed, discontinuous Kfs bands.

The quartzo-feldspathic gneiss (Pl+Qtz+Kfs+Bt+Grt+Sil+Ms+Mag+Ilm+Hem) ranges in composition from quartz monzonite to granodiorite to granite. Sil is the most common polymorph of Al_2SiO_5 , although Ky occurs in nonfoliated quartzo-feldspathic gneiss. Bt is a commonly occurring minor constituent (5-15 volume %) along with Grt and rarely Ms. Grt and Al_2SiO_5 seldom occur together in the same sample, and they never coexist as abundant phases. Bt coexisting with Sil (Q-3) has a higher $\text{Mg}/(\text{Mg}+\text{Fe})$ (fig. 11) than Bt occurring with Grt (FG-1A). Although the analytical data are limited, it appears the $\text{Mg}/(\text{Mg}+\text{Fe})$ of the rock may control the occurrence of Grt, with compositions having $\text{Mg}/(\text{Mg}+\text{Fe})$ less than 0.56 producing Grt. The presence of Ti could alter the composition of coexisting Fe-Mg silicates by combining with Fe^{2+} to form ilmenite, resulting in more Mg-rich silicates. Ilmeno-hematite, present in sample Q-3, is absent in FG-1A.

The mineral assemblages for Bt-Hbl granulite and Bt-Grt granulite are Hbl+Pl+Bt+Opx+Qtz+Kfs+Mag+Ilm and Hbl+Pl+Bt+Grt+Qtz+Kfs+Mag+Ilm. Cum occurs as a retrograde product associated with blue-green Hbl and Opx in both units.

Several Opx-producing reactions in Hbl granulites have been proposed by de Waard (1965). Two of the reactions that may be applicable to the mineral assemblages observed in the mafic granulites at Winding Stair Gap are:



Textural evidence supporting either reaction is inconclusive. However, reaction 1 appears to be a possible Opx-forming reaction in the Bt-Grt granulite. Grt, a very common mineral in Opx-free portions of the unit, occurs with Opx on a scale as small as hand-specimen, although the two have not been observed in contact. If equilibrium on the scale of hand-specimen can be assumed, a reaction involving Grt and Opx is likely.

In the Bt-Hbl granulite, reaction 2 may be a likely Opx-producing reaction. Grt is only sporadically present in the Bt-Hbl granulite unit, generally occurring with Bt rather than with Bt and Hbl. Opx-free portions of the unit are commonly composed of Bt and Hbl. Mineral reactions to produce Opx are not limited to reactions 1 and 2; without convincing textural evidence, these reactions must be considered only possibilities.

The mafic granulite assemblages are shown on a modified CFM diagram (fig. 12) (Abbott, 1982) projected through Qtz,

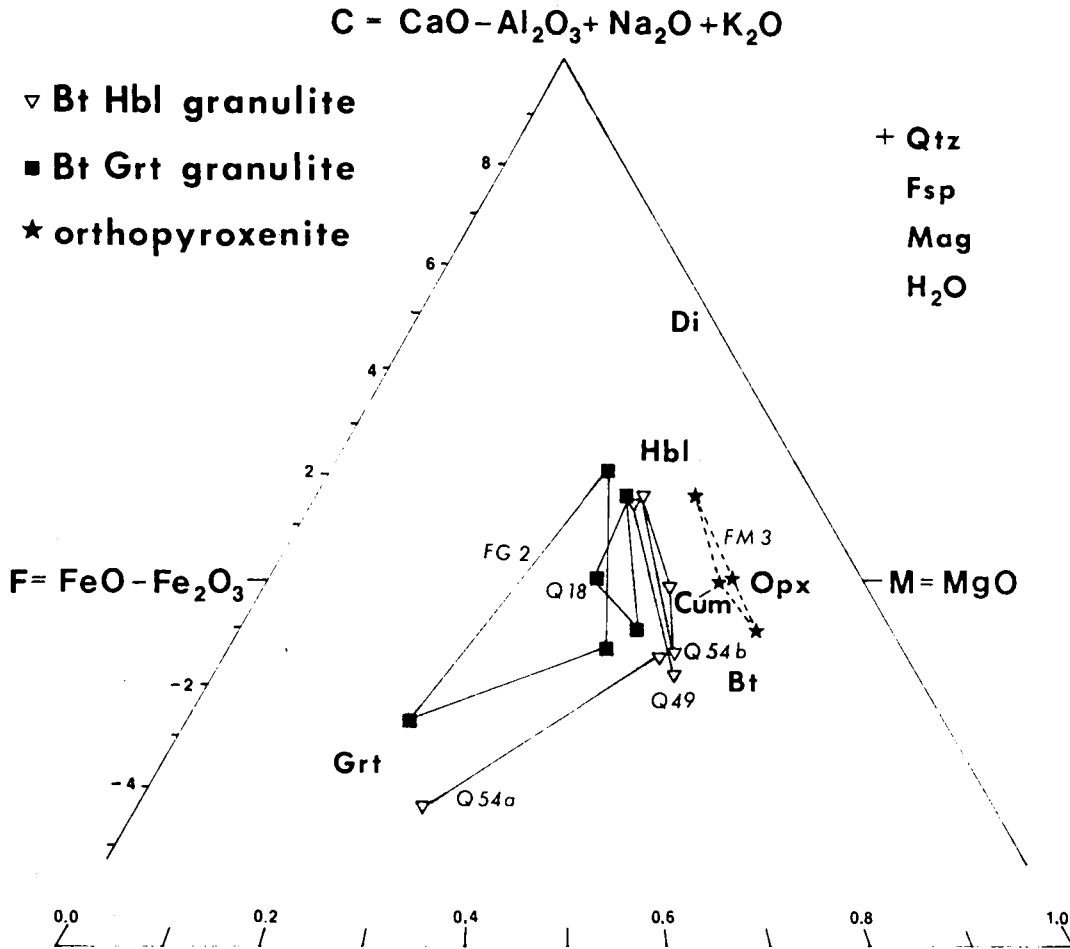
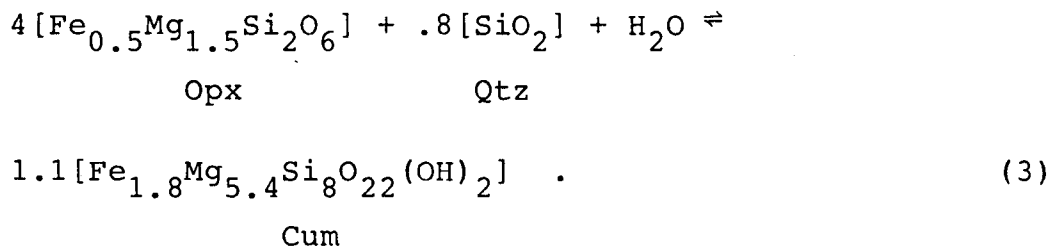


Figure 12. CFM projection through Qtz, Pl, Kfs, Mag, and water (Abbott, 1982) showing phase relations in the mafic granulites. Crossing tie lines may be related to difficulties in determining the amount of ferric iron in microprobe analyses. Italics refer to the sample number; Q-54a and Q-54b are separate assemblages within sample Q-54.

Kfs, Pl, Mag, and H_2O . A problem with the CFM projection involves difficulty in determining Fe^{3+} from microprobe analyses, particularly in Hbl. An increase in the estimated Fe^{3+} shifts the Hbl position toward MgO. The apparent reversal in the position of Opx relative to the Hbl-Bt tie line in sample Q-54b may be related to errors in estimating Fe^{3+} . Despite difficulty in accurately determining Fe^{3+} , the CFM projection allows determination of potentially important variations in $Mg/(Mg+Fe)$ in the mafic granulites. $Mg/(Mg+Fe)$ for Hbl, Bt, and Opx (fig. 12) shows a progressive increase from the Bt-Grt granulite unit to the Bt-Hbl granulite unit to the orthopyroxenite. Differences in $Mg/(Mg+Fe)$ for the coexisting phases probably reflect differences in bulk composition. Tie lines connecting Bt, Hbl, and either Opx or Grt reflect increased $Mg/(Mg+Fe)$ of the Bt-Hbl granulite relative to Bt-Grt granulite. The Ca-content of Pl coexisting with the Fe-Mg silicates increases with increasing $Mg/(Mg+Fe)$ in the mafic granulites.

The orthopyroxenite unit is composed of Opx and Pl with minor amounts of Bt, Hbl, Cum, Qtz, Po, Py, and Mag. Hbl and Cum appear to be retrograde reaction products rimming Opx. Cum forms coronas around Opx and is subsequently rimmed by blue-green Hbl. A simple hydration reaction involving Opx and Cum with compositions approximating those found at Winding Stair Gap is:



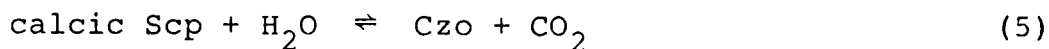
Blue-green Hbl may be produced by a second reaction involving Cum as a transitional phase. Secondary Hbl surrounding Opx has been described by Sen and Oliver (1981). They suggest a reaction in which Opx and calcic Pl combine with H_2O to produce Hbl, Mag, and a more sodic Pl. High Ab-content in the Pl of the orthopyroxenite suggests the original Pl composition may have been altered by the retrograde reactions. If Hbl, Cum, and the sodic Pl are retrograde products, the unaltered rock, consisting of Opx, calcic Pl, Bt, and Qtz, could have been an igneous norite or feldspathic orthopyroxenite.

The calc-silicate gneiss (Cal+Qtz+Scp+Pl+Hbl+Grt+Spn+Di+Ap) is a petrologically complex unit in which mineralogical banding and retrograde reactions mask the prograde mineral assemblage. Ternary graphical representations of the most abundant phases in the calc-silicate gneiss result in crossing tie lines. The apparent disequilibrium may be caused by omission of components, such as H_2O in Hbl and CO_2 in Scp and Cal. Skeletal grains of Grt and Hbl with abundant inclusions do not, however, provide a convincing argument for equilibrium.

Experimental synthesis of Scp coexisting with Cal and Pl according to the reaction:



indicates the presence of two three-phase fields (Orville, 1975). Scp (Me_{76}) at Winding Stair Gap coexists with Pl (An_{86}) in the more calcic of the three-phase fields. Orville (1975) has suggested that Pl of composition An_{40-85} should not occur with Cal and Scp. Pl pseudomorphs of Scp having a composition of An_{73} fall within the "composition gap" indicating retrograde breakdown of Scp. Aitken (1983) reported a similar occurrence of Pl pseudomorphs after Scp which he attributed to retrograde metamorphism at lower temperatures but continued high X_{CO_2} . A second reaction involving Scp at Winding Stair Gap is:



indicated by Czo rims around Scp and by Scp inclusions within Czo.

IV. METAMORPHIC CONDITIONS

The Winding Stair Gap exposure, with six units of distinctly different chemical character, permits conditions for both prograde and retrograde metamorphism to be constrained rather tightly. Because all six units are confined to a single continuous outcrop, pressure and temperature constraints for one unit can be assumed valid for the entire outcrop. Even the orthopyroxenite, though of uncertain origin, was emplaced prior to or during the metamorphic peak and thus records metamorphic conditions.

Univariant curves that provide limits on pressures and temperatures of peak and retrograde metamorphism are summarized in figure 13. Prograde metamorphism at Winding Stair Gap is bounded at the low temperature end by the Ms-out reaction (fig. 13, curve A) in the presence of Qtz. Primary Ms is absent in the Qtz-bearing migmatite gneiss and Sil schist units, although Ms is present as a retrograde mineral and as a minor constituent of nonfoliated quartzofeldspathic gneiss. The high pressure limiting reaction is $\text{Grt} + \text{Di}$ replacing Opx (fig. 13, curve B), separating the Hbl-granulite subfacies from the Grt-Di-Qtz subfacies. Cpx has not been observed in any unit other than the calc-silicate gneiss, but Opx and Pl are common. Crd is absent (fig. 13, curves C and D) in the Sil schist unit, placing a

Figure 13. P-T diagram for prograde and retrograde assemblages at the Winding Stair Gap exposure. $\text{Ms} + \text{Qtz} \rightleftharpoons \text{Al}_2\text{SiO}_5 + \text{Kfs} + \text{H}_2\text{O}$ at $X_{\text{H}_2\text{O}} = 1.0$ (curve A) and $X_{\text{H}_2\text{O}} = 0.5$ (curve A') (Kerrick, 1972; Chatterjee and Johannes, 1974) define the low temperature limit for prograde metamorphism. Reactions $\text{Opx} + \text{Pl} \rightleftharpoons \text{Grt} + \text{Di} + \text{Qtz}$ (curve B) (Hapuararchchi, 1972) and $\text{Bt} + \text{Sil} + \text{Qtz} \rightleftharpoons \text{Kfs} + \text{Crd} + \text{H}_2\text{O}$ (curve C) (Thompson, 1976) define upper and lower pressure limits, respectively. $\text{Bt} + \text{Sil} + \text{Qtz} \rightleftharpoons \text{Crd} + \text{Ms}$ (curve D) (Thompson, 1976) is the low pressure limit for retrograde metamorphism. Other univariant curves which affect retrograde metamorphism are $\text{Chl} + \text{Ms} \rightleftharpoons \text{Bt} + \text{Sil} + \text{Qtz}$ (curve F) (Bird and Fawcett, 1973), $\text{Ky} \rightleftharpoons \text{Sil}$ (curve G) (Holdaway, 1971), and the minimum melting curves of granite at $X_{\text{H}_2\text{O}} = 1.0$ (curve E) and $X_{\text{H}_2\text{O}} = 0.5$ (curve E') (Kerrick, 1972; Boettcher and Wyllie, 1968). The reaction $\text{Crd} \rightleftharpoons \text{Grt} + \text{Sil} + \text{Qtz} + \text{H}_2\text{O}$ is shown for Crd having composition $\text{Fe}/(\text{Fe}+\text{Mg}) = .20$ (curve H) and Mg-Crd (curve H') to show effect of composition on the Crd-out reactions (Holdaway and Lee, 1977). Calculated geothermometers and the Grt-Pl geobarometer, with error bars, are shown for comparison.

minimum pressure limit on prograde and retrograde metamorphism. Use of the Crd-out reaction is complicated because the divariant field of coexisting Grt and Crd is a function of $Mg/(Mg+Fe)$ (fig. 13, curves H and H'). A maximum temperature for prograde metamorphism is indicated by the intersection of univariant curves B and C (fig. 13). Prograde metamorphism at Winding Stair Gap, determined from the stability fields of these key mineral assemblages, is confined to temperatures of 710°-825°C at pressures of 6.0-7.8 kb.

Pressure and temperature values determined from mineral exchange equilibria (Table 6 and fig. 13) overlap the mineral stability fields described above. Fe^{2+} -Mg exchange between coexisting Bt and Grt were determined using calibrations of Ferry and Spear (1978) and Goldman and Albee (1977). Although temperature values are reported in Table 6 for Grt cores and rims, the Grt core values are erroneously high. The use of Grt core compositions and matrix Bt for exchange geothermometry has been justified by Chamberlain and Lyons (1983) and Tracy and others (1976) in rocks having minor Grt compared with Bt, or Grt with narrow, retrograde rims. However, as Grt in most samples at Winding Stair Gap occur in subequal amounts with Bt, the Bt is probably not in equilibrium with Grt cores.

Ferry and Spear (1978) indicated their calibration can be used without correction for $(Ca+Mn)/(Ca+Mn+Fe+Mg)$ less

Table 6. Data for Temperature, Pressure, and Fluid Composition Calculations

Reaction	Rock Type	Sample	Chemical Data for Exchange						T, °C	
Exchange			Geothermometry							
Grt-Bt (Fe ²⁺ -Mg)			Grt (Mg/Fe)	Ca+Mn		Bt (Mg/Fe)	Al ^{VI} +Ti		lnK _D	
				Ca+Mn+Fe+Mg			Al ^{VI} +Ti+Fe+Mg			
Bt-Grt granulite		FG-2	core	.407		1.239		-1.113	865 + 25	
			rim	.371	.22	1.239	.13	-1.206	812	
Bt-Hbl granulite		Q-54	core	.467		1.869		-1.387	721	
			rim	.422	.28	1.869	.15	-1.488	677	
Sil schist		FS-2	core	.616		2.230		-1.286	770	
			rim	.588	.09	2.230	.12	-1.333	746	
Sil schist		P-9	core	.349		1.501		-1.459	689	
			rim	.333	.10	1.501	.15	-1.506	669	
(Ferry and Spear, 1978)										
Grt-Bt (Fe ²⁺ -Mg)			lnK _D	Bt X _{Fe}	Bt X _{Ti}	Bt ^{IV} X _{Al}	Grt X _{Mn}	Grt X _{Ca}		
Bt-Grt granulite		FG-2	core	-1.11	.446	.075	.055	.048	.168	836 ± 25
			rim	-1.21			.041	.171	768	
Bt-Hbl granulite		Q-54	core	-1.39	.349	.044	.110	.042	.079	704
			rim	-1.49			.044	.082	664	
Sil schist		FS-2	core	-1.29	.310	.058	.061	.045	.046	703
			rim	-1.33			.046	.051	.689	
Sil schist		P-9	core	-1.46	.400	.066	.081	.063	.042	600
			rim	-1.50			.060	.041	585	
(Goldman and Albee, 1977)										
Scp-Pl (NaSi = CaAl)			Scp X _{Me}	Pl X _{An}	f ₁	f ₂				
calc-silicate gneiss		FG-1	.760	.868	2258	-820			778 ± 50	
(Goldsmith and Newton, 1977)										

Table 6 (continued)

Reaction	Rock Type	Sample	Chemical Data for Exchange						T, °C
Pl-Hbl (NaSi = CaAl)			X _{Ca} ^{Pl}	X _{Na} ^{Pl}	Na(M4)	Ca(M4)	InK _D		
	Bt-Hbl granulite	Q-49	.781	.219	.319	1.681	-.390		718 ± 50
	Bt-Hbl granulite	Q-54	.799	.198	.252	1.748	-.542		705
	calc-silicate gneiss	FG-1A	.868	.132	.145	1.855	-.665		695
	Bt-Grt granulite	Q-18	.460	.535	.338	1.599	-1.705		616
	orthopyroxenite	FM-3	.399	.599	.469	1.531	-1.589		624
									(Spear, 1980)
<u>Geobarometry</u>									
3 An = Grs + 2 Sil + Qtz			T, °C	X _{An} ^{Pl}	a _{An}	X _{Grs} ^{Grt}	X _{Pyp} ^{Grt}	X _{Alm} ^{Grt}	a _{Grs}
	Sil schist	FS-2	750	.340	.469	.050	.335	.569	.046
									55.6
									6.7 ± 0.8
									(Newton and Haselton, 1981)
<u>Fluid Composition</u>									
<u>Dehydration</u>									
Bt + Sil + 2 Qtz = Kfs + Grt + H ₂ O			T, °C	a _{Kfs}	a _{Alm} ^{Grt}	a _{Ann} ^{Bt}	K*	InK*	a _{H₂O}
	Sil schist	FS-2	750	.08	.184	.016	9.2	2.22	0.2
									(Phillips, 1980)

than 0.2 in Grt and $(Al^{VI}+Ti)/(Al^{VI}+Ti+Fe+Mg)$ less than 0.15 for Bt. Two of the four samples recorded in Table 6, including samples FG-2 which has the highest calculated temperature, exceed the maximum amounts of additional components allowed and may be of questionable value. A second calibration of the Fe^{2+} -Mg exchange between Grt and Bt (Goldman and Albee, 1977) does take into account additional components. Although the values for the Goldman and Albee (1977) calibration (Table 6) are lower than corresponding values determined by the Ferry and Spear (1978) calibration, both give maximum temperatures around 750°C. Both Fe^{2+} -Mg calibrations are essentially pressure insensitive, changing only 5°-10°C/kb.

Other geothermometers include NaSi = CaAl exchange between coexisting Pl and Hbl in the calc-silicate gneiss, orthopyroxenite, and mafic granulites and NaSi = CaAl exchange between Pl and Scp in the calc-silicate gneiss. Scp-Pl geothermometry (Goldsmith and Newton, 1977) gives a value of $778 \pm 50^{\circ}C$ (Table 6), which is consistent with the temperature estimated from the Grt-Bt geothermometer. Temperatures calculated from NaSi = CaAl exchange in Pl and Hbl are 50°-150° lower than the maximum values for the Grt-Bt and Scp-Pl geothermometers. Part of the discrepancy may rest with the difficulty in estimating Na in the M4 site of Hbl and the nonideality of the exchange (Spear, 1980;

1981b). Hbl-Pl geothermometry at Winding Stair Gap is based on Hbl normalization to 13 cations excluding Ca, Na, and K (Table 3, p. 42). In addition, reequilibration may result in calculated temperatures lower than the metamorphic peak. Geothermometry of NaSi = CaAl exchange in Pl and Hbl of the orthopyroxenite undoubtedly reflects a value lower than peak metamorphism because Hbl has been produced as a retrograde mineral.

A cluster of calculated temperatures in the vicinity of 750°-775°C (fig. 13) probably reflects the maximum temperature of prograde metamorphism. Other values, between 650°-700°C and near 600°C, probably reflect points along the retrograde path at which reequilibration occurred. The lowest temperature calculated from Grt-Bt geothermometry (Ferry and Spear, 1978) occurs in sample P-9 of the Sil schist unit in which Ms- and Ky-bearing Kfs segregations are present. Ms, and less commonly Ky, in nonfoliated quartzofeldspathic gneiss confine temperatures of melt crystallization below the Ms-out curve (fig. 13). Point counts of two nonfoliated quartzofeldspathic gneiss samples* (Q-4: Qtz = 25%; Kfs = 22%; An = 8%; Ab = 45%; and Q-12: Qtz = 38%; Kfs = 9%; An = 20%; Ab = 33%) indicate crystallization at

*Error estimated as less than 3% based on 1000 counts (van der Plas and Tobi, 1965). Pl recalculated into Ab and An based on optically determined composition.

approximately 640°C and 690°C, respectively, at $P_{H_2O} = 5$ kb determined from cotectic surfaces in the system Qtz-Ab-Or-An-H₂O (Winkler, 1979). A minimum temperature in sample P-9 of the Sil schist and from the nonfoliated quartzofeldspathic gneiss can be derived from the Hem-Ilm miscibility gap of Lindsley (1973). The composition estimated for the ilmeno-hematite grains prior to exsolution (Table 5, p. 51) indicates crystallization above 630°C.

Ca-distribution between Pl and Grt for the assemblage Pl+Grt+Sil+Qtz, calibrated by Newton and Haselton (1981), gives a pressure of prograde metamorphism of 6.7 ± 0.8 kb (Table 6) at 750°C. An additional pressure estimate can be calculated from Grt compositions in the Sil schist unit using a Fe-Mg-Mn ternary diagram and isopleths of Grt in equilibrium with Crd and Sil (Tracy and others, 1976, fig. 6, p. 34). Grt-bearing pelitic assemblages lacking Crd occur at higher pressures than assemblages containing Crd, so the isopleths can be used to define minimum pressures for the Crd-absent assemblages. Grt compositions at Winding Stair Gap indicate minimum pressures of 6.5 kb at 750°C and 6.2 kb at 650°C, using temperatures derived from Grt-Bt geothermometry for samples FS-2 and P-9, respectively. No error estimate for the pressure determination of Tracy and others (1976) was reported. Based upon the Grt-Pl geobarometer and the Crd-absent Grt compositions, a pressure

range of 6.5-7.0 kb appears to be reasonable for prograde metamorphism. A 6.4 kb minimum pressure for retrograde metamorphism is indicated by the presence of Ky in the nonfoliated quartzo-feldspathic gneiss and by the absence of Crd in the retrograde Sil schist sample, P-9. No maximum pressure can be determined from the coexisting mineral assemblages at Winding Stair Gap, but a pressure increase during cooling is unlikely.

Fluid composition at Winding Stair Gap can be less precisely determined than the intensive parameters temperature and pressure in part because fluid composition may have changed dramatically during retrograde metamorphism. Internal control of fluid composition is most evident in the calc-silicate gneiss. Although the calc-silicate unit is volumetrically insignificant at Winding Stair Gap, the abundance of Cal and carbonate Scp suggests high X_{CO_2} . Absence of Wo in the presence of Cal and Qtz indicates a minimum value of $X_{\text{CO}_2} = 0.25$ at 750°C (fig. 14, curve A). Cal is the only CO_2 -bearing mineral in units other than the calc-silicate gneiss, occurring in trace amounts as narrow selvages between grains or as replacement of Pl.

Activity calculations for products and reactants of the Grt-producing dehydration reaction:

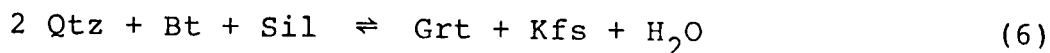


Figure 14. $T-X_{\text{CO}_2}$ diagram for the calc-silicate gneiss. Minimum X_{CO_2} values for prograde metamorphism are defined by $\text{Wo} + \text{Co}_2 \rightleftharpoons \text{Cal} + \text{Qtz}$ (curve A) (Jacobs and Kerrick, 1981). $\text{Pl} + \text{Cal}$ replacing Scp (curve B) (Aitken, 1983) occurred at temperature greater than 625°C and X_{CO_2} greater than 0.2 during initial cooling. Lower temperature or X_{CO_2} produces Czo (curve C) (Aitken, 1983; Jacobs and Kerrick, 1981). A minimum temperature of 550°C is indicated for retrograde reactions by the absence of Rt (curve D) (Hunt and Kerrick, 1977).

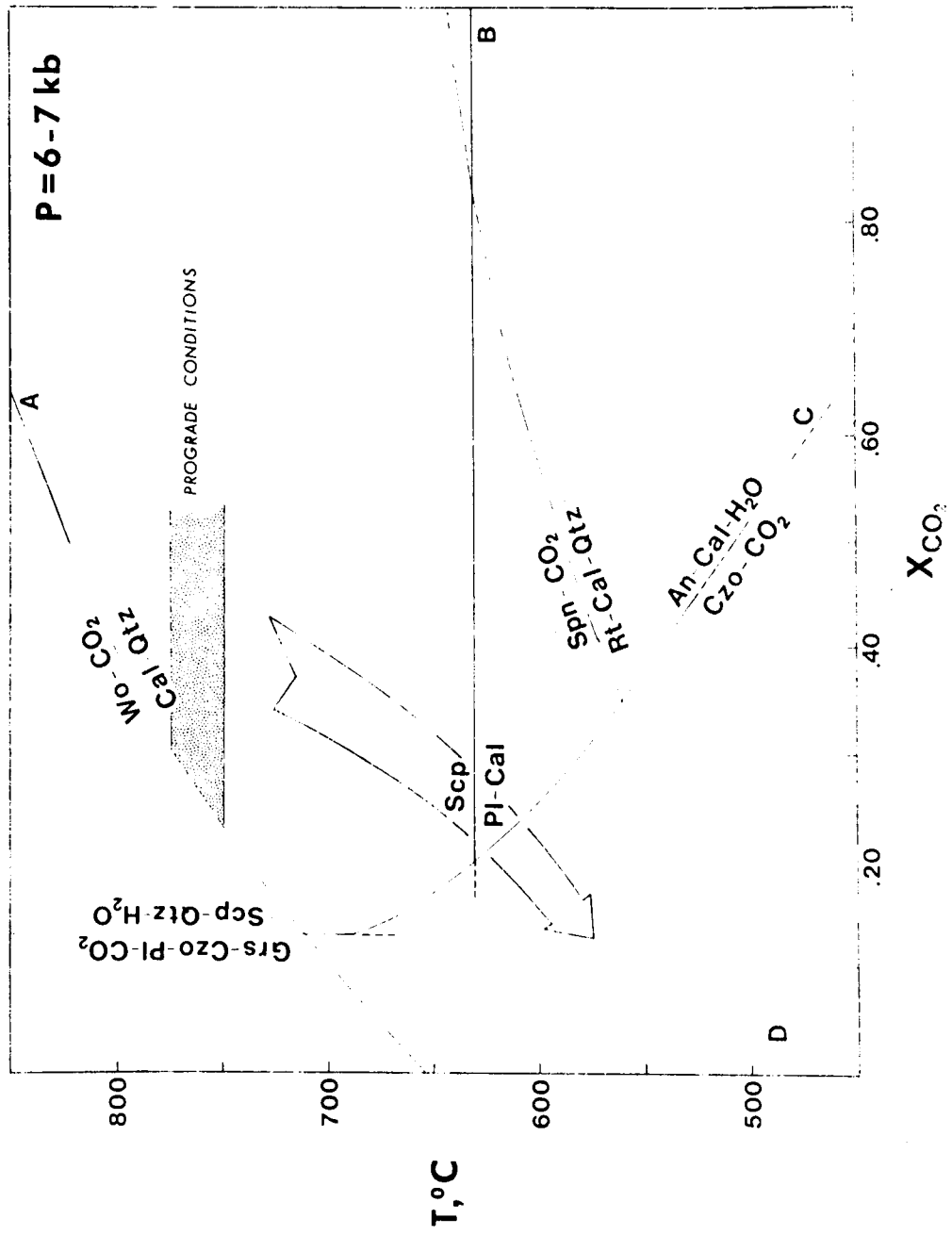


Figure 14.

in the Sil schist unit give an estimate of $a_{\text{H}_2\text{O}}$ (Phillips, 1980). If $P_{\text{fluid}} = P_{\text{total}}$ and ideal mixing of fluid species is assumed, $a_{\text{H}_2\text{O}} = X_{\text{H}_2\text{O}}$. For $P_{\text{fluid}} = P_{\text{total}}$, $X_{\text{H}_2\text{O}} \cdot P_{\text{total}} = P_{\text{H}_2\text{O}}$. Calculated activity values for reaction 1 (Table 6) indicate $a_{\text{H}_2\text{O}} = 0.2$ ($P_{\text{H}_2\text{O}} = 1.3 \text{ kb}$) under prograde conditions. $P_{\text{H}_2\text{O}}$ approximately 0.1-0.3 times total pressure has been argued for granulite facies rocks in India (Janardhan and others, 1982) and Greenland (Wells, 1980). Slightly higher values (0.35-0.6) were reported by Phillips (1980) for granulite facies rocks of the Broken Hill area, Australia.

During retrograde metamorphism, $P_{\text{H}_2\text{O}}$ increased significantly. Ms in nonfoliated quartzo-feldspathic gneiss indicates $X_{\text{H}_2\text{O}}$ is greater than 0.5 in the melt (fig. 13, curves A' and E') according to data presented by Kerrick (1972). Retrograde hydration of Opx to Cum, blue-green Hbl, and Bt in the orthopyroxenite unit and the formation of minor Chl in Grt fractures also indicate an increase in $P_{\text{H}_2\text{O}}$. A similar fluid-temperature path can be traced in the calc-silicate gneiss unit. Cooling from a metamorphic peak of 750°C may have involved little initial change in X_{CO_2} to 625°C, at which point Scp conversion to Pl and Cal (Aitken, 1983) (reaction 4) occurred (fig. 14, curve B). A continued decrease in temperature, or an increase in $X_{\text{H}_2\text{O}}$, would result in intersection of the Czo-in reaction (fig. 14,

curve C). Czo formation related to the introduction of H_2O -rich fluid into metacarbonates has been recognized elsewhere by Ferry (1976). Czo formation takes place at approximately 625° - $600^{\circ}C$, the temperature calculated for Opx hydration in the orthopyroxenite. The presence of Spn rather than Rt in the calc-silicate gneiss indicates retrograde reactions occurred at temperatures above curve D (fig. 14).

$\log f_{O_2}$ of approximately -20 has been determined for the Bt-Hbl granulite (sample Q-49) using the composition of Ilm in Table 5 (p. 51) at the calculated temperature of $700^{\circ}C$ (Table 6) (Spencer and Lindsley, 1981). Coexisting Fe-Ti oxides indicate $\log f_{O_2}$ is less than -19 for prograde assemblages containing Mag and Ilm (Rumble, 1973). Higher $\log f_{O_2}$ values, between -18 and -19, exist for Kfs segregations in the Sil schist unit and nonfoliated quartzo-feldspathic gneiss containing ilmeno-hematite and hemo-ilmenite (Rumble, 1973) and are consistent with localized introduction of water into the system during cooling (Rollinson, 1980). Prograde metamorphism restricted to f_{O_2} values below the HM buffer is suggested by experimental studies of amphibole stability by Spear (1981a). Opx appears as a stable reaction product at temperatures of 750° - $800^{\circ}C$ only at f_{O_2} near the QFM buffer under low P_{H_2O} conditions (Spear, 1981a).

V. PETROGENESIS

Barrovian metamorphism of the southwestern North Carolina-northeastern Georgia area and the peak metamorphic conditions at Winding Stair Gap indicate higher temperatures than would be produced solely from burial. One source for the additional heat necessary to produce granulite facies mineral assemblages at Winding Stair Gap could be magmatic activity. The orthopyroxenite, interpreted earlier as possibly an igneous body, is not of sufficient size to account for elevated temperatures for the Winding Stair Gap exposure. Furthermore, granulite facies rocks in southwestern North Carolina occur on a regional scale, necessitating a regional heat source. Several syntectonic plutons (Whiteside, Rabun, Pink Beds, and Looking Glass) of trondhjemitic to granodioritic composition occurring in the Hayesville thrust sheet (Miller and others, 1983; Sando and others, 1983) may be the regional heat source. An age range of 460-390 m.y. (Miller and others, 1983) is consistent with other dates for Taconic metamorphism reported earlier. Isotopic data indicate that these magmas were produced from a depleted mantle source contaminated by continental crust (Sando and others, 1983; Miller and others, 1983).

Crustal heating derived from magmatic intrusions rather than deeper burial is supported by the apparently isobaric cooling path, from a peak temperature of 750°-775°C to a

retrograde temperature of 600°C, at Winding Stair Gap (fig. 13). Isobaric cooling paths from other granulite facies localities (Corbett and Phillips, 1981; Bohlen, 1983) have been interpreted as resulting from cooling of magma beneath regionally metamorphosed terranes. Cooling of the rocks at Winding Stair Gap to approximately 600°C (the approximate lower limit to retrograde metamorphism) would restore the regional geothermal gradient. Another possible mechanism for isobaric cooling is conduction of heat under low erosion rates (England and Richardson, 1977); however, low erosion rates for the southern Appalachians during the Taconic orogeny are not consistent with an eastern sediment source area for Ordovician clastic rocks in the Valley and Ridge. A more plausible mechanism involves heat loss through removal of anatectic melts. Numerous small post-metamorphic pegmatitic and trondhjemitic dikes in the Ky and Sil zones of the southern Blue Ridge (Carpenter, 1970) may be the result of anatectic melts moved to higher levels. As the overlying metamorphic sequence would be cooler than the melt source, the intrusives would appear to be postmetamorphic.

Producing granulite facies mineral assemblages requires low P_{H_2O} in addition to elevated temperatures. Low water fugacities may be inherited from relatively anhydrous rocks or from an earlier metamorphic event. The stratigraphy of

Winding Stair Gap is dominated by presumably wet metasediments which have suffered no prior metamorphism. High P_{H_2O} could be lowered by addition of other volatiles which dilute an aqueous fluid phase, a method convincingly documented by Janardhan and others (1982) and Newton and Hansen (1983). Dilution of H_2O by addition of volatiles does not appear to have been important at Winding Stair Gap, however. The thin calc-silicate gneiss could not have provided an adequate CO_2 source. Pervasive passageways for infusion of a CO_2 -rich fluid are not obvious at Winding Stair Gap.

Dehydration reactions, documented for the Sil schist and mafic granulite units, are concurrent with localized partial melting. Coexistence of a granitic melt with solid phase assemblages would result in partitioning of water into the melt (Grant, 1973; Phillips, 1980; Wells, 1980). Removal of the granitic melt would result in removal of water as well. The remaining granitic melt would release water during crystallization, causing retrograde metamorphism. If only limited amounts of in situ partial melt remain, as is the case at Winding Stair Gap, the retrograde metamorphism would be restricted.

Retrograde metamorphism associated with cooling of anatectic melts could be mistakenly interpreted as a second metamorphic event (Acadian?). However, it seems unlikely that a separate metamorphic event of sufficient intensity to

produce anatectic melts would overlap Taconic isograds. In addition, retrograde metamorphism is largely confined to areas of the highest metamorphic grade, precisely the same zones which would be producing partial melts, would retain elevated temperatures for the longest time, and would be most out of equilibrium with lower grade conditions.

The Paleozoic granulite facies rocks at Winding Stair Gap are similar to older granulite facies rocks in having Sil as the alumino-silicate polymorph, Opx in the mafic granulites, and perthitic Kfs in the Sil schist and quartzo-feldspathic gneiss units. The mineral assemblages in the mafic granulites at Winding Stair Gap are different from other granulite facies rocks, however (fig. 15). The Winding Stair Gap assemblages are Hbl+Grt+Bt, common in upper amphibolite facies rocks, and Hbl+Bt+Opx. Opx does not occur with Di or Grt, although such an assemblage is common in older granulite terranes. The absence of typical mineral assemblages in the mafic granulites may indicate Winding Stair Gap did not reach the temperature extremes of older granulite terranes. Alternatively, the presence of two abundant hydrous phases, Hbl and Bt, rather than the anhydrous phases, Di and Grt, may indicate the rocks at Winding Stair Gap were not as dry during prograde metamorphism as other granulite facies rocks.

Figure 15. Comparison of mineral assemblages for mafic granulites at Winding Stair Gap with other granulite facies rocks shown on ACF diagrams. The stable assemblages at Winding Stair Gap are Hbl-Grt-Bt, corresponding to upper amphibolite facies, and Hbl-Bt-Opx, corresponding to granulite facies. The absence of Opx-Cpx and Opx-Grt assemblages, common in other granulite facies terranes, suggests important differences in metamorphism at Winding Stair Gap.

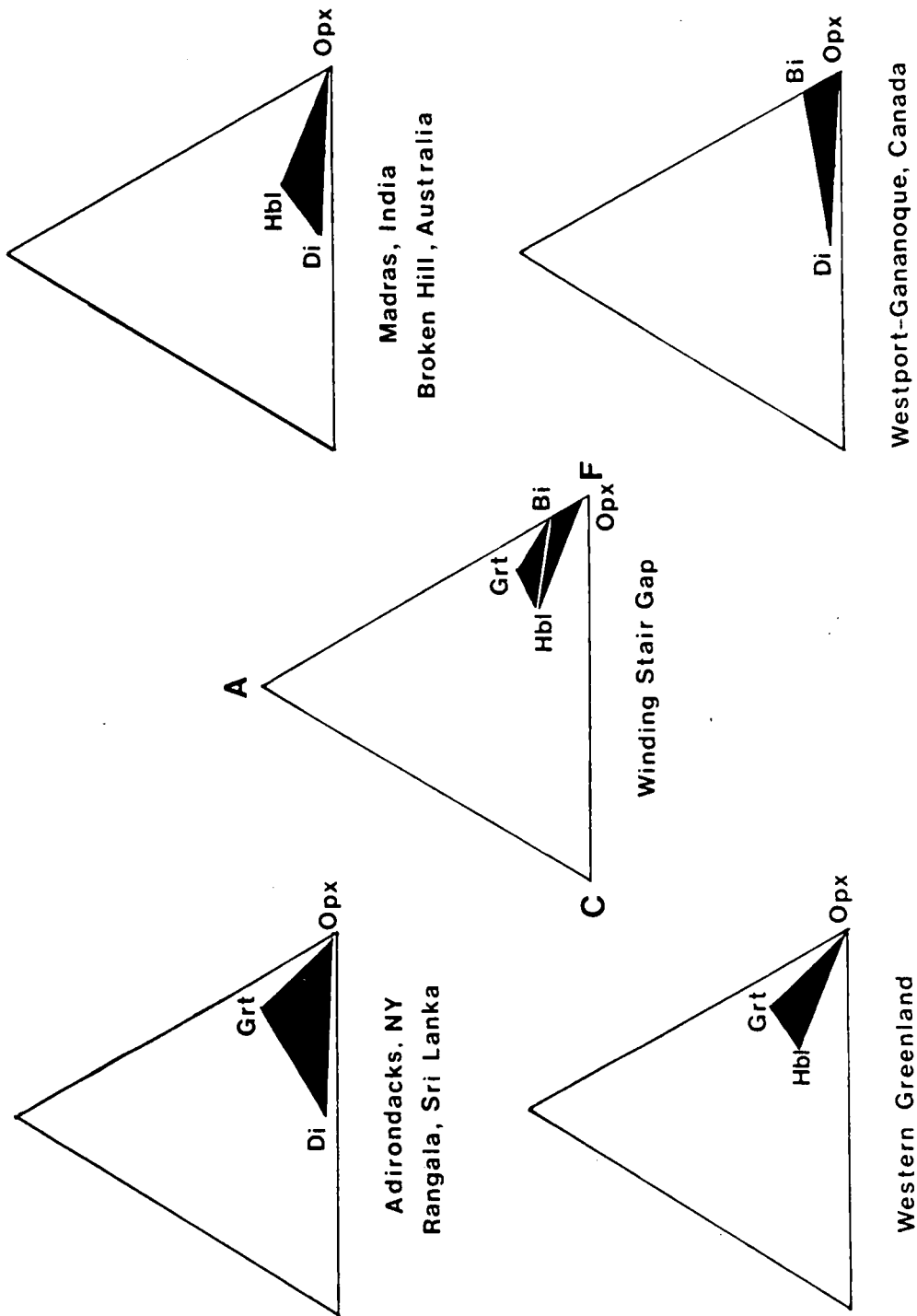


Figure 15.

VI. CONCLUSION

The Winding Stair Gap exposure has provided important information concerning the metamorphic and deformational history of the southwestern North Carolina-northeastern Georgia Blue Ridge. The metamorphic history of the Winding Stair Gap area is summarized as follows:

1. Late Precambrian to early Cambrian sediments, interlayered with basaltic flows or intruded by mafic sills prior to deformation, were deposited in a shelf edge to ocean basin environment. The Winding Stair Gap lithologies correlate with one of several intervals in the Tallulah Falls Formation or the upper part of the Coweeta Group. The orthopyroxenite unit does not fit into the stratigraphy and may be an igneous body intruded or structurally emplaced prior to metamorphism and F_2 deformation. This unit may be related to possible ophiolitic slices occurring elsewhere in the Hayesville thrust sheet.
2. Early Taconic deformation (F_1 , S_1 ?) preceded the thermal peak of granulite facies metamorphism. F_2 and S_2 , the dominant folds and foliation, coincided with peak metamorphism. Mapped isograd patterns for the southern Appalachian Blue Ridge indicate

the regional geothermal gradient follows a normal (Barrovian) path.

3. Prograde metamorphism at $T = 750^{\circ}\text{--}775^{\circ}\text{C}$, $P = 6.5\text{--}7.0$ kb for the granulite zone probably reflects regional magmatic activity in the form of trondhjemitic to granodioritic plutons emplaced within the Hayesville thrust sheet during Taconic metamorphism. Water from dehydration reactions formed migmatitic melts, resulting in $P_{\text{H}_2\text{O}}$ less than P_{total} .
4. Isobaric cooling, probably facilitated by removal of some partial melts to higher structural levels, may have been accompanied by F_3 deformation.
5. Remaining in situ partial melts released water during crystallization below 700°C , resulting in increased $P_{\text{H}_2\text{O}}$, slightly increased f_{O_2} , and retrograde hydration reactions. Decreasing temperature allowed the formation of Ky in nonfoliated quartzofeldspathic gneiss and in Kfs segregations in the Sil schist.

Any interpretation of the metamorphic history of a large portion of the southern Appalachian orogenic belt based upon data from a single, albeit impressive, outcrop, is somewhat speculative. However, the information from this study suggests the importance of Winding Stair Gap is

disproportionate to its size. The Winding Stair Gap exposure has enabled documentation of the original lithologic variations, deformational history, and metamorphic conditions for the highest grade rocks in the Paleozoic metamorphic belt of the southern Blue Ridge. The complexity of these features at the Winding Stair Gap exposure suggests that the full potential of this high grade terrane for our understanding of the tectonic history of the southern Blue Ridge may not yet have been realized.

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APPENDICES

APPENDIX A

MINERAL ABBREVIATIONS

Ab	albite	Hyp	hypersthene
Alm	almandine	Ilm	ilmenite
An	anorthite	Kfs	K feldspar
Ap	apatite	Ky	kyanite
Bt	biotite	Mag	magnetite
Cal	calcite	Ms	muscovite
Ccp	chalcopyrite	Opx	orthopyroxene
Chl	chlorite	Or	orthoclase
Cpx	clinopyroxene	Phl	phlogopite
Crd	cordierite	Pl	plagioclase
Cum	cummingtonite	Po	pyrrhotite
Czo	clinozoisite	Prp	pyrope
Di	diopside	Py	pyrite
En	enstatite	Qtz	quartz
Ep	epidote	Rt	rutile
Fsp	feldspar	Scp	scapolite
Fs	ferrosilite	Sil	sillimanite
Grt	garnet	Spn	sphene
Grs	grossular	Sps	spessartine
Hem	hematite	Wo	wollastonite
Hc	hercynite	Zrn	zircon
Hbl	hornblende		

(from Kretz, 1983)

APPENDIX B

SAMPLE LOCATION AND PETROGRAPHY

Thin sections of selected samples from the Winding Stair Gap exposure (locations in fig. 16) have been studied in transmitted and reflected light. Mineralogy of each thin section is summarized in Tables 7-12. Oxide and sulfide phases identified in polished thin sections of some representative samples are listed in Table 13. "x" indicates an abundant mineral, usually constituting greater than 5 volume % of the sample. "-" indicates a mineral is present in amounts less than approximately 5 volume %. " " signifies a mineral was not observed in a particular thin section. "*" indicates samples for which major element chemistry has been determined by electron microprobe analysis.

Sil Schist

P-7. Strongly foliated Bt-Grt-Sil schist contains segregations (4-10 cm length) of Qtz-Kfs-Pl. Microperthitic Kfs appears as unstrained grains in straight to slightly sigmoidal-shaped lenses (1-3 cm length). Sil is generally less abundant around Kfs lenses. Small kink bands are sometimes present in Sil and Bt grains, but the kinks never form a pervasive deformational fabric. Qtz is generally absent in Grt-Bt-Sil bands, though common in association with Pl, Kfs, and Bt.

Table 7. Mineralogy of the Sil Schist

	Ap	Bt	Cal	Chl	Grt	Hc	Kfs	Ky	Ms	Pl	Qtz	Sil	Zrn	opaque minerals
P-7	x	x	-	-	x	-	-	-	-	-	-	x	-	-
P-8	x	x	-	-	x	-	-	-	-	-	-	x	-	-
P-9	x	x	-	-	x	-	x	-	-	-	-	x	-	-
P-20	x	x	-	-	x	-	x	-	-	-	-	x	-	-
FS-2	x	x	-	-	x	-	-	-	-	-	-	x	-	-
FS-3	-	x	-	-	x	-	x	-	-	x	-	x	-	-
FS-10	-	x	-	-	x	-	x	-	-	-	-	x	-	-
FS-11	-	x	-	-	x	-	x	-	-	-	-	x	-	-

Table 8. Mineralogy of the Calc-Silicate Gneiss

	Ap	Alm	Bt	Cal	Czo	Di	Grs	Hbl	Kfs	Ms	Phl	Pl	Qtz	Scp	Sil	Spn	Zrn	opaque minerals
C-1	+	+	+	+			+	+	+	+		+	+	+		+	+	+
C-3A	+		+	+		+	+	+		+		+	+	+		+	+	+
C-3B	+	+	+	+		+	+	+	+	+		+	+	+		+	+	+
Q-22	+			+	+		+	+	+	+		+	+	+		+	+	+
Q-31	+		+	+	+		+	+	+	+		+	+	+	+	+	+	+
Q-33	+		+	+	+		+	+	+	+		+	+	+	+	+	+	+
FG-1			+	+			+	+	+	+	+	+	+	+	+	+	+	+
FG-1A	+	+	+	+	+	+	+	+	+	+		+	+	+		+	+	+

Table 9. Mineralogy of the Bt-Hbl Granulite

	Ap	At	Cal	Cum	Grt	Hbl	Hc	Kfs	Opx	Pl	Qtz	Sil	Zrn	opaque minerals
Q-6	-	x	-	-	-	x	-	-	-	x	-	-	-	-
Q-10	-	x	-	-	x	x	-	-	-	x	-	-	-	-
Q-14	-	x	-	-	-	x	-	-	-	x	-	-	-	-
Q-38	-	x	-	-	-	x	-	-	-	x	-	-	-	-
Q-39	-	x	-	-	x	x	-	-	-	x	-	-	-	-
Q-49	-	x	-	-	x	x	-	-	-	x	-	-	-	-
Q-54	-	x	-	x	x	x	-	-	x	x	-	-	-	-
Q-57	-	x	-	-	-	x	-	-	x	x	-	-	-	-

Table 10. Mineralogy of the Bt-Grt Granulite

	Ap	Bt	Cal	Cum	Ep	Grt	Hbl	Kfs	Ms	Opx	Phl	Pl	Qtz	Sil	Zrn	opaque minerals
Q-18	+	+	+	+			+	+		+		+	+		+	+
Q-19	+	+	+			+	+	+				+	+		+	+
Q-24		+	+			+		+	+			+	+			+
Q-26	+	+	+			+	+	+		+		+	+		+	+
Q-27	+	+	+			+		+	+			+	+		+	+
Q-29	+	+	+			+	+	+				+	+			+
Q-30	+	+	+				+	+				+	+		+	+
Q-52	+	+	+		+		+	+	+			+	+	+	+	+
Q-58	+	+	+			+	+	+			+	+	+	+		+
FG-2	+	+	+			+	+	+				+	+			+
FG-3	+	+	+	+			+	+			+	+	+			+
FM-10	+	+	+	+		+	+	+	+		+	+	+		+	+

Table 11. Mineralogy of the Quartzo-Feldspathic Gneiss

	Ap	Bt	Cal	Chl	Cum	Grt	Hbl	Kfs	Ky	Ms	Pl	Qtz	Sil	Zrn	opaque minerals
Q-1		x	-			-		x		-	x	x	-	-	-
Q-2		x		-		x		x		-	x	x		-	-
Q-3	-	x	-			-		x		-	x	x	-	-	-
Q-4		x	-	-		x		x	-	-	x	x	-	-	-
Q-7		x	-					x		-	x	x	-	-	-
Q-9		x	-			x		x			x	x		-	-
Q-12	-	x	-			x		x		-	x	x	-	-	-
Q-16	-	-	-	-		x		x		-	x	x		-	-
Q-17	-	x				x		x		-	x	x		-	-
Q-23		x	-			x		x		-	x	x		-	-
Q-32	-	x						x		-	x	x		-	-
Q-36	-	x	-	-	-	x	-	x			x	x	-	-	-
Q-37		x			-	-	-	x			x	x	-	-	-
Q-41	-	x	-	-		x		x		-	x	x	-	-	-
Q-42	-	x	-			x		x		-	x	x		-	-
Q-46		x		-		x		x			x	x		-	-
Q-47		x	-	-		x		x		-	x	x	-	-	-
Q-50	-	x				x		x		-	x	x		-	-
Q-53		x				x		x			x	x	-	-	-
Q-55	-	x	-			x		x		-	x	x		-	-
GRF	-	x	-	-		x		x	-	-	x	x	-	-	-
P-4B		x				x		x	-	-	x	x	-	-	-

Table 12. Mineralogy of the Orthopyroxenite

	Ap	Bt	Cal	Cum	Grt	Hbl	Hc	Opx	Pl	Qtz	Zrn	opaque minerals
M-1	-	x	-	-		-		x	-	-	-	-
M-2	-	x							-			-
M-3		x		-		-		x	-		-	-
M-4	-	x		x		-		x	-	-		-
M-5	-	x	-		x		-		x	-	-	-
FM-1		x	-	x		-		x	-	-		-
FM-3		x		-		-		x	-	-		-

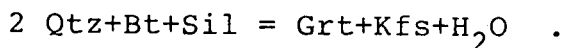
Table 13. Oxide and Sulfide Minerals

	Ccp	Hem	Ilm	Mag	Po	Py
P-9		x	x	-		
FS-2		x	x	-		
FG-1	-				-	-
FG-1A	-				-	-
Q-49	-		x	-	-	-
Q-54	-		-	-	-	-
Q-18	-			-	-	-
FG-2	-			-		-
FG-3	-		-	-		-
Q-3		-	-	-		
FM-1	-			-	-	-
FM-3	-			-	x	-

P-8. Bands of Bt-Sil schist appear as isolated blocks within gneissic bands of Kfs-Pl-Qtz and monomineralic Grt bands. Coarse-grained Sil is absent in the Grt-rich bands except where present as inclusions within Grt cores.

P-9*. Kfs grains are microperthitic with string or thread exsolution lamellae (Spry, 1969, p. 182). The microperthitic lamellae are commonly absent near the Kfs rims, suggesting diffusion of material to the grain boundaries. Alignment of Sil inclusions in Grt parallel to the foliation surface argues against postkinematic formation of Grt. Sil inclusions in Bt grains are also common.

P-20. Bt and Sil form strong foliation planes in a zone generally devoid of Qtz. Grt cores contain Sil grains aligned parallel to schistosity. Grt rims frequently are inclusion-free. In some of the more Sil-rich zones, ragged Bt grains are common. Textural features suggest the following reaction has taken place in this sample and in other specimens in the Sil schist:



Microperthitic Ksp contains inclusions of Bt, Sil, and opaque minerals.

FS-2*. Grt (0.2 mm dia.) with triple point boundaries occur as an almost homogeneous mass within the sample. The Grt masses form distinctive "froth" textures in hand-specimen. Grt-rich zones are often concentrated in the

hinge zones of tight, isoclinal folds. Sil cores and inclusion-free rims are common. Bt and opaque minerals occur within the Grt-rich layers. Bt and Sil with ragged grain boundaries are present as discontinuous layers separating Grt-rich zones.

FS-3. Poikiloblastic Grt (1 cm dia.) are much larger than usual in the Sil schist unit. Bt, Sil, and Hc inclusions are common. Grt edges are usually mantled by Sil or Bt, but seldom both. Pl, often with retrograde sericite replacement, is more abundant in sample FS-3 than is typical for the Sil schist.

FS-10. Ky and Ms are present in Kfs-Pl-Qtz segregations within the sample, but absent in the Bt-Grt-Sil zones. Opaque minerals occur in both zones, but those in the Kfs-Pl-Qtz zone are significantly larger. Examination of the opaque phases in reflected light shows Ilm and Mag within the Bt-Grt-Sil zone occur as separate, homogeneous grains. Opaque minerals in the Kfs-Pl-Qtz assemblage are ilmeno-hematite and less commonly, hemo-ilmenite. Phyllosilicate minerals in the Kfs-Pl-Qtz zone lack a consistent preferred orientation suggesting the Kfs-Pl-Qtz segregations are postkinematic.

FS-11. Ky and Ms are present in a quartzo-feldspathic vein in the sample. Sil is absent from the quartzo-feldspathic vein. Skeletal Ky and Bt grains in the vein

suggest retrograde recrystallization has occurred. Poikilitic Kfs with Sil, Bt, Pl, and Qtz inclusions occurs in the Bt-Grt-Sil zone. Sil inclusions in Grt are occasionally oriented at high angles to the planar foliation, though synkinematic crystallization of all Grt grains is not substantiated.

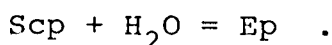
Calc-Silicate Gneiss

C-1. A traverse across the contact from quartzofeldspathic gneiss to the enclosed calc-silicate gneiss shows an increase of Qtz, Cal, and Grs near the contact and a decrease in Bt and Ms. Ilm changes to Spn in the calc-silicate zone. The Ca-content of Pl increases from An_{50} to An_{72} at the contact. Scp replacement of Pl begins at approximately 1 mm from the edge of the calc-silicate boudin. Hbl (X = light green; Y = dark green; Z = greenish-brown) appears toward the interior of the boudin.

C-3A. Bt within the calc-silicate zone has a different pleochroic formula (X = brown; Y = Z = orange-brown) compared with the pleochroic formula (X = yellow-brown; Y = Z = dark brown) of Bt in the quartzofeldspathic gneiss. Hbl occurs near the upper calc-silicate boundary and Di near the lower boundary, although the enclosing quartzofeldspathic gneiss appears to be identical at both contacts.

C-3B. Qtz- and Cal-rich segregations occur in addition to the usual segregations of mafic minerals in this sample. The mafic segregations form discontinuous, rod-like bodies. Grs grains are skeletal and poikilitic with optically continuous inclusions of Scp.

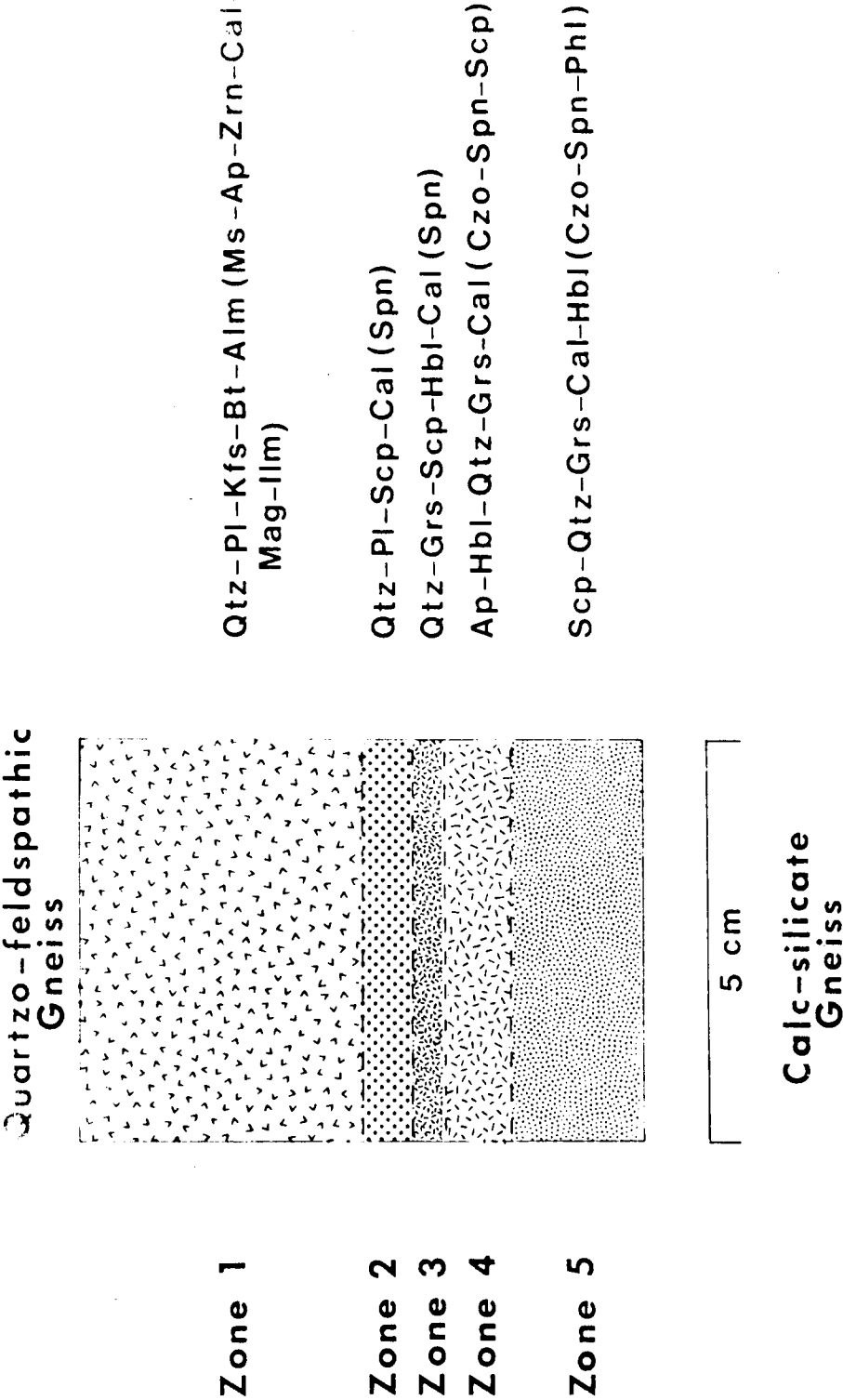
Q-22. A 1 cm wide band containing nearly 50% Ap is indicative of the strong banding of this sample. Four distinct zones are recognizable in a distance of less than 5 cm (fig. 17). In addition to Scp, Qtz, Grs, Cal, Hbl, and Spn, the zones are composed of: Czo and Phl, Ap and Czo. Some Scp are rimmed by Ep indicating the following retrograde reaction:



Q-31. Mineral zones are not symmetrically arranged within any of the calc-silicate boudins, although rod-like segregations of Grs, Hbl, and Czo separated by Qtz, Cal, and Scp are common. Elongate, spindle-shaped Qtz is oriented at a high angle to phyllosilicate minerals and Hbl. The amoeboid Qtz grain boundaries may indicate recrystallization of Qtz under a stress field different from that present during peak metamorphism.

Q-33. Quartzo-feldspathic gneiss surrounding the calc-silicate boudins is composed of Alm, Bt, Kfs, Pl, and Qtz with minor amounts of Ms, Ap, Zrn, Cal, and fibrolitic

Figure 17. Zonation patterns in a calc-silicate boudin. Zone 1 represents the quartzo-feldspathic gneiss surrounding the boudin; zone 5 is at the interior of the calc-silicate nodule.



Sil. Opaque phases within the quartzo-feldspathic gneiss are Ilm, Py, Po, and Ccp. Spn is an important accessory mineral within the calc-silicate gneiss. Czo, occurring as skeletal grains with Scp inclusions, is common. Hbl (X = light green; Y = dark green; Z = greenish-brown) also occurs as skeletal grains with inclusions. Bt is present only at the calc-silicate gneiss boundary.

FG-1*. The contact between calc-silicate gneiss and surrounding quartzo-feldspathic gneiss is marked by calcic Pl. Within the calc-silicate zone, Pl is highly altered and replaced by Scp. Alm and Bt are common in the quartzo-feldspathic gneiss; Grs is present in the calc-silicate zone. Bt foliation in the quartzo-feldspathic gneiss is oblique to the long axis of the calc-silicate boudin, indicating folding and boudinage of the calc-silicate unit prior to peak metamorphism. Mineral grains in both the calc-silicate gneiss and surrounding rock have triple point boundaries.

FG-1A*. Strongly foliated Bt in the quartzo-feldspathic gneiss parallels the calc-silicate gneiss contact. Bt, Czo, and Di are present within the calc-silicate boudin. Grs, Hbl, and Di often occur in rod-like bodies separated by Scp, Qtz, and Cal.

Bt-Hbl Granulite

Q-6. Bt grains (0.6-2 mm length) and Hbl (0.6-1 mm dia.) form a weak foliation fabric in this sample. Grt are very sparse, usually small (2-3 mm dia.), and occur in association with intruding veinlets or at contacts with petrographically dissimilar units. Hbl (X = yellow; Y = green; Z = greenish-brown) have straight, low-energy grain boundaries. A narrow zone of skeletal Hbl (X = yellow; Y = blue-green; Z = green) is also present. Fibrolitic Sil along Pl grain boundaries occurs in the vicinity of blue-green Hbl.

Q-10. Grt and Hbl, although present within a single thin section, do not generally occur in contact. Grt are extensively embayed with Pl, Ap, Qtz, and Bt inclusions comprising as much as one-fifth of the area of the Grt (1-6 mm dia.). In hand-specimen, Grt occur as sporadically distributed grains with no obvious layering or banding. Although Grt and Hbl seldom occur in contact, the boundary between Grt- and Hbl-bearing portions is not distinct in either thin section or hand-specimen. There is no apparent difference in the amount, size, or optical properties of other phases in the sample. Bt (X = yellow; Y = Z = dark brown) and Hbl (X = yellow; Y = green; Z = greenish-brown) form a weak planar fabric in the sample. Minor fibrolitic Sil occurs along Pl and Kfs boundaries. Cal occurs along

grain boundaries and as thin lamellae cutting across Pl and Kfs grains.

Q-14. This sample was collected at the contact between Bt-Hbl granulite and quartzo-feldspathic gneiss. The contact is sharp with a thin band of comminuted Bt and satellite Fsp grains around larger, rounded Pl and Kfs at the gneiss boundary. Hbl (0.5-2 mm dia.) exhibits both types of pleochroism (X = yellow; Y = blue-green; Z = green and X = yellow; Y = green; Z = greenish-brown). Blue-green Hbl have skeletal grain boundaries and greenish-brown Hbl have straight grain boundaries. A strong foliation is present in the Hbl-rich portion of the sample.

Q-38. Hbl (X = yellow; Y = green; Z = greenish-brown) (0.5-1.5 mm dia.) and less commonly Bt (X = yellow; Y = Z = dark brown) produce a well-defined fabric in the rock. Hbl shows well-developed, low-energy grain boundaries, especially at Hbl-Hbl and Hbl-Pl contacts. Grt (0.5 cm dia.) are occasionally present in hand-specimen but were not observed in thin section. Fibrolitic Sil is present at Fsp and Qtz grain boundaries.

Q-39. Skeletal Grt (2-3 mm dia.) occur in contact with Hbl (X = yellow; Y = green; Z = greenish-brown) near the edge of a quartzo-feldspathic gneiss vein. Grt is less common away from the contact and Hbl is more abundant. Bt (X = yellow; Y = Z = dark brown) (0.5-1 mm dia.) does not

show a discernable increase or decrease from the Grt-bearing to the Grt-free zone. Bt and Hbl are strongly foliated in this sample.

Q-49*. A 1-2 mm wide Qtz vein with sulfide mineralization as small clots transects the Bt-Hbl granulite sample. Hbl (X = yellow; Y = green; Z = greenish-brown) forms a lineation. Skeletal Grt (2-7 mm dia.) are widely scattered throughout the sample and may crystallize at the expense of Hbl, which decreases in abundance near Grt. In some Bt-Hbl granulite samples, very large Grt (up to 3 cm dia.) have coronas of Pl 0.5 cm wide in which Hbl is absent, suggesting a possible late-stage Grt-producing reaction.

Q-54*. A Grt-Bt assemblage occurs in knife-sharp contact with a Hbl-Bt-Cum zone. Bt (X = yellow; Y = Z = dark brown) grains (1-2 mm dia.) occur in the Grt-Bt zone oriented parallel to the contact. The Grt-Bt zone has less than 10% Pl and Qtz. Grt (0.2-2 mm dia.) have core inclusions of Bt, opaque minerals, Sil, and rare Hc. Grt rims are inclusion-free. The contact between Grt-Bt and Hbl-Bt-Cum assemblages is marked by a 3 mm wide band of comminuted Bt and recrystallized Qtz. Cum and Hbl (X = yellow; Y = green; Z = greenish-brown) are present adjacent to the contact with Cum diminishing and Opx appearing approximately 5 mm from the contact. Cum occurs as rounded clots bordered by a discontinuous rim of Mag. Opx grains (0.2-1.8 mm dia.)

are anhedral to subhedral. The Grt-Bt assemblage occurs as a 1 m long, lens-shaped body completely enclosed by the Hbl-Opx-Cum assemblage.

Q-57. The Bt-Hbl granulite sample occurs enfolded with Sil schist. A strong foliation is produced by Hbl and Bt (0.2-1 mm dia.). Hbl and Opx layers occur as dark-colored gneissic bands separated by 1 mm wide Fsp-rich bands. Large Grt are present in the non-gneissose, weakly foliated portions of the hand-specimen. Hbl grains (X = yellow; Y = green; Z = greenish-brown) have well-developed, triple-point grain boundaries. Less commonly Hbl (X = yellow; Y = blue-green; Z = green) occurs exclusively as rims around Cum, which in turn surrounds relict Opx grains. Fibrolitic Sil is present at Pl and Kfs grain boundaries.

Bt-Grt Granulite

Q-18*. Large Grt (4-5 cm dia.), although not observed in thin section, are widely scattered in the Opx-bearing sample. Lens-shaped layers of coarse-grained Bt are also present. The texture is generally equigranular with no apparent foliation or lineation of mineral grains. Opx contains Bt and Hbl (X = yellow; Y = green; Z = greenish-brown) inclusions. Reaction rims of Cum, Hbl (X = yellow; Y = blue-green; Z = green), and opaque minerals may surround Opx.

Q-19. Closely spaced euhedral Grt (5-7 mm dia.) in a matrix of Bt, Hbl, and Pl is a diagnostic feature of this sample and the Bt-Grt granulite unit. No foliation fabric is present, although a 1 mm wide band of Bt transects the specimen. Fsp-Fsp contacts are low-energy, triple-point junctions. Hbl (X = yellow; Y = green; Z = greenish-brown) and Grt are present within the thin section, though Bt mantles around Grt generally separate the two phases.

Q-24. A Kfs-rich vein at least 15 m long cuts across bedding planes of the Bt-Grt granulite. The width of the vein varies from 3 to 5 cm. Coarse-grained Bt (1 cm dia.) and very fine-grained (0.1 mm dia.) Bt, Qtz, Pl, and Kfs grains mark the vein boundary. Sigmoidal deformation of the planar foliation of the fine-grained material may indicate the vein was emplaced along a shear zone. Grt grains are extensively embayed and resorbed with coronas of Ms in radiating bundles. Ms also occurs as overgrowths on Bt. Near the center of the vein, Pl and Kfs grains are highly sericitized; radiating aggregates of coarse-grained Ms, apparently replacing Pl and Kfs, are common.

Q-26. The fine-grained sample contains Opx and skeletal, poikiloblastic Grt (1 cm dia.). Much of the Opx appears to be in disequilibrium, commonly mantled by Hbl (X = yellow; Y = blue-green; Z = green). Symplectic intergrowths of Bt-Qtz and Hbl-Qtz occur near relict Opx grains.

Q-27. Coarse-grained (2-4 mm dia.) Bt forms a strongly foliated fabric in the euhedral Grt-bearing sample. Bt (X = yellow; Y = Z = dark brown) grain boundaries show a stair-step pattern. Rims of Chl surround some of the opaque phases.

Q-29. Skeletal, elongated Grt (2-5 mm dia.) are aligned in a narrow band in a nonfoliated Bt-Hbl-Pl matrix. Grt occurring outside this band are rare, widely separated, and much larger (1-3 cm dia.). An inverse relationship between Grt size and Grt frequency is typical throughout the Bt-Grt granulite unit and may reflect differences in nucleation behavior of Grt. Qtz occurs in symplectic intergrowths with Hbl (X = yellow; Y = green; Z = greenish-brown), Bt (X = yellow; Y = Z = dark brown), and opaque minerals. Minor amounts of Hbl (X = yellow; Y = blue-green; Z = green) are present.

Q-30. Incipient banding of Bt-rich lenses (1-4 cm length) and Bt-poor Qtz-Pl-Kfs bands characterize the sample. Opx and Grt (0.5-1 cm dia.) are present in areas not polarized into Bt-rich and Bt-poor. Opx adjacent to Qtz-Pl-Kfs zones has been altered to Hbl (X = yellow; Y = blue-green; Z = green) with Cum and numerous opaque mineral inclusions. The sample occurs adjacent to granofelsic Qtz-Pl-Kfs gneiss.

Q-52. The fine-grained Bt-Hbl assemblage is located near the edge of the Bt-Grt granulite unit. A narrow band

of Qtz, Kfs, and Pl with clots of dark green minerals lies parallel to a microscopically defined foliation of Hbl and Bt. The presence of zoned Ep along narrow shear zones (0.2 mm wide) and Hbl (X = yellow; Y = blue-green; Z = green) is evidence the sample has undergone some retrograde metamorphism. Fibrolitic Sil is present along Pl and Kfs grain boundaries and within Qtz grains.

Q-58. Pl-rich veins with blue-green clots appear to intrude finer-grained Bt-rich rock. Relict Opx with Hbl (X = yellow; Y = blue-green; Z = green) and Cum rims are restricted to the Pl-rich veins.

FG-2*. Pl, Hbl (X = yellow; Y = green; Z = greenish-brown), and Bt (X = yellow; Y = Z = dark brown) occur in roughly equal proportions in the nonfoliated sample. Large skeletal Grt (5-8 mm dia.) contain rounded inclusions of Bt, Hbl, Kfs, Pl, and Qtz. Triple point junctions between mineral grains are common.

FG-3*. Relict Opx grains are surrounded by Hbl (X = yellow; Y = blue-green; Z = green), Cum, and Bt (X = yellow; Y = Z = light green). A strong lineation is produced by alignment of Hbl grains. Bt in the unaltered areas does not show a preferred orientation. The alteration clots are surrounded by Pl and Kfs with only minor Bt.

FM-10. Pink Kfs, apple-green Pl (1 cm dia.), and square clots of dark green minerals occur near the edge of

the Bt-Grt granulite unit. Relict Opx grains are surrounded by radiating aggregates of Cum, Hbl (X = yellow; Y = blue-green; Z = green), and Bt (X = yellow; Y = Z = light green). Cum generally surrounds relict Opx and is in turn mantled by Hbl and Bt.

Quartzo-Feldspathic Gneiss

Q-1. An overall weakly-developed gneissic banding is apparently produced by isolation of diffusely bounded gneissic blocks within nonfoliated granofels. Qtz-Qtz and Qtz-Fsp grain boundaries are often rounded with embayments. Rounded inclusions of Qtz and Fsp are common. A narrow band of dendritic opaque minerals surrounding Pl, Kfs, and Qtz grains may represent late-stage mineralization. Fibrolitic Sil is present along some Fsp grain boundaries, and Ms occurs as rims around Bt.

Q-2. Foliated Bt-rich granofels with widely scattered but evenly distributed Grt (2-5 mm dia.) is in sharp contact with nonfoliated, Bt-poor granofels. Large Grt grains (1 cm dia.) are concentrated at the boundary between the two granofels types. The coarser-grained Bt-poor granofels cuts across the planar foliation of the Bt-rich granofels and is interpreted to be an intrusive vein introduced after peak metamorphism.

Q-3*. Fine-grained lenticular inclusions of Bt-Kfs-Pl schist are isolated within coarse-grained Fsp granofels.

Grt (3-5 mm dia.) are present in the coarse-grained material. Foliation is weakly developed in the fine-grained lenticular inclusions. Fsp-Fsp and Fsp-Qtz boundaries are curved, low-energy contacts. Mortar texture, consisting of Pl and Kfs (0.8-2 cm dia.) in a matrix of smaller Qtz, Pl, Kfs, Ms, and Bt is common in the coarse-grained granofels.

Q-4. Grt-Bt restite occurs as 1 cm wide bands and as irregularly-shaped pods in the coarse-grained pinkish-gray granofels. Bt (3-8 mm dia.) in the granofels layers is not aligned to form a planar fabric. Bt grains in the restite are smaller and form a strong schistosity. Opaque minerals and Zrn are common inclusions in the Bt of the melanosome layers, whereas Bt of the leucosome layers is largely inclusion-free. Mortar texture is common in the granofels layers. Small grains of Ky are present in the sample along with fibrolitic Sil along Fsp grain boundaries. Grt in contact with the lighter-colored granofels commonly contains Chl along fractures. Pl and Kfs grains commonly have thin veins of sericite and Cal.

Q-7. The leucocratic granofels occurs as veins intruding other granofelsic rocks. Grt is absent. Qtz-Qtz and Qtz-Fsp grain boundaries are curved with numerous embayments. Bt may be weakly foliated in small areas, but no pervasive planar fabric is present. Fibrolitic Sil is sporadically present along Kfs and Pl grain boundaries. Ms, where present, is usually interlaminated with Bt.

Q-9. Bt-Grt bands containing prominent Py and Ccp mineralization alternate with Qtz-Pl-Kfs bands. Schistosity, strongly developed in the coarse-grained restite, is absent or only weakly developed in the Qtz-Pl-Kfs layers. Grt and sulfide minerals show a strong elongation fabric within the restite.

Q-12. This sample is a well-foliated migmatitic gneiss with Qtz-rich lighter-colored layers and darker-colored bands of Bt, Grt, and lesser amounts of Sil. Bt, Sil, and Pl inclusions in Grt are common. Sulfide minerals, probably Py and Ccp, are present only in the dark-colored bands. Qtz in the leucosome are frequently myrmeketically intergrown with Pl. Fsp-Qtz grain boundaries are curved and embayed.

Q-16. Grt in the nonfoliated granofels has Chl-filled fractures. Bt and Chl are often intergrown. Ms grains occur parallel to cleavage planes in ragged Bt. Both Chl and Ms may be reaction products of Bt. Ms is also an apparent retrograde product of Kfs.

Q-17. This is a banded gneiss with Bt-Grt restite layers and discontinuous Qtz-Pl-Kfs bands. Foliation is well developed in the Grt-Bt layers but only weakly developed in the Qtz-Pl-Kfs zones.

Q-23. The abundance of Qtz in the sample gives a sugary texture to the lighter-colored layers. Small Grt (1 mm dia.) are irregularly scattered throughout the

Qtz-rich portions. Well-foliated Bt-rich layers and clumps of Bt-Grt schist appear to be abruptly terminated by the Qtz-rich veins. Qtz-Fsp grain boundaries are often curved; Qtz-Qtz grain boundaries are amoeboid. Pl and Kfs are moderately sericitized. Skeletal Ms flakes are often in contact with sericite and may indicate recrystallization of sericite to Ms.

Q-32. A strongly-foliated Bt-Qtz schist with an apparently isolated lens of Kfs-Bt-Ms granofels occurs near the contact with Bt-Grt granulite. Coarse-grained foliated Bt separates the two textures. The schistose zone is composed of slightly elongated Qtz and Bt parallel to the contact. Ms and Fsp are absent from the schistose zone. The granofels layer has abundant Kfs and Ms. Phyllosilicate minerals form a symmetrical crenulation fabric with crenulation axes almost perpendicular to the Bt-Qtz schist contact. The crenulation is cut by narrow bands of comminuted Bt, Kfs, and Pl.

Q-36. Clots of relict Opx surrounded by Hbl (X = yellow; Y = blue-green; Z = green), Bt, and Cum occur with Grt in a coarse-grained (0.5-2 cm dia.) Pl and Kfs granofels. Cal is especially abundant in the vicinity of Cum. The nonfoliated granofels is located near the boundary of the Bt-Grt granulite and probably has assimilated and altered portions of the granulite unit. Grt (4-6 mm dia.)

are often associated with mafic minerals in the granofels and may be a late-stage phase. Chl occurs in fractures of Grt.

Q-37. The nonfoliated granofels occurs near Bt-Hbl granulite and Bt-Grt granulite units. Clots of relict Opx are surrounded by Hbl (X = yellow; Y = blue-green; Z = green) and Cum. Grt (4-8 mm dia.) are unaltered isolated phases in the granofels. Fibrolitic Sil is present in the finer-grained portions of the mortar-textured sample.

Q-41. Gneissic banding is absent in the sample, although finer-grained material occurs as blocks within more coarse-grained granofels. Wispy bands of Grt and Bt restite are also present. Grt (5 mm dia.) are surrounded by Pl, Kfs, and Ms. Microscopically, the Grt are extensively embayed and surrounded by radiating aggregates of Ms. Bt, aligned to produce a weak planar fabric, are absent in a 1 mm wide zone around Grt.

Q-42. A continuous Qtz-rich vein 1 cm wide cuts across the sample. Dark-colored Grt and Bt bands (1-2 cm wide) surround the Qtz-rich vein, gradually becoming lighter-colored and more Fsp-rich away from the Qtz vein. Bt is generally fine-grained and forms only a weak schistosity. Fsp-Fsp grain boundaries are curved. Qtz-Qtz grain boundaries are often amoeboid. A thin band of Ms separates Kfs from Grt.

Q-46. Bt is weakly foliated and parallel to a 3 mm wide continuous Qtz-rich band. The fine-grained Bt and small skeletal Grt (1 mm dia.) form an apparently homogeneous texture. Fsp-Fsp and Fsp-Qtz boundaries are curved but seldom embayed. Chl alternation is present along Grt fractures.

Q-47. This is a banded gneiss composed of layers of foliated Bt-rich material and weakly foliated Qtz-Pl-Kfs granofels. A distinctive band of euhedral Grt (4-12 mm dia.) in Qtz is also present. Microscopically, Bt foliation is weak but discernible throughout the thin section. Ms does not show a preferred orientation. Mortar texture with fibrolitic Sil along matrix Fsp boundaries, amoeboid Qtz grain boundaries, and Bt grains with ragged edges are typical features.

Q-50. Rounded grains of Pl and Kfs (0.5-1.5 cm dia.) are surrounded by a matrix of fine-grained foliated Bt, Qtz, and Fsp. A 2 mm wide band of intensely fragmented Bt and Grt with isolated Fsp grains cuts across the sample. Narrower, discontinuous bands of fine-grained foliated Bt, Qtz, and Fsp surround Pl and Kfs porphyroblasts. Texturally, the sample resembles a protomylonite. It is located near an area of tight, isoclinal folding in the Sil schist unit.

Q-53. A strong foliation is developed by Bt grains parallel to discontinuous gneissic bands. Qtz-rich

segregations (5 mm wide) are present, but dark bands of Bt and euhedral Grt (1-2 mm dia.) are more common. Coarse-grained Sil occurs within the thickest Bt layers but never in contact with Qtz, Pl, and Kfs. Qtz and Fsp symplectites are common in the felsic bands.

Q-55. The coarse-grained (0.5-1 cm dia.) Kfs-rich band of granofels intrudes well-foliated migmatitic gneiss. Coarse-grained Bt with no preferred orientation occurs as discontinuous layers (1 cm wide) in the Kfs band along with finer-grained blocks of Qtz, Bt, Grt, Pl, and Kfs. The finer-grained blocks show a weakly developed foliation. Grt cores contain inclusions of Bt, Pl, Kfs, and Qtz. Rims of Grt grains are generally inclusion-free, but Sil needles may be present. Qtz-Qtz grain boundaries are lobate and sutured; Fsp-Fsp grain boundaries are generally curved. White mica and Cal are present as alteration products of Kfs.

GRF. Regularly-spaced Grt (1 mm dia.) with Bt inclusions and Chl along fractures are ubiquitous. Banding of light-colored and dark-colored minerals is absent, although irregular patches of Bt-rich and Bt-poorer material may represent incipient segregation. Schistosity is not well developed in this sample. Fibrolitic Sil occurring as borders along Pl grains and skeletal Ky are both present in the thin section but do not occur in contact.

P-4B. The contact between Sil Schist and nonfoliated granofels contains Ky as an apparently stable phase. Mortar texture is common with fibrolitic Sil present at the finer-grained Fsp boundaries. Rounded inclusions of Pl and Kfs within Fsp and the common mortar texture are evidence for more than one crystallization episode. The granofels may have been produced by a series of small injections of material rather than a single intrusive event. Ms alteration of Kfs is confined to fractures and cleavage planes.

Orthopyroxenite

M-1. Subhedral to euhedral Opx (1-2 mm dia.) with polygonal grain boundaries display faint pleochroism (X = pink; Y = yellow; Z = green). Bt (X = yellow; Y = Z = dark brown) grains are smaller, usually less than 1 mm dia., except where adjacent to Pl-Qtz veins. Pl and Qtz grains (2-4 mm dia.) occur predominantly in a 2 cm wide vein in this sample. Ragged grain boundaries of Opx within the vein and at the vein-orthopyroxenite contact are often rimmed by Hbl and Cum. Opaque minerals are ubiquitous in the orthopyroxenite portion of the sample but are absent in the Pl-Qtz veins.

M-2. Coarse-grained Bt (2-4 mm dia.) occurs in masses surrounding orthopyroxenite blocks and may represent alteration of the orthopyroxenite. Partially replaced grains of

Opx are sporadically preserved. A small percentage of the Bt grains are kinked, indicating postcrystallization deformation. Most Bt grains, however, show no deformational features and are presumed to be postkinematic.

M-3. Opx (2-3 mm dia.) and Bt (1 mm dia.) make up the bulk of the sample. Pl and Bt occur as a narrow band through the Opx-rich areas. Cum and Hbl occur at the contact between the orthopyroxenite and Pl-Bt band. Bt and Hbl inclusions within Opx have a generally consistent orientation along cleavage directions of a single Opx grain but no systematic orientation between grains, forming a decussate texture.

M-4. Cum occurs in radiating aggregates, as inclusions in Opx, and as rims around the corroded edges of Opx grains. Hbl (X = yellow; Y = blue-green; Z = green), where present, is separated from Opx by a Cum rim. Pl is virtually absent from this specimen, though veinlets of Pl are present in hand-specimen.

M-5. Hc occurs as rare inclusions within Grt. Pl (1-2 mm dia.) and Bt surround Grt (4 mm dia.). Grt are usually embayed and poikiloblastic. One relict grain of Opx surrounded by Pl was observed in this sample. Field relationships of the Grt-bearing Bt-rich zones within the orthopyroxenite unit and the presence of relict Opx grains suggests the Bt-rich zones are of retrograde origin.

FM-1*. Opx (3 mm dia.) has numerous inclusions of Bt, opaque minerals, Cum, Hbl, and Opx. The Opx inclusions have optical properties identical with the host Opx. Opx rimmed by Cum in turn rimmed by Hbl (X = yellow; Y = blue-green; Z = green) is common.

FM-3*. Opx has Bt, Qtz, Cum, and Opx inclusions. Cum generally separates Opx and Hbl, although rare Opx-Hbl contacts do occur. Cum often is present as narrow replacement veins extending into the cores of Opx.

Oxide and Sulfide Minerals

Mag occurs as apparently homogeneous, discrete grains in all units at Winding Stair Gap except the calc-silicate gneiss. Systematic occurrence of Mag with other sulfide and oxide phases was not observed. Ilm occurs as discrete, homogeneous grains in the Bt-Hbl granulite unit and as exsolution lamellae in Hem in the quartzo-feldspathic gneiss and Sil schist units. Ilm abundance increases as Bt abundance decreases in the Bt-Hbl granulite unit. Ilm is absent in the orthopyroxenite and is replaced by Spn in the calc-silicate gneiss. Hem occurs only in the nonfoliated quartzo-feldspathic gneiss and in Ky-bearing Or blebs in the Sil schist. The stability of Hem rather than Mag suggests a change in oxygen fugacity during retrograde metamorphism. Hem and Ilm probably occurred as a homogeneous phase which exsolved during cooling.

Po, Py, and Ccp are present in all units except the Sil schist. Although sulfide minerals do not occur in the Qtz- and Fsp-rich portions of the quartzo-feldspathic gneiss, they are commonly associated with Bt and Grt in the restite portion of migmatitic gneiss and probably represent refractory material. Discrete grains of Py and Po are common, but Ccp is always associated with Py, Po, or both. Rounded grains containing Po, Py, and minor Ccp are especially common in the orthopyroxenite.

VITA

Bobby Steven Absher was born in Jefferson, North Carolina, on 23 November 1955. He attended Wake Forest University, graduating with a Bachelor of Arts degree in Philosophy in May 1978. He studied Geology at Appalachian State University, graduating with a Bachelor of Science degree in December 1981. While at Appalachian State University, he was an active member of the Geology Club, serving as president in 1981. He also received the Outstanding Senior award presented by the Geology Department. In January 1982 he accepted a teaching assistantship with The University of Tennessee, Knoxville. He received a Master of Science degree in Geology, March 1984.