8-1992

Late Proterozoic Rifting of Laurentia: Source and Deposition of Conglomerate Units of the Grandfather Mountain Formation, North Carolina Blue Ridge

Michael J. Neton
University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Michael J. Neton entitled "Late Proterozoic Rifting of Laurentia: Source and Deposition of Conglomerate Units of the Grandfather Mountain Formation, North Carolina Blue Ridge." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Steven G. Driese, Major Professor

We have read this thesis and recommend its acceptance:

Robert D. Hatcher, Jr., Harry Y. McSween

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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LATE PROTEROZOIC RIFTING OF LAURENTIA: SOURCE AND DEPOSITION OF CONGLOMERATE UNITS OF THE GRANDFATHER MOUNTAIN FORMATION, NORTH CAROLINA BLUE RIDGE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Michael Joseph Neton

August 1992

ACKNOWLEDGMENTS

These acknowledgments are in addition to those following Parts 2 and 3.

Peter M. Sadler, Marilyn A. Kooser, James Renfrew, and John Hillenbrand (that is, Sadler and others, 1989) are acknowledged for their deep insight into why conglomerates have received so much attention and use in basin analysis – "because they are there and because they are coarse".

My mother, father and brothers (Ted and Jim) deserve a million thanks for their encouragement, prayers, love and support; and their understanding of the lack of visits or aborted stays (usually much to my chagrin also) in the "motherland" of Wisconsin. **GO BADGERS!!!!!!**

My advisor, Dr. Steven G. Driese is thanked for his three insightful field excursions up to Grandfather Mountain. He is further acknowledged for making it through that cold, snowy January night at the Banner Elk shack with a summertime sleeping bag. His help in the lab and field and willingness to discuss problems and theories were invaluable.

I am grateful to Mark G. Adams (University of North Carolina) for the use of his shack, buried in the shadow of Beech Mountain, north of Banner Elk, as the North Carolina branch office of the UT Geological Sciences Tectonics and Sedimentation Research Group. Likewise, "Old Man" Townsend is thanked for use of his Snakeden Ridge-top land as headquarters in early stages of field work.

Bob Hatcher, Dan Walker, and Joachim Dorsch are especially acknowledged for graciously allowing me use of their Macintosh™ computers. Tim Davis, Dan Walker, Don McClanahan, Lincoln Foreman and Ian Richards answered varying amounts of "the best way to manipulate the computer" questions.

The secretarial staff, in the main office and Dr. Hatcher's office, is thanked for their help regarding a multitude of affairs. Marvin Bennett is acknowledged for his thin-section making efforts, especially on those hard metarhyolites.

Thanks are due many present and some former M.S. and Ph.D. students and friends at UT - Knoxville, who were almost always ready to discuss any and all geologic problems - most especially, members and former members of the "Sandbar": Joachim Dorsch, Dan Walker, Anne Gogola, Chris Bolton, and Marta Corbin. Also thanked for their gift of gab are Timothy Davis, Brent Couzens, Jeff Connelly, Kent Waggoner, Michael Quinn, Chris Olson, Peter Souza, Tony Tingle, Beth McClellan, Chris Vyhnal, Kenneth Tobin, Karen Walker, Tony "it's an anticline" Caldanaro, and Michael Green.

Particular thanks go to fellow "Sandbar" and TVA colleague Joachim "Mr. Foreland Basin" Dorsch for broadening my appreciation for and recognition of the elegance of the facies concept and for being a fellow "T and S" man. Hopefully, my enthusiasm for extensional tectonics and fluvial sedimentation heightened his for compression and marginal marine sedimentation of the SW Virginia Ordovician-Silurian molasse. Thanks also are due "the Rabbit".

Steven C. Young at the TVA Engineering Lab is gratefully acknowledged for providing financial support through a TVA internship. His recognition that sedimentary facies, and the depositional processes responsible for those facies, exert a first-order control on groundwater flow through heterogeneous fluvial aquifers, provided the proper atmosphere for an enlightening delve into the voluminous, tectonics and sedimentation and fluvial literature.

Friends and apartmentmates at 123A, Chris Vyhnal and Brent Couzens ("the best apartmentmate I ever had"), as well as Ellen Williams, Maria Leary, and Kent Waggoner and the rest of the Taliwa Court crew are thanked for their additions to the "fun factor". Likewise, Chris Olson and Kelly Gardner are thanked for their Monday and other night additions.

GO VOLS!!!!!!!!!

ABSTRACT

Crustal extension and initiation of rifting of Laurentia during the Late Proterozoic resulted in formation of a northeast-trending system of discontinuous to continuous, half-graben basins situated cratonward of the Iapetus Ocean spreading ridge. Thick accumulations of sandstone, siltstone, bimodal volcanic rocks, conglomerate, diamictite, and minor limestone were deposited largely in response to rifting and relief formation on the basin margins.

The Grandfather Mountain Formation contains five stratigraphically and compositionally distinct conglomerate/diamictite units and one pebbly sandstone unit which cap coarsening-upward, basin-fill sequences. The progradational sequences average 1300 m thick and are composed of a succession of volcanic flows (basalt/rhyolite) and/or siltstone, succeeded by fine- to coarse-grained feldspatholithic sandstone, succeeded by pebbly sandstone and conglomerate. Major rifting events (or clusters of events) occurred during deposition of volcanic rocks and fine-grained lacustrine or marine, and fluvial sediment near the basin margin fault. After a time lag, alluvial fans and fan-deltas prograded basinward from the margin over the fine-grained sediment. Smaller-scale coarsening-upward sequences (few to 10's m) are attributed to avulsion and lobe progradation due to inherent fan/fan-delta/subaqueous slope processes and to progradation following localized faulting events.

Southwest-fining along strike of three of the five conglomerate units suggests: 1) derivation from the northeast, possibly from an accomodation zone and from the Mount Rogers Formation, or 2) more extensive, coarser-grained, southeastward progradation in the northern half of the basin. The Grandfather Mountain and Mount Rogers basins may have developed as an asymmetric, alternating, half-graben pair and at various times were joined or separated by an accommodation zone.

The polymictic conglomerate of the Grandfather Mountain Formation iis dominated by felsite and basalt clasts and contains lesser amounts of crystalline basement and sedimentary clasts. Two compositional sequences (upper and lower) are present within the conglomerate and are delineated by the presence or absence of perthite phenocrysts in felsite clasts. The lower sequence is dominated by porphyritic *quartz-*

perthite felsite clasts and details an unroofing sequence: felsite → sandstone and siltstone → crystalline basement. In contrast, the upper sequence is dominated by felsite clasts containing *only quartz phenocrysts* (in the Banner Elk conglomerate) and basalt clasts (in the Broadstone Lodge diamictite).

Certain conglomerate clasts are most reliably matched to nonconformably underlying Grenvillian Blowing Rock Gneiss and the intraformational Montezuma basalt. Felsite clasts may be derived from either Grandfather Mountain Formation or Mount Rogers Formation rhyolite. Other clasts were derived from other, as yet unidentified, source terranes that have been eroded away or are not exposed.

Four facies associations are composed of thirteen descriptive facies. Lateral and vertical changes in facies and facies associations of the conglomerate units of the Grandfather Mountain Formation indicate that coarse-grained alluvial fans, fan-deltas/subaqueous slopes, and braidplains prograded from the basin margins displacing finer-grained braidplain and marine or lake deposits back toward the basin center. Subaqueous (marine or lake?) slope and large-scale subaqueous channel deposits are more significant basin fill environments in the Grandfather Mountain Formation than previously thought. Their presence is particularly indicative of high relief due to basin-margin faulting.

Differing clast composition and grain size between conglomerate units as well as interpreted hydrodynamics produce heterogeneous longitudinal bar sequences, braidplain and fan styles. The heterogeneous styles are due to heterogeneous fluvial processes and the complex interplay between proximal and distal environments such as at the alluvial fan-to-braidplain transition. Evidence in support of a glacial or proglacial origin for deposits in the upper part of the Grandfather Mountain Formation is either absent or ambiguous at best.

Methods used in this study, if applied to other ancient rift sequences, especially those exposed in the Appalachian Blue Ridge, will further delineate rifting episodes, rift shoulder and basin paleogeography, and provide insight into subsurface stratigraphic patterns within rift basins along modern passive margins.

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INTRODUCTION AND PURPOSE

Thick gravel successions are deposited in sedimentologically and tectonically dynamic systems directly adjacent to abrupt relief formed by tectonic disturbance. As such, the clasts represent unambiguous pieces of original source rock and are a direct indicator of basin tectonism (Sharp, 1948; Steel, 1976; Boggs, 1992). Vertical and lateral conglomerate clast and sandstone framework grain population trends, coupled with vertical and lateral clast size trends and facies analysis, are particularly attractive and powerful tools for unravelling complex basin history. Conglomerate clast population and average maximum clast size (AMCS) trends can delineate source regions/units, faulting events, and unroofing histories of adjacent basin flanks, providing a detailed basin history. Studies employing one or more of these data types have been performed in many compressional, transform and extensional terranes (for example, Follo and Siever, 1984; Mack and Rasmussen, 1984; Graham and others, 1986; Ingersoll and others, 1990; McKee and others, 1990). These studies elucidated basin relationships developed largely during the Cenozoic. Difficulty is encountered in older sequences because metamorphism/deformation are generally more pronounced. Despite this, conglomerate units survive deformation relatively intact and therefore serve as useful marker units (J. D. Walker, 1988). Workers studying older successions, however, have primarily concentrated on minimally deformed and relatively unmetamorphosed units (for example, Hazlett, 1978: Triassic of Virginia; Steel and Wilson, 1975; Steel and others, 1977; Gloppen and Steel, 1981: Devonian of Norway; Middleton and Trujillo, 1984: Upper Proterozoic of Arizona). Similarly focused studies of rift-related conglomerate within Upper Proterozoic successions of the Appalachian Blue Ridge have generally not been made, other than in passing observation (exceptions: Neton and others, 1990; Neton and Driese, 1992; Hutson and Tollo; 1991; 1992).

Alluvial fans and fan-deltas develop along high relief basin margins. Finer-grained lacustrine or marine and low-gradient fluvial systems occupy the basin center, and after basin subsidence rapidly migrate toward the margin, covering proximal fans/fan-deltas. After basin margin tectonism wanes, fans and fan-deltas can prograde over and displace finer-grained environments basinward during relative tectonic quiescence. Blair (1987), Blair and Bilodeau (1988), and DiGuiseppi and Bartley (1991) documented this stratigraphic style in Tertiary and younger basins. Facies analysis permits reconstruction of depositional environments, paleogeography, paleohydraulics, and delineation of stratigraphic style due to tectonism on basin margins.

Detailed facies analyses and stratigraphic studies in the Grandfather Mountain Formation (GMF: Upper Proterozoic, North Carolina) and in correlative units have been sparse. Because of this fact, the internal stratigraphy of these units is generally poorly constrained. Facies analysis of these units, such as that of Blondeau and Lowe (1972), Schwab (1976), and Miller (1986), all in the Mount Rogers Formation, as well as Wehr (1986: Rockfish Conglomerate) and Neton and others (1990), Neton and Driese (1992: GMF) will lead to a clearer understanding of depositional environments along the rift trend, aiding in tectonic/paleogeographic reconstruction. They will help to resolve the complex rift stratigraphy and allow assessment of possible interconnectedness of the now disparate basin fills. Increased use of sandstone framework grain, and conglomerate clast size, and population trends to delineate Upper Proterozoic rift basin tectonics will provide a more comprehensive and precise knowledge of development of the Late Proterozoic-Cambrian Iapetus margin and the nature of continental rifting in general.

Presented here are lateral and vertical clast composition data, clast size data and facies analysis of five discontinuously mappable, distinct conglomerate units of the GMF. The purpose of this thesis is fivefold: 1) to review and present new ideas regarding the complex stratigraphy and tectonics of the GMW area, GMF, and other correlative Late Proterozoic units (Part 1); 2) to provide new information on the stratigraphy of the GMF in relation to the five conglomerate units (Part 2); 3) to determine depositional environments of the GMF with particular emphasis on the five conglomerate units (Part 3); 4) to determine Grandfather Mountain basin history and assess possible interaction with other rift basins developing coevally along the Laurentian margin during Late Proterozoic time (Parts 2 and 3); and 5) to propose an unroofing sequence and a generalized paleogeography of rift basin shoulders (Part 3). Part 4 is a summary and conclusion of Parts 1, 2, and 3, with ideas for future study of the GMF and other Blue Ridge rift to passive margin sequences.

TECTONIC SETTING

Following the Grenville orogeny (1.1 Ga) and construction of the Grenville continent (Laurentia), rifting occurred along an irregular southwest-northeast trend in what is now eastern North America (Rankin, 1975, 1976; Rankin and others, 1989; Hatcher, 1972, 1978; Thomas, 1991). The continental rift system that formed is interpreted to have developed as a system of asymmetric, alternately facing half-grabens possibly with a large scale geometry of a widely extended region similar to that of the Basin and Range (southwest United States) (Hatcher and Goldberg, 1991). Recent studies indicate that rifting of Laurentia occurred in two major pulses: the first beginning about 700 Ma, with rift initiation no doubt varying along the trend, and the second occurring approximately 570 Ma (Badger and Sinha, 1988; Aleinikoff and others, 1991). As rifting proceeded the developing rift basins received thick and varied fills of bimodal volcanic rocks (Misra and McSween, 1984), clastic sediment, and minor amounts of limestone. Remnants of this ancient rift system are presently exposed along the axis of the Appalachians from Alabama to Newfoundland. They represent sections of a discontinuous(?) rift system developed cratonward (west) of the major rift axis which developed into the Iapetus Ocean (Rankin, 1975, 1976; Hatcher, 1978; Schwab, 1986a; Thomas, 1991). Basins of similar age and with similar stratigraphy also developed east of the Iapetus Ocean axis, one example of which is the sparagmites of southern Norway (Bjørlykke and others, 1976). The central rift axis eventually developed into the Iapetus spreading ridge that was flanked by conjugate, irregular, passive margins with possible intervening, isolated basement blocks (Thomas, 1977, 1991; Hatcher, 1978, 1987; Rodgers, 1982; Walker and others, 1989; Walker and Simpson, 1991).

The basins, passive-margin, detached basement blocks and later developing island arcs were subsequently deformed and metamorphosed during Appalachian orogenesis and closing of the Iapetus Ocean (Rankin, 1975, 1976; Rodgers, 1982; Hatcher, 1987, 1989). As such, their original geometries cannot be reconstructed with confidence, in contrast to the early Mesozoic rift system of eastern North America. These Mesozoic basins can generally be delimited by listric normal faults which are likely border faults defining half-grabens, with sense of motion alternating from basin to basin, being either down-to-the-southeast or down-to-the-northwest (Luttrell, 1989; Manspeizer and others, 1989). Whereas this geometry is likely the case for the Late Proterozoic basins, only in the broadly correlative Fauquier Formation of Virginia, and adjacent basement, have possible rift-related mylonitic zones, border faults, and intervening horsts been reliably identified (Espenshade, 1986; Kline and others, 1991).

The Upper Proterozoic Grandfather Mountain Formation represents deposition in part of this western trend or in an isolated rift basin along, or adjacent to, the western rift trend (Schwab, 1977, 1986a; Boyer, 1978), and probably was situated east of the eventual Lower Cambrian passive-margin shelf edge (Hatcher and Goldberg, 1991; Thomas, 1991). It is a northeast-trending (40 x 15 km width as presently exposed) sedimentary and volcanic succession exposed only in the northwest corner of the Grandfather Mountain window (GMW) in the western Blue Ridge of northwest North Carolina (Figs. 1-1 and 1-2; Bryant and Reed, 1970a, 1970b) The GMF is broadly correlative with many other Upper Proterozoic rocks along both the northwest and southeast flanks, and the axis of the Blue Ridge anticlinorium. It is, however, most closely correlative with the Ocoee Supergroup (King and others, 1968; Hadley, 1970; Rast and Kohles, 1986) to the southwest and with the following stratigraphic units to the northeast: the Mount Rogers Formation (King and Ferguson, 1960; Blondeau and Lowe, 1972; Schwab, 1976; Rankin, 1967, 1975, 1976; Miller, 1986; Walker and Neton, 1989), Swift Run and overlying Catoctin

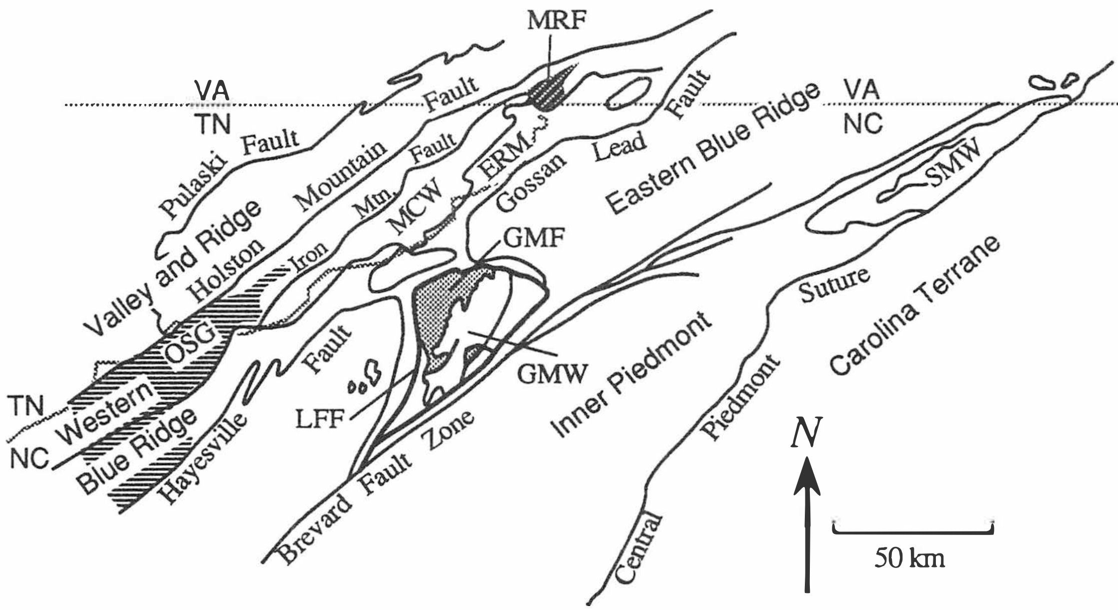


Figure 1-1. Tectonic map of Grandfather Mountain window (GMW) region of the southern Appalachian orogen in North Carolina, Tennessee, and Virginia. GMF = Grandfather Mountain Formation, LFF = Linville Falls fault zone, MRF = Mount Rogers Formation, ERM = Elk River Massif (basement), MCW = Mountain City window, OSG = Ocoee Supergroup, SMW = Sauratown Mountains window. Modified from Bryant and Reed (1970a), Bartholomew and Lewis (1984), Hatcher and others (1990).

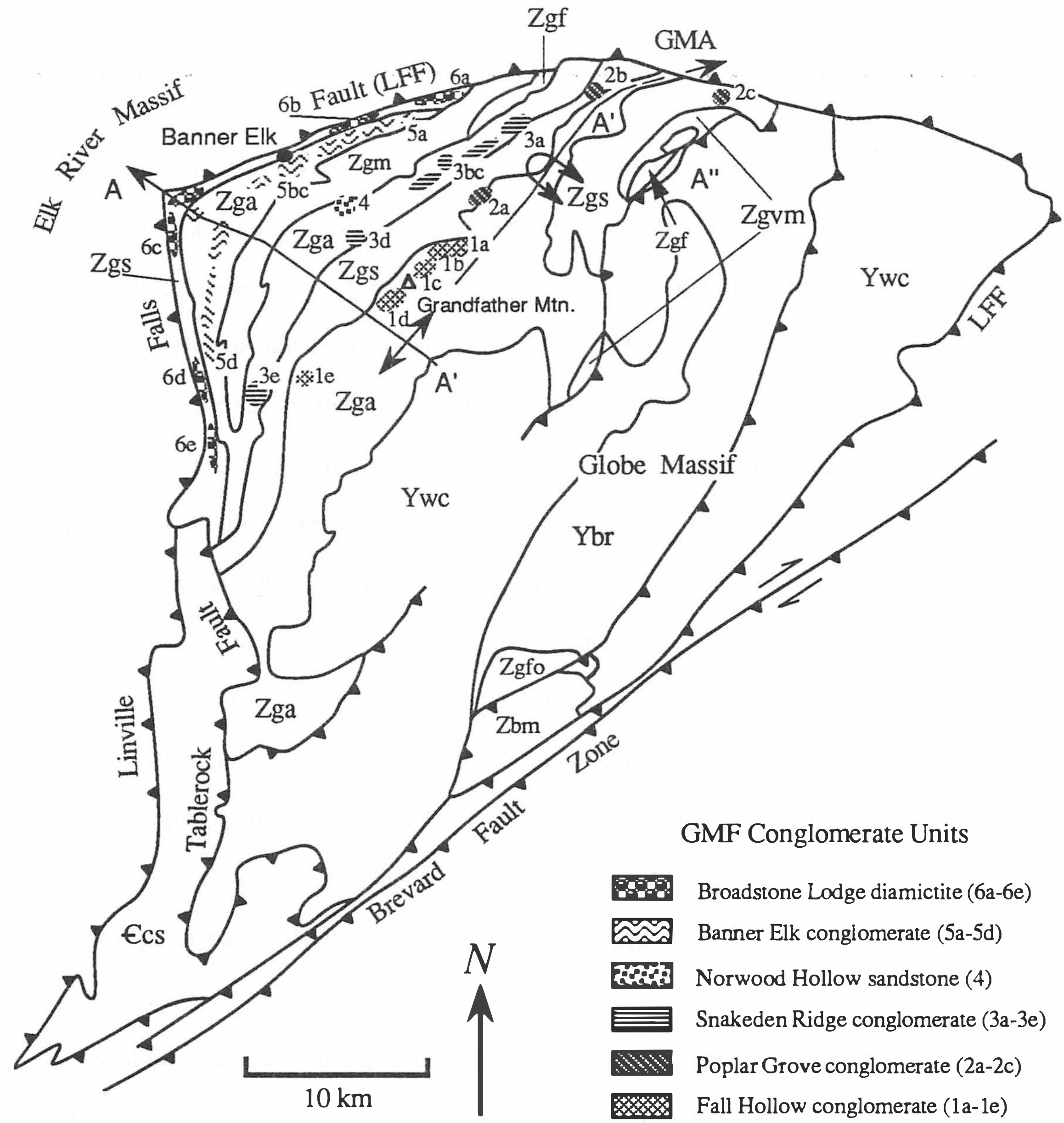


Figure 1-2. Generalized geologic map of the GMW and GMF showing distribution of major conglomerate units. Numbers 1a through 6e denote outcrops within discontinuously mappable units (see Figure 1-3). A-A'-A" denotes trend of cross section (Figure 2-3). GMA = Grandfather Mountain anticline. Map units: GMF: Zga = lower, middle, and upper arkose; Zgs = lower and upper siltstone; Zgf = felsic volcanics (lower and upper rhyolite); Zgfo = outlier rhyolite; Zgvm = lower mafic volcanic rocks; Zgm = Montezuma basalt. Crystalline basement (Globe massif): Ywc = Wilson Creek Gneiss; Ybr = Blowing Rock Gneiss; Zbm = Brown Mountain Granite. Other: €cs = Chilhowee Group and Shady Dolomite in Tablerock thrust sheet; Zl = Linville Metadiabase (not shown). Modified from Bryant and Reed (1970a), Boyer (1978), Bartholomew and Lewis (1984), and Brown and many others (1985).

Formations (Wehr, 1985; Wehr and Glover, 1985; Espenshade, 1986) of the western Blue Ridge. Also to the northeast, but, on the axis and southeast flank of the Blue Ridge anticlinorium are the Rockfish Conglomerate (Wehr and Glover, 1985; Wehr, 1986), Mechum River Formation (Schwab, 1974; Hutson and Tollo, 1991; 1992), Reusens Migmatitic Rhyolite (Wang and Glover, 1991), Fauquier Formation (Espenshade and Clark, 1976; Espenshade, 1986; Kline and others, 1991), Lynchburg Group and Catoctin Formation (Fullagar and Dietrich, 1976; Misra and McSween, 1984; Wehr, 1985; Wehr and Glover, 1985; Espenshade, 1986) and the Peters Creek Formation (Gates and others, 1991). The GMF has also been regarded as a proximal equivalent of the structurally overlying Ashe Formation (of the eastern Blue Ridge) with a possible basement high separating the two basins (Boyer, 1978). Rankin (1970) speculated that gneissic rocks within the GMW (southeast side), which are lithologically very similar to Ashe Formation may actually be Late Proterozoic (Ashe Formation outliers) instead of Grenvillian Wilson Creek Layered Gneiss as they were mapped by Bryant and Reed (1970a; Fig. 1-2). The Mount Rogers Formation is palinspastically the closest of these units (Fig. 1-1) and perhaps contains the most similar stratigraphy.

Great lithologic and stratigraphic variability is commonplace in all the above named units. Lens-like internal lithosome geometries and rapid facies changes prevail. All the units rest nonconformably on Grenville basement and the Upper Proterozoic Crossnore Plutonic Suite (for example, King and others, 1968; Bryant and Reed, 1970a; Schwab, 1974, 1976; Wehr and Glover, 1985; Hutson and Tollo, 1991, 1992). The more sheet-like, upper Proterozoic-Lowermost Cambrian (Walker and Driese, 1991) Chilhowee Group unconformably or structurally overlies all these units (Bryant and Reed, 1970a; Simpson and Eriksson, 1989; Walker and Simpson; 1991). The above described complex stratigraphy permits interpretation of the units as being deposited in rift basins.

Whether these Upper Proterozoic rift successions developed largely in a continuous trend (broad terrane hypothesis) or in isolated half or full grabens (local basin hypothesis) or in some combination of these hypotheses over time and space (for example, Rio Grande rift of New Mexico; Seager and others, 1984; Morgan and others, 1986) is unknown. By analogy, similar speculation concerning the early Mesozoic rift basins of eastern North America has generally led to more fruitful conclusions (see Luttrell, 1989; Manspeizer and others, 1989). These disparate Upper Proterozoic successions are generally similar in their stratigraphic occurrence. Beyond that, internal stratigraphy of each is highly variable and similarities between successions, seemingly, are few. Original depositional relationships between these Upper Proterozoic successions may never be fully known due to their structural detachment and the varying degree of deformation and metamorphism they have experienced. This thesis addresses relationships between the Grandfather Mountain, Mount Rogers and Ocoee basins

REGIONAL GEOLOGY

The GMF is an approximately 7 km thick succession of feldspatholithic arenite and wacke, siltstone, basalt and rhyolite, conglomerate and diamictite, and very minor carbonate, in approximately decreasing order of abundance (Bryant and Reed, 1970a; Schwab, 1977). The entire GMF is metamorphosed to lower greenschist facies. Iron-rich muscovite is pervasive, with chlorite being less so. These two minerals impart a green color to the rocks, as does epidote, which occurs locally and especially in basalt (greenstone) units (Bryant and Reed, 1970a). Siltstone, sandstone, and basalt of the GMF rest nonconformably upon and in thrust contact with crystalline basement within the GMW (Figs. 1-2 and 1-3). Grenville (1.1 Ga) crystalline basement rocks are composed of augen gneiss (Blowing Rock Gneiss), layered gneiss containing schist and phyllonite (Wilson Creek Gneiss), and metagabbro (Davis and others, 1962; Bryant and Reed, 1970a). The 735 Ma, Upper Proterozoic Brown Mountain Granite (Odom and Fullagar, 1984) (Figs. 1-2 and 1-3; Bryant and Reed, 1970a) of the fluorite- and apatite-bearing granitic Crossnore Complex (Rankin, 1970) intrudes Grenvillian rock and nonconformably underlies (and

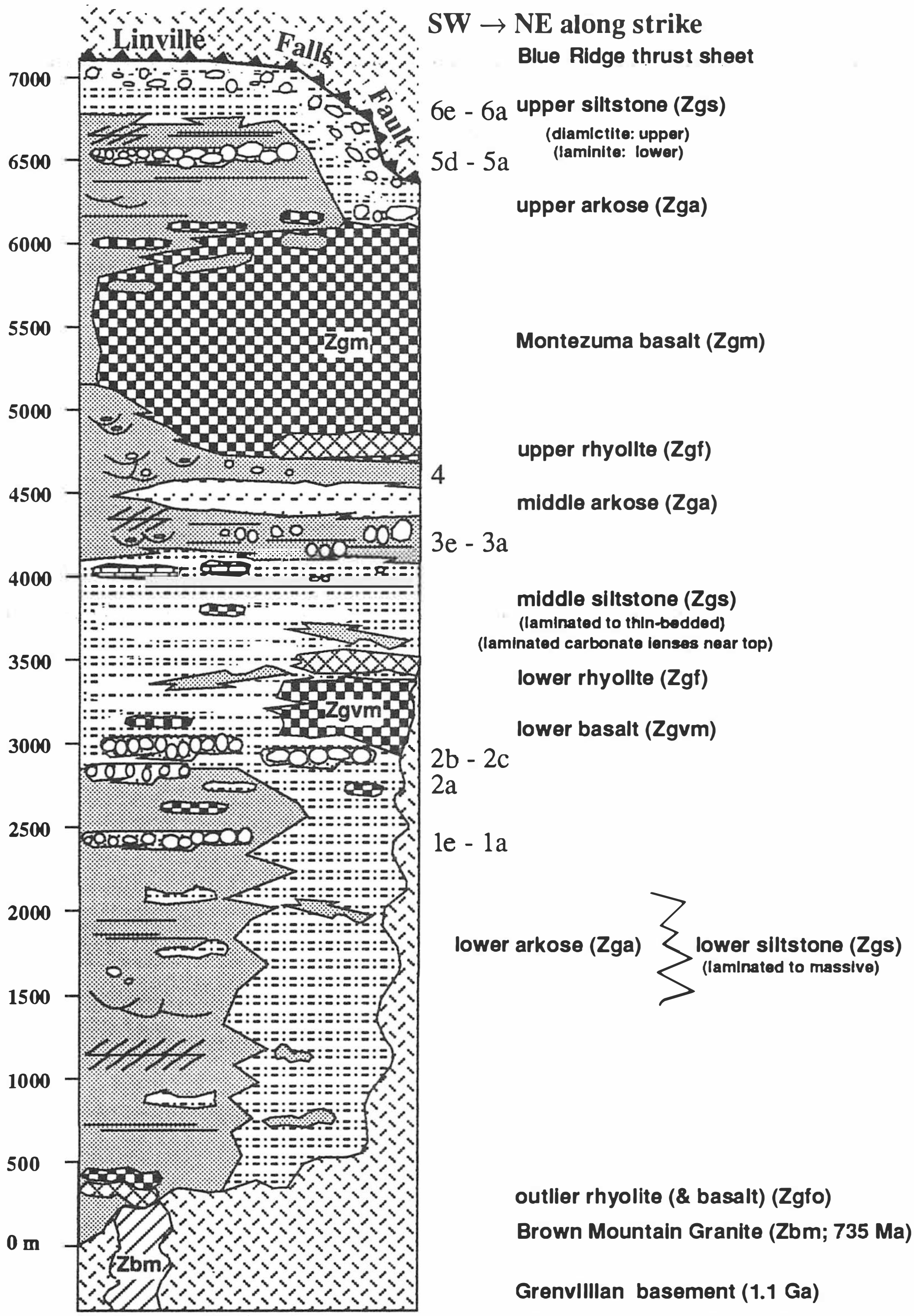


Figure 1-3. Generalized GMF stratigraphy constructed from map thickness data. Rock unit designations of Bryant and Reed (1970a). Lower and middle siltstones of Bryant and Reed (1970a) interpreted as same unit repeated on limbs of Granfather Mountain anticline after Boyer (1978; 1984) and data of this study and Neton and Driese (1992). Numbers denote conglomerate sections and bodies defined in Figure 1-2. Linville Metadiabase dikes and sills not pictured. Column not intended to show all variability across and along strike. Depiction of basal nonconformity does not imply true depositional relief, but merely depicts units which are known to rest nonconformably upon basement.

thrust contact) the GMF. Together these crystalline units are known as the Globe Massif (Bartholomew and Lewis, 1984; McSween and others, 1991). Grenvillian gneiss and Crossnore-type granite (Beech Granite and Crossnore Pluton) of the Elk River massif (Bartholomew and Lewis, 1984) tectonically overlie the GMW above the Linville Falls fault that frames the GMW, in the Blue Ridge thrust sheet in the structural low between the GMW and the Mountain City window (Fig. 1-1; Bryant and Reed, 1970a; Bartholomew and others, 1983; Gulley, 1985). Relative age and stratigraphic nomenclature of the GMW and overlying Blue Ridge thrust sheet are shown in Table 1-1.

Both ductile and brittle deformation have occurred in the Linville Falls fault zone at various times, the most recent being brittle (Boyer, 1978; Trupe and Adams, 1991). Latest movement in the Linville Falls fault zone was Alleghanian (fault tectonite = 300 Ma; Van Camp and Fullagar, 1982).

Dikes and sills of the Linville Metadiabase intrude both the Globe Massif (within the GMW) and the GMF, and are interpreted to represent feeder dikes of the Montezuma basalt in the upper part of the GMF because they do not occur stratigraphically above the Montezuma (Bryant and Reed, 1970a). The Chilhowee Group and Shady Dolomite structurally overlie the GMF in a complex manner and comprise a tectonic slice above the Tablerock thrust in the southwest corner of the GMW (Fig. 1-2; Bryant and Reed, 1970a; Boyer, 1978; Hatcher and Butler, 1986).

The Ashe and Alligator Back Formations overlie Grenvillian basement in the Blue Ridge thrust sheet (Table 1-1), either unconformably or in fault relationship (Bryant and Reed, 1970a). They are interpreted to represent either deposition in another larger rift basin eastward of the GMF (Boyer, 1978) and/or Iapetus Ocean slope-and-rise sedimentation and volcanism ongoing in or near the central, successful Iapetus spreading ridge and partially in fan-delta/submarine fan environments (Hatcher, 1978; Misra and Conte, 1991; Whisonant and Tso, 1992).

TABLE 1-1. RELATIVE AGE OF ROCKS OF THE GRANDFATHER MOUNTAIN WINDOW AND VICINITY. STRATIGRAPHIC AND INTRUSIVE RELATIONSHIPS NOT SHOWN. MODIFIED FROM DATA OF BRYANT AND REED (1970a), BARTHOLOMEW AND LEWIS (1984), AND MANY OTHERS.

<table>
<tr><th>Age</th><th colspan="3">Blue Ridge Thrust Sheet</th><th colspan="3">Grandfather Mountain Window</th></tr>
<tr><td rowspan="2">Upper Proterozoic</td><td colspan="2">Bakersville Gabbro (dikes)</td><td>Alligator Back Formation
Ashe Formation
Mount Rogers Fm.
Ocoee Supergroup</td><td>Grandfather Mountain Formation (clastic and volcanic rocks)</td><td colspan="2">Linville Metadiabase (dikes and sills)
Unnamed porphyroclastic granite gneiss</td></tr>
<tr><td rowspan="3">Elk Park Massif</td><td>Crossnore Plutonics</td><td>Beech Granite
Crossnore Pluton
Unnamed quartz monzonite and granite gneiss</td><td colspan="2">Brown Mountain Granite</td><td rowspan="3">Globe Massif</td></tr>
<tr><td rowspan="2">Middle Proterozoic</td><td rowspan="2">Grenvillian</td><td>Cranberry Gneiss Complex
Max Patch Granite</td><td>Wilson Creek Gneiss Complex</td><td>Blowing Rock Gneiss</td></tr>
<tr><td>Unnamed mica schist
mica gneiss
amphibolite</td><td colspan="2">Unnamed metadiorite
gabbro</td></tr>
</table>

AGE RELATIONS: GRANDFATHER MOUNTAIN FORMATION

The exact age of the GMF is unknown. The following data permit a Late Proterozoic to possibly earliest Cambrian age to be most probable.

1) GMF rests nonconformably upon Grenville crystalline basement (1.1 Ga; Davis and others, 1962; Bryant and Reed, 1970a, 1970b; Fullagar and Odom, 1973; Bartholomew and Lewis, 1984).

2) GMF rhyolite (southeastern outlier) rests nonconformably upon Brown Mountain Granite (Bryant and Reed, 1970a; 735 Ma, Odom and Fullagar, 1984) which is one of the Crossnore Plutonic Suite (730 - 650 Ma; Odom and Fullagar, 1984; Sinha and Bartholomew, 1984; Tollo and others, 1991).

3) GMF rhyolite (southeastern outlier) interpreted to contain clasts of Brown Mountain Granite (Bryant and Reed, 1970a).

4) GMF and Mount Rogers Formation rhyolite yields discordant Pb - U age of 820 Ma (Rankin and others, 1969).

5) entire GMF is metamorphosed to lower greenschist facies (350 Ma; see Schwab, 1977).

6) GMF apparently completely lacks fossils.

7) Stratigraphic dissimilarity to more sheet-like, structurally overlying Upper Proterozoic - Cambrian Chilhowee Group.

8) General stratigraphic similarity to Ocoee Supergroup and Mount Rogers Formation as well as better constrained units farther north along the Blue Ridge axis.

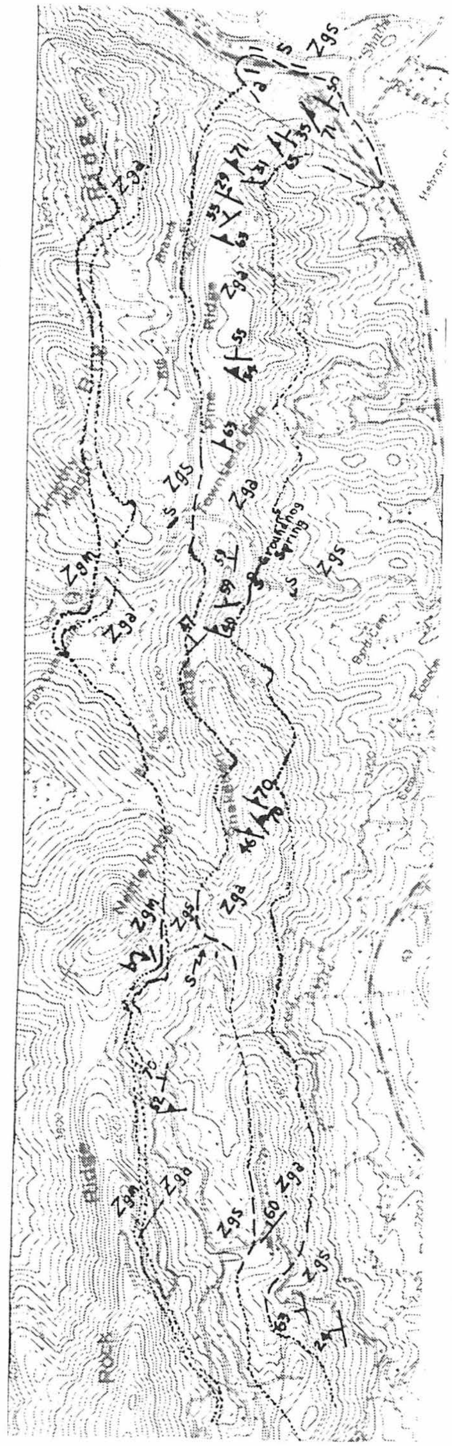
Points 1 through 3 constrain the base of the GMF to be no older than approximately 700 Ma, assuming rapid emplacement, uplift and erosion of the Brown Mountain Granite. The 820 Ma date for rhyolite of the GMF and Mount Rogers Formation (Point 4) is thought to be too old by many investigators because a mixed zircon population is present in these rhyolite bodies, producing the discordance (Odom and Fullagar, 1984; Rankin and others, 1989). Point 5 delimits a maximum upper age of 350 Ma since the GMF was deposited long before it was metamorphosed. The Chilhowee Group does not stratigraphically overlie the GMF, but is in thrust contact. Similar stratigraphic occurrence to other units (Point 8), however, which are known to underly the Chilhowee Group either conformably or unconformably is permissive evidence that the GMF is older than the Chilhowee Group. The Chilhowee Group is known to contain Cambrian trace and body fossils which place the Precambrian - Cambrian boundary within the middle to upper part of the basal Cochran/Unicoi Formation (see for example, Walker and Driese, 1991). Recent rediscovery (Broadhead and others, 1991) of C-shaped, soft-bodied, metazoan fossils within the uppermost formation (Sandsuck) of the Ocoee Supergroup in Tennessee (Rackley, 1951; Phillips, 1952) may lower the Precambrian-Cambrian boundary further into the Ocoee. Stratigraphic debate has been fueled by the discovery of possible Paleozoic(?) fossils in the Wilhite Formation (Unrug and Unrug, 1990; Unrug and others, 1991) which underlies the Sandsuck within the Ocoee Supergroup. Discussion and assessment of this stratigraphic controversy can be found in Broadhead and others (1991) and Walker and Rast (1991) as well as other papers in the same volume. To date no fossils have been discovered in the GMF and its internal stratigraphy is highly lenticular compared to the more laterally extensive strata of the Chilhowee. From this discussion an upper age limit of the GMF is probably around 570 Ma.

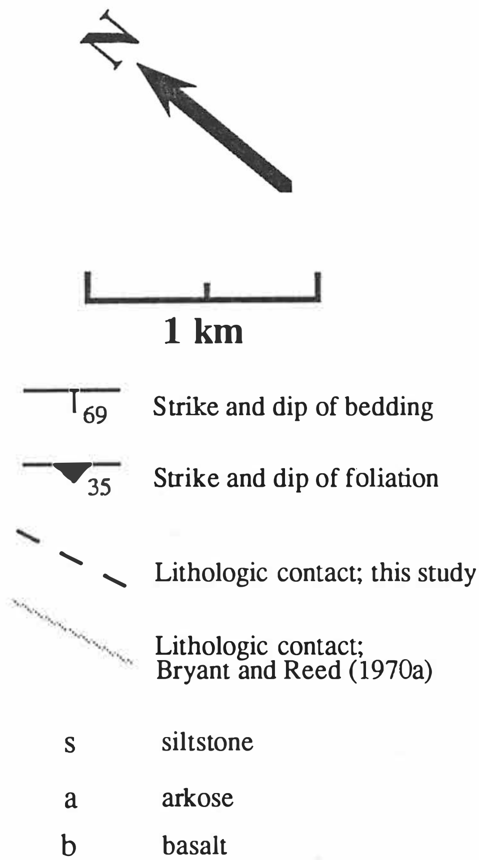
It is also suggested here that if the Montezuma basalt member of the upper GMF (never dated) is directly correlatable to the Catoctin Formation (570 Ma; Mose and Nagel, 1984; Badger and Sinha, 1988; Aleinikoff and others, 1991) and with the thin basalt flows near the base of the Unicoi Formation (Tennessee and Virginia; Misra and Walker, 1990; Aleinikoff and others, 1991), and represents the same extrusive event, then all GMF strata above the Montezuma are Early Cambrian. If this is the case, the GMF basin underwent nearly continuous(?) deposition from approximately 700 Ma to 560 Ma and contains a record of both major rifting events (730-650 Ma and 610-540 Ma) of Laurentia in the southern Appalachians. In addition, the nonconformity at the base of the GMF then represents a 300 to 400 Ma hiatus.

STRUCTURAL RELATIONSHIPS

The GMW (72 km long x 32 km wide) is a window, formed as erosion breached the Blue Ridge thrust sheet over what has been interpreted as an antiformal stack duplex that domed the sheet forming a structural high (Bryant and Reed, 1970a; Boyer, 1978; Boyer and Elliott, 1982). The Blue Ridge thrust sheet has been thrust northwestward a minimum of 55 km (restore Grenville leading edge in Blue Ridge thrust sheet to southeast edge of Grenvillian rocks exposed in GMW) over rocks within the GMW as well as other Grenvillian rocks and Cambrian sedimentary rocks of the Unaka Mountains on the Tennessee/North Carolina border (King and Ferguson, 1960; Bryant and Reed, 1970a; Schwab, 1977; Boyer, 1978). The rocks within the window are also most probably allochthonous (Rankin, 1970). Various reconstructions require these rocks to undergo tectonic movement from possibly 200 km southeast of their present position (Boyer and Elliott, 1982; Rankin and others, 1992; Thomas, 1991). Thomas' (1991) reconstruction places the Grandfather Mountain basin southeast of the Lower Cambrian shelf edge. The successful "central" Iapetus spreading ridge then would lay further to the east (Ashe and Alligator Back Formations).

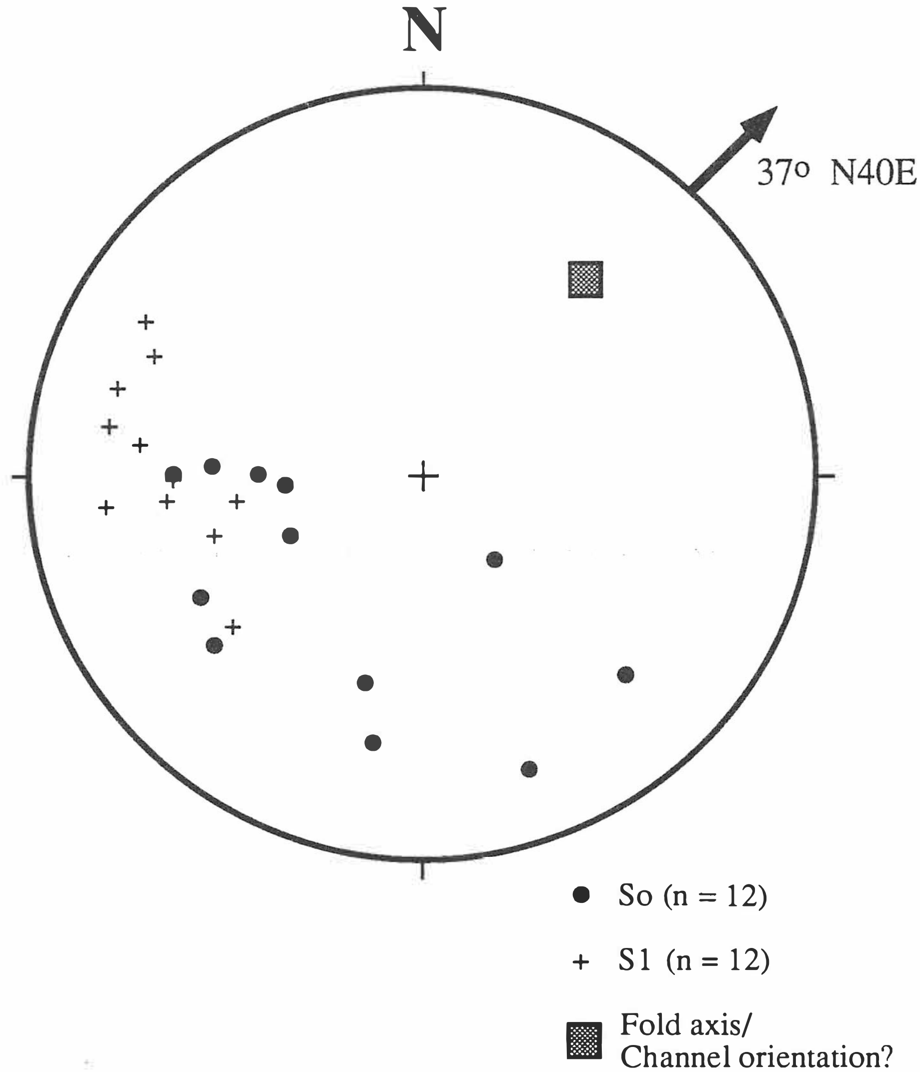
The GMF is locally cleaved and is folded internally (Boyer, 1984). Major internal faulting, however, which repeats or deletes stratigraphy has never been identified. Bryant and Reed (1970a), Boyer (1984), and this study documented that cleavage generally parallels bedding southeast of Grandfather Mountain (elev. 5964 ft.),but that it commonly intersects bedding in the upper part of the Formation where large-scale folds are generally open (Figs. 1-4 and 2-12). Ductile conglomerate clasts (fine-grained rhyolite and siltstone) are commonly flattened into the





a) Geologic strip map. For rock units see Fig. 1-2.

Figure 1-4. Geologic strip map and equal area diagram of Pine - Snakeden Ridge northwest of Foscoe, NC.



b. Equal-area diagram of poles to bedding and poles to cleavage.

Figure 1-4 continued.

plane of cleavage and locally elongated parallel to the northwest-southeast lineation (Bryant and Reed, 1970a). In contrast, nearby outcrops of pebbly mudstone and matrix-supported conglomerate exhibit little to no clast deformation; most of the deformation being concentrated in the relatively ductile, claystone to sandy siltstone matrix.

Most prominent folds are northwest-vergent, overturned synclines, which are in some cases isoclinal. These folds appear to be parasitic to larger overturned synclines of the same form which probably lend control to the Valley and Ridge-like outcrop pattern (sandstones forming ridges, siltstones forming valleys). The entire GMF is said to occupy the southeast limb of a complex, overturned, northwest-vergent synclinorium on the northwest flank of the Blue Ridge anticlinorium (Bryant and Reed, 1970a, 1970b). Excellent examples of overturned synclines exist at Broadstone Lodge (Locality 6a) and Newland (Locality 5d; Fig. 1-2). Northeast - trending fold axes are broadly warped about a secondary N60W trending box-fold axis (Bryant and Reed, 1970a; Boyer, 1978). Bedding data in the GMF are very nonuniform. Thickness and lithology change abruptly perpendicular and parallel to strike. The highly complex nature of GMF stratigraphy is doubtless a product of both high variability in depositional strike (for example, Nilsen, 1969; Galloway and Hobday, 1983), typical of rift deposits, as well as fold superposition, and other structural complications resulting from as many as three episodes of deformation.

Despite deformation and metamorphism in greenschist terranes, original mineralogy is typically well preserved and framework grain composition of sandstone and conglomerate can be directly interpreted (J. D. Walker, 1988). Although clasts are flattened locally in the GMF, Bryant and Reed (1970a) stated that in the arkose and siltstone units, "grains larger than 0.1 to 0.2 mm retain their clastic outlines and rock fragments their original textures."

Despite the high degree of deformation in some parts of the GMF, the majority of conglomerate and sandstone exposures, especially those below the Montezuma basalt (Figs 1-2 and 1-3), contain well-preserved sedimentary structures. These include primary bedding and lamination, trough- and planar-tabular cross-stratification, load structures, graded beds, ripples, ripple cross-laminae, and imbrication(?) in approximately decreasing order of abundance and ease of recognition. Exposures in these lower units exhibit outcrop patterns controlled locally by bedding as well as by cleavage.

Though the upper GMF (Montezuma basalt through upper siltstone; nearest Linville Falls fault zone) is pervasively deformed, locally planar-tabular and trough cross-strata, mud laminae, soft-sediment deformation structures, pebble stringers, and undulatory conglomerate/sandstone contacts are readily evident (Schwab, 1977; Neton and others, 1990; Neton and Driese, 1992).

METHODS/TERMINOLOGY

At 22 exposures containing conglomerate, diamictite, or gravelly sandstone, clast size (Appendix 4) and clast composition (Appendix 5) data were collected (see Part 2). Vertical facies analysis (as modified from Neton and others, 1990 and Neton and Driese, 1992) was performed on sixteen of these exposures (see Part 3). Appendix 2 gives detailed descriptions of the 13 lithofacies of the GMF defined in this study, and their occurrences. A number of other exposures were more generally described and some of these are referred to in the text. Localities are numbered on Figures 1-2 and 1-3. Geologic mapping was also performed along two ridges, primarily to tie roadcut and quarry observations together and to better understand facies relationships and transitions as well as structural style.

Measured Sections and Facies Analysis

No sections were measured in intervening siltstone, limestone, and sandstone (especially lower arkose), or volcanic successions, but observations of these lithologies were made in the course of road reconnaissance and field mapping. Observations of these lithologies by Bryant and Reed (1970a), Schwab (1977, 1986b), and Boyer (1978) are also utilized.

Miall (1985, 1988) discussed limitations of vertical facies analysis and proposed a new approach (after Allen, 1983) termed "architectural element analysis", which is especially useful in the study of fluvial sequences. Architectural element analysis requires large, high-quality exposures where channel features and lateral extent of beds can be mapped and subsequently classified into a hierarchy of bounding surfaces. This approach ultimately leads to a more precise interpretation of ancient channel/bar geometry, paleohydraulics, and paleogeography. Most exposures, however, in the GMF as well as throughout the Blue Ridge do not lend themselves to this approach due to the previously mentioned relatively high degree of weathering, deformation, metamorphism and commonly diminutive exposure. In light of this, vertical facies analysis was employed in study of the GMF. Wherever possible, lateral extent and geometry of lithologic units was noted. Despite shortcomings with regard to deciphering lateral facies geometries, vertical facies analysis will most certainly add to the stratigraphic and ultimately the tectonic understanding of the GMF as well as other related successions in the southern Appalachians.

Discernment of sedimentary bed thickness in some outcrops was difficult. Some highly unorganized diamictite and matrix-supported conglomerate sequences contain successions up to 20 m thick with no readily apparent grain size change. This phenomenon also occurs at Locality 1b in massive clast-supported conglomerate (up to 100 m thick), where original single bed thickness is almost impossible to define, yet was no doubt far less than 100 m. Hooke (1967), Bull (1972), and Miall (1985) noted that beds in alluvial fan and fluvial settings commonly range between 0.1 m to a few meters thick, rarely exceeding 3 to 4 m. The above described units, therefore, most probably are composed of amalgamated beds. Measured sections, therefore, were constructed from units delineated by definite grain-size changes. Locally indeterminant bed thickness characteristics are due to both the sedimentary nature of crudely and diffusely-bedded, coarse-grained conglomerate/diamictite facies as well as the locally pervasive cleavage, folding, greenschist facies metamorphism, and poor to fair exposure. Measured sections are sedimentologically and stratigraphically accurate, and can be used to interpret depositional environments.

Rock textures of diamictite, clast and matrix-supported conglomerate, sandstone, and mudstone were classified after Folk (1954). Diamictite is defined as a terrigenous sedimentary rock containing particles ranging in size from clay to boulder (Frakes, 1978). Diamictite may vary from poorly-sorted, clast-supported, cobble conglomerate through bouldery claystone to shale containing isolated clasts larger than 2 mm. This definition is too broad as it includes all conglomerate types as well as gravelly sandstones and gravelly mudstones as classified by Folk (1954). The definition of diamictite used herein is restricted to encompass only a portion of Folk's (1954) triangular diagram and is as follows: poorly-sorted clastic sedimentary rock containing a trace to 35% clasts larger than 2 mm and possessing a sand to mud ratio of less than 9:1 (Fig. 1-5). This definition therefore does not encompass clast or matrix-supported conglomerate or gravelly sandstone.

Conglomerate Clast Composition

Conglomerate clast composition data were collected by laying a 90 cm Jacob staff across the exposure, perpendicular to bedding, and using it as a point-counting guide. A chalk mark was placed every 5 cm. At each chalk mark either matrix type or a particular clast lithology was identified and tallied in grid form in the field. The clast data was recalculated to 100 percent composing frequency percent data. If more than one chalk mark intersected a clast, the "extra" chalk marks were ignored to prevent biasing. Clasts smaller than 5 cm which landed between chalk marks were still noted. This method of using the chalk marks only as a template to follow over "outcrop space" is particularly useful in very poorly-sorted conglomerate/diamictite where any interval chosen for the grid (for example, chicken wire or netting) will be either too large or too small anywhere along the transect.

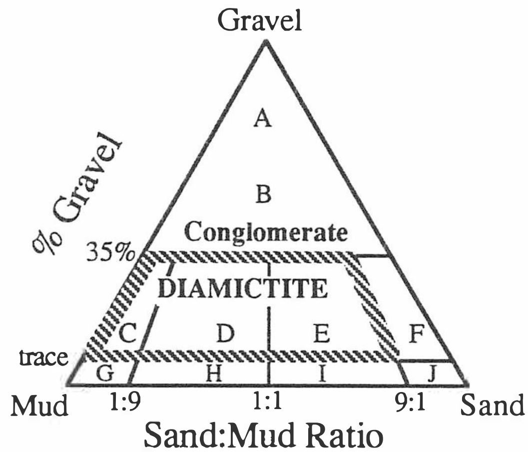


Figure 1-5. Textural groups used in this study and resulting rock names. Conglomerate: A) clast-supported , B) matrix-supported; diamictite: C) gravelly mudstone, D) gravelly sandy mudstone, E) gravelly muddy sandstone; sandstone/mudstone: F) gravelly sandstone, G) mudstone, H) sandy mudstone, I) muddy sandstone, J) sandstone. Modified from Folk (1954).

Between 100 and 400 clasts were counted and identified at each outcrop. See Appendix 5 for clast count data (raw frequency). Clast identification in the field was substantiated and refined during later slab description and thin-section microscopy. Conglomerate clast lithology was also compared to Grenvillian, Brown Mountain Granite, intraformational, and Mount Rogers Formation lithologies in hand sample and thin section. In all, 130 thin sections were examined.

Average Maximum Clast Size (AMCS)

Conglomerate/diamictite clast size data were collected by measuring the apparent clast long axis and the perpendicular axis on two-dimensional outcrop faces. Where clasts could be removed, or exposure was three dimensional, three mutually perpendicular axes were measured. Ductile (incompetent) and nonductile (competent) lithologies for greenschist metamorphic terranes as defined by Ramsay (1982) were modified for the GMF (Table 1-2). Between 10 and 40 of the largest clasts of both ductile and nonductile lithologies at each outcrop were measured. The largest ten ductile and largest ten nonductile clasts at each outcrop were then averaged to produce an "AMCS ductile" and an "AMCS nonductile" value for each exposure. See Appendix 4 for raw clast size data and AMCS for each outcrop. In some exposures where clasts still retain angular depositional shapes or where deformation was clearly confined to a more ductile matrix instead of the clasts, the ductile/nonductile distinction was not strict.

Geologic Mapping

Bryant and Reed (1970a) did not map conglomerate bodies separately, but included them with either their arkose (Zga) or siltstone (Zgs) map units. Lateral extent and facies relationships of conglomerate between road exposures was not known. Two ridges, in particular, were traversed: Snakeden Ridge (northwest of Grandfather Mountain) and Horse Bottom Ridge

TABLE 1-2. RELATIVE CLAST DUCTILITY: GMF. MODIFIED FROM RAMSAY (1982).

generally increasing ductility ↓	Clast type	
	Vein quartz	Non-ductile (competent)
	Granite/granitoid/gneiss	
	Feldspar	
	Sandstone	
	Quartzite	
	Chert	
	Basalt	
	Purple porphyritic felsite	Ductile (incompetent)
	White/green felsite	
	Volcanic breccia	
	Purple/red siltstone	
	Greenish yellow laminated siltstone	
	Siltstone	

(northeast of Banner Elk, NC). A strip map (Fig. 1-4a) and stereoplot of bedding and cleavage relationships (Fig. 1-4b) on Snakeden Ridge are presented here. Observations of facies relationships along Snakeden Ridge are discussed primarily in Part 3. A geologic strip map (Fig. 2-13a) and stereoplot of bedding and cleavage relationships (Fig. 2-13b) along Horse Bottom Ridge are presented in Part 2. Paleodispersal implications are discussed in Part 2 and facies interpretations aided by the Horse Bottom Ridge traverse are discussed in Part 3. On both strip maps bedding data were gathered primarily from unambiguous conglomerate/sandstone contacts, but in some cases from sandstone outcrops which displayed well-developed planar stratification and grain size changes.

CLAST DEFORMATION

Clast deformation is most severe in clast-supported conglomerates, especially those containing a mix of ductile and nonductile clast types. In this case most strain was accomodated by the ductile clasts instead of the nonductile varieties. This style of deformation is most evident in the Banner Elk conglomerate of the upper GMF (Figs. 1-2 and 1-3). At Locality 5a (0.3 km from the LFF trace) cobble clast-supported conglomerate is mildly mylonitized and locally at Locality 5a, nonductile clast types are also minimally flattened into the plane of cleavage. Despite this arguably high degree of deformation, the following sedimentologic, petrologic, and petrographic data suggest that clast deformation in the Banner Elk conglomerate as well as the rest of the GMF is not enough to significantly alter clast dimensions or AMCS trends.

Modern Gravel: Cassi Creek, Tennessee

A cross-stratified purple quartzite cobble from Locality 5a measures 19.5 x 14.0 x 8.5 cm. This disc-shaped clast is very similar to common shapes observed in modern gravelly rivers including those observed in Cassi Creek near Mount Carmel, Tennessee. Cassi Creek is a gravelly, ephemeral, relatively straight channel that drains off the Blue Ridge front and flows northwest. The bed consists of imbricated pebbles, cobbles, and boulders of quartzite, grey limestone, and basalt. The quartzite clasts are derived from the Chilhowee Group and are either disc, bladed, or equant in shape. Many clasts contain perfectly identifiable trough cross-strata, horizontal lamination and pebble horizons, indicative of clasts most probably derived from the basal Unicoi Formation. By size and shape analogy to the clasts in Cassi Creek, it is argued that clast deformation in the Banner Elk conglomerate as well as the rest of the GMF is not significant enough to alter original depositional AMCS trends. In addition, the perfectly preserved cross-strata in the GMF quartzite cobble above also suggest minimal internal clast deformation and therefore minimal dimensional alteration.

Clast Angularity

Whereas original depositional shapes may not be generally preserved throughout the GMF, angular to very angular clasts such as those observed at localities 2a, 3b, and 6a argue against severe clast deformation. No doubt, the majority of the deformation was confined to sand and mud matrices at these and other localities, rather than the clasts.

Petrographic Data

Petrographic data also support minimal internal clast deformation throughout the GMF and therefore minimal dimensional alteration. Cobble to boulder conglomerate at Locality 1b locally contains pressure-solution seams at clast contact points. The presence of between-clast pressure solution minimizes the possibility that other deformation mechanisms such as crystal boundary migration and rotational recrystallization were significant within the clast. Thin-section comparison of sand and gravel grains from relatively undeformed localities (3c, 3d and 4) and those of relatively deformed localities (2c, 5bc) show no differences in internal grain textures. Many clasts within the Banner Elk conglomerate and the upper siltstone (Broadstone Lodge diamictite) contain unaltered sedimentary and volcanic textures, including quartz overgrowths, lamination, euhedral phenocrysts, and amygdules (some flattened). Because these textures are preserved and are representative of the source rock, then metamorphic and intrusive textures are also representative of the source and have not been significantly altered by subsequent Paleozoic Appalachian orogenesis. Further, foliated quartz pebbles in the Banner Elk conglomerate were petrographically observed with the foliation oriented perpendicular to the foliation within the conglomerate. This texture strongly suggests an original depositional metamorphic clast that may or may not have been subsequently rotated during cleavage formation and is further evidence against internal clast recrystallization and attendant clast dimensional alteration. Bryant and Reed (1970a; p. 84) also maintained that sand and gravel grains within the GMF preserve their original depositional textures, especially within the upper siltstone unit, and therefore are representative of the source rock.

Scale Considerations

In regard to significance of clast dimensional alteration, it is also pointed out that a difference of 1 mm between sand grains is highly significant, but 1 mm between cobbles/boulders is trivial (Pettijohn and others, 1987; p. 71). Although Pettijohn and others (1987) stated this in relation to hydraulic properties of grains, this scale-related concept can also be applied to deformation of gravel-size material. A pebble or cobble with the long axis extended by *even 5 cm* will most likely still fall within the pebble or cobble grain-size range and not be extended to boulder size. Along this same line, in-field misclassification of a pebble conglomerate as a cobble or boulder conglomerate and vice versa is nearly impossible. It is also noted that "penciled" clasts were *not* observed in the GMF and that clast long axis extension or shortening is nowhere deemed to be greater than a few centimeters.

In conclusion, despite local flattening of clasts into the plane of cleavage, petrologic and petrographic evidence suggests that clast dimensions (especially those of nonductile clasts) throughout the GMF are not significantly altered and that AMCS data can be used to delineate sedimentologic and tectonic trends which developed during GMF basin formation.

FIELD GUIDEBOOKS

Appendix 1 may be used as a general field guide to conglomeratic and diamictic exposures within the GMF. Other field guides to the GMF and GMW are within Boyer (1978), Hatcher and Butler (1986), Schwab (1986b), Butler and Hatcher (1989), and Raymond and others (1992).

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2. Repeated Late Proterozoic rifting of the Laurentian continent and resultant sedimentation: Conglomerate units of the Grandfather Mountain Formation, North Carolina Blue Ridge

ABSTRACT

Crustal extension and initiation of rifting of Laurentia during the Late Proterozoic resulted in deposition of thick clastic and volcanic sequences in a northeast-trending set of continuous to discontinuous rift basins situated cratonward of the Iapetus Ocean spreading ridge. The Grandfather Mountain Formation contains five stratigraphically and compositionally distinct conglomerate/diamictite units and one pebbly sandstone unit which cap coarsening-upward basin-fill sequences. The progradational sequences average 1300 m thick and are typically composed of a succession of volcanic flows (basalt/rhyolite) and/or siltstone, succeeded by fine- to coarse-grained feldspatholithic sandstone, succeeded by pebbly sandstone and conglomerate. Major rifting events (or clusters of events) occurred during deposition of volcanic rocks and fine-grained lacustrine or marine, and fluvial sediment near the basin margin fault. After a time lag, alluvial fans and fan-deltas prograded basinward from the margin over the fine-grained sediment.

Southwest-fining along strike of three of the five conglomerate units suggests: 1) derivation from the northeast, possibly from an accomodation zone and from the Mount Rogers Formation, or 2) more extensive, coarser-grained, southeastward progradation in the northern half of the basin. The Grandfather Mountain and Mount Rogers basins may have developed as an asymmetric, alternating, half-graben pair and at various times were joined or separated by an accommodation zone.

The polymictic conglomerate of the Grandfather Mountain Formation is dominated by felsite and basalt clasts and contains subsidiary amounts of crystalline basement and sedimentary clasts. Two compositional sequences (upper and lower) are present within the conglomerate and are delineated by presence or absence of perthite phenocrysts in felsite clasts. The lower sequence is dominated by porphyritic *quartz-perthite* felsite clasts and details an unroofing sequence: felsite → sandstone and siltstone → crystalline basement. In contrast, the upper sequence is dominated

by felsite clasts containing *only quartz phenocrysts* (in the Banner Elk conglomerate) and basalt clasts (in the Broadstone Lodge diamictite).

Certain conglomerate clasts are most reliably matched to nonconformably underlying Grenvillian Blowing Rock Gneiss and the intraformational Montezuma basalt. Felsite clasts may be derived either from Grandfather Mountain Formation or Mount Rogers Formation rhyolite. Other clasts were derived from other, as yet unidentified, source terrains that may be eroded away or are not exposed. Application of these techniques to other ancient rift sequences, especially those exposed in the Appalachian Blue Ridge, may further delineate rifting episodes, rift shoulder and basin paleogeography, and provide insight into subsurface patterns within rift basins along modern passive margins.

INTRODUCTION

Thick gravel successions are deposited in sedimentologically and tectonically dynamic systems directly adjacent to abrupt relief formed by tectonic disturbance. As such, the clasts represent unambiguous pieces of original source rock and are a direct indicator of basin tectonism (Sharp, 1948; Steel, 1976; Boggs, 1992). Vertical and lateral conglomerate clast population trends, coupled with vertical and lateral clast size trends, are particularly powerful tools for unravelling complex basin history. Conglomerate clast population and average maximum clast size (AMCS) trends can delineate source regions/units, faulting events, and unroofing histories of adjacent basin flanks, providing a detailed basin history. Studies employing one or more of these data types have been performed in many compressional, transform and extensional terranes (for example, Follo and Siever, 1984; Mack and Rasmussen, 1984; Graham and others, 1986; Ingersoll and others, 1990; McKee and others, 1990). These studies dealt with Cenozoic and younger basins. Difficulty is encountered in older sequences because metamorphism/deformation are generally more pronounced. Despite this, conglomerate units survive deformation relatively intact and therefore serve as useful marker units (J. D. Walker, 1988). Workers studying older successions have primarily concentrated on minimally deformed and relatively unmetamorphosed units (for example, Hazlett, 1978: Triassic of Virginia; Steel and Wilson, 1975; Steel and others, 1977; Gloppen and Steel, 1981: Devonian of Norway; Middleton and Trujillo, 1984: Upper Proterozoic of Arizona). Similarly focused studies of rift-related conglomerate within Upper Proterozoic successions of the Appalachian Blue Ridge have generally not been made, other than in passing observation (exceptions: Neton and Driese, 1992; Hutson and Tollo; 1991, 1992).

Detailed facies analyses and stratigraphic studies in the Grandfather Mountain Formation (GMF: Upper Proterozoic, North Carolina) and in correlative units are sparse. Because of this, the internal stratigraphy of these units is generally poorly constrained. Detailed facies analysis of these units, such as that of Blondeau and Lowe (1972), Schwab (1976), and Miller (1986), all in the Mount Rogers Formation, as well as Wehr (1986: Rockfish Conglomerate) and Neton and others (1990), Neton and Driese (1992: GMF), will lead to a clearer understanding of depositional environments along the rift trend, aiding in tectonic/paleogeographic reconstruction, and will help to resolve the complex rift stratigraphy. Increased use of sandstone framework grain and conglomerate clast size and population trends, to delineate Upper Proterozoic rift basin tectonics will provide a more comprehensive and precise knowledge of development of the Late Proterozoic-Cambrian Iapetus margin and the nature of continental rifting in general.

Presented here are lateral and vertical clast composition and clast size data of five discontinuously mappable, conglomerate units of the GMF. The purpose of this paper is threefold: 1) to provide new information on the stratigraphy of the GMF in relation to these conglomerate units; 2) to interpret Grandfather Mountain basin history and assess possible interaction with other rift basins developing coevally along the Laurentian margin during the Late Proterozoic; and 3) to propose an unroofing sequence and a generalized paleogeography of Grandfather Mountain basin shoulders.

TECTONIC SETTING

See Part 1 for details regarding correlative Upper Proterozoic units (Fig. 1-1), large-scale Late Proterozoic rift geometry and stratigraphy, and comparisons to the Mesozoic rift system of eastern North America.

REGIONAL GEOLOGY

See Part 1 for details of Grandfather Mountain window (GMW) location, stratigraphy and age relationships (Table 1-1 and Figs. 2-1 and 2-2).

STRUCTURAL RELATIONSHIPS

See Part 1 for details regarding GMW and GMF structural style (Figs. 1-1 and 1-4 and Figs. 2-1 and 2-3) and clast deformation (Table 1-2).

METHODS

See Part 1 for detailed discussion of methods (conglomerate clast composition and average maximum clast size (AMCS)) as well as conglomerate and diamictite definition (Fig. 1-5 and Table 1-2).

STRATIGRAPHY: GRANDFATHER MOUNTAIN FORMATION

Due to the high depositional and structural variability as well as discontinuous and commonly deeply weathered exposure of particular lithologies (that is, thick siltstone successions that produce poor exposure), a composite stratigraphic section of the GMF has never been measured. Neither Bryant and Reed (1970), Boyer (1978), nor Schwab (1977; 1986a) presented

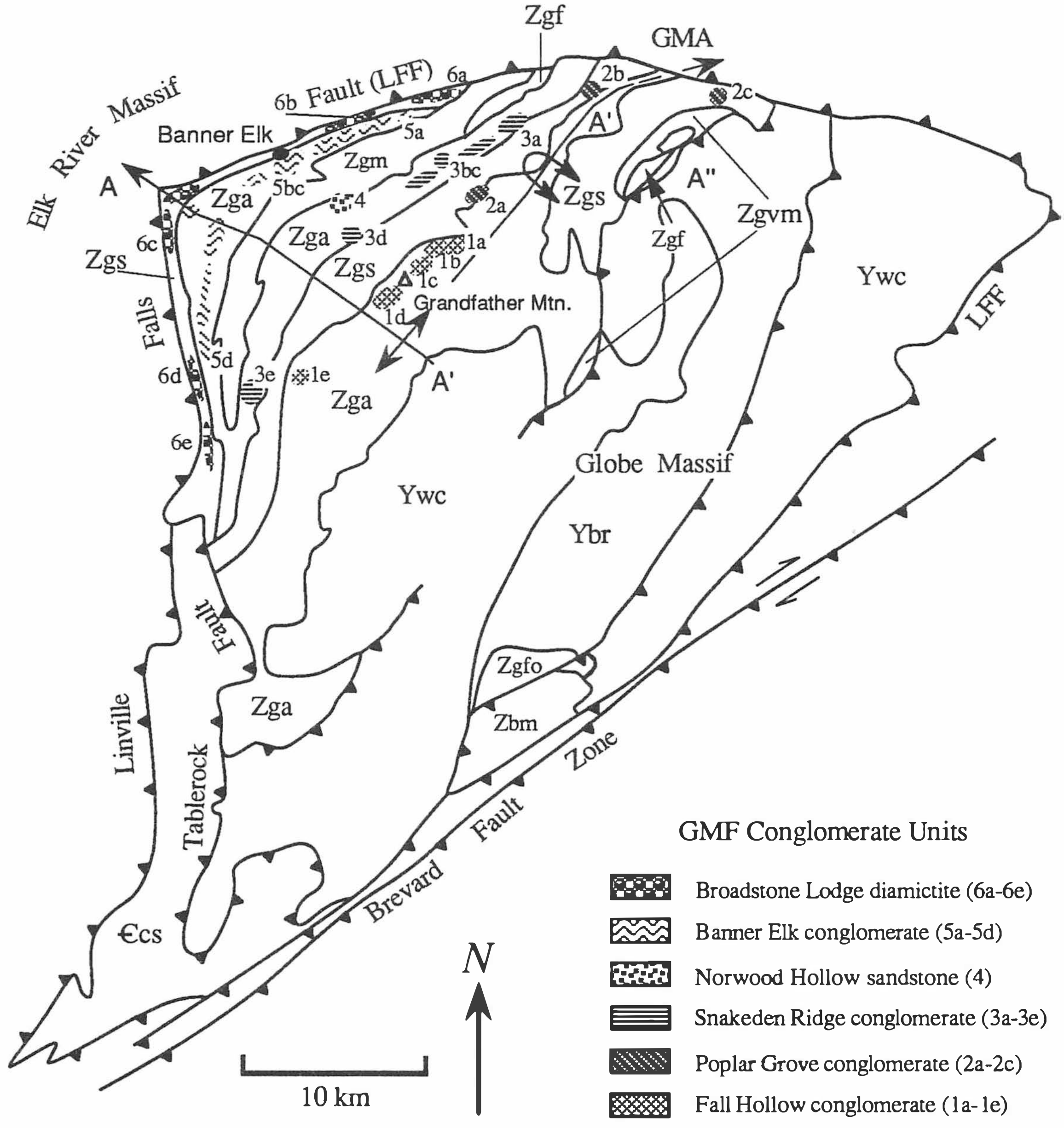


Figure 2-1. Generalized geologic map of the GMW and GMF showing distribution of major conglomerate units. Numbers 1a through 6e denote outcrops within discontinuously mappable units (see Figure 2-2). A-A'-A" denotes trend of cross section (Figure 2-3). GMA = Grandfather Mountain anticline. Map units: GMF: Zga = lower, middle, and upper arkose; Zgs = lower and upper siltstone; Zgf = felsic volcanics (lower and upper rhyolite); Zgfo = outlier rhyolite; Zgvm = lower mafic volcanic rocks; Zgm = Montezuma basalt. Crystalline basement (Globe massif): Ywc = Wilson Creek Gneiss; Ybr = Blowing Rock Gneiss; Zbm = Brown Mountain Granite. Other: €cs = Chilhowee Group and Shady Dolomite in Tablerock thrust sheet; Zl = Linville Metadiabase (not shown). Modified from Bryant and Reed (1970a), Boyer (1978), Bartholomew and Lewis (1984), and Brown and many others (1985).

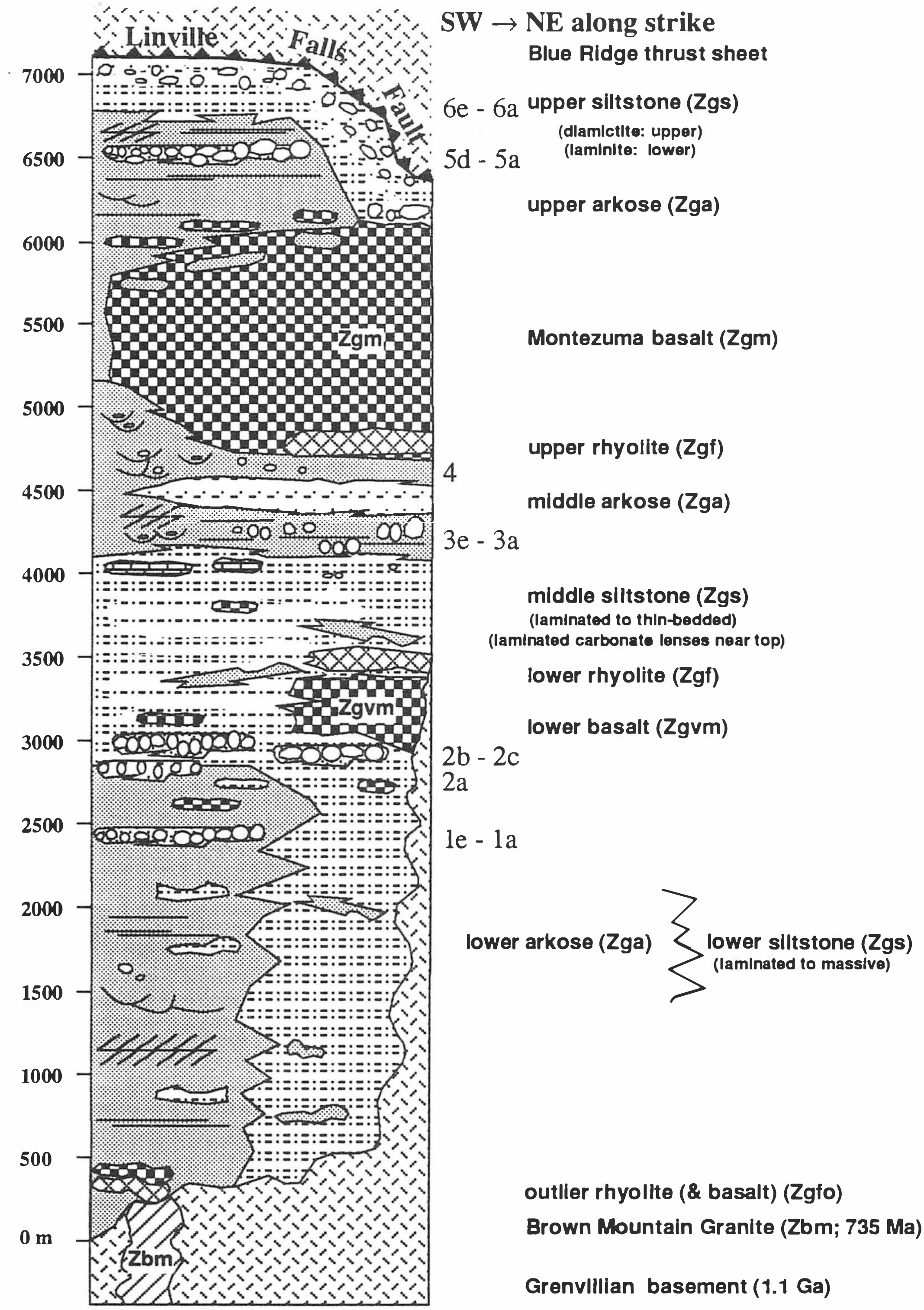


Figure 2-2. Generalized GMF stratigraphy constructed from map thickness data. Rock unit designations of Bryant and Reed (1970). Lower and middle siltstones of Bryant and Reed (1970) interpreted as same unit repeated on limbs of Granfather Mountain anticline after Boyer (1978; 1984) and data of this study and Neton and Driese (1992). Numbers denote conglomerate sections and bodies defined in Figure 2-1. Linville Metadiabase dikes and sills not pictured. Column not intended to show all variability across and along strike. Depiction of basal nonconformity does not imply true depositional relief, but merely depicts units which are known to rest nonconformably upon basement.

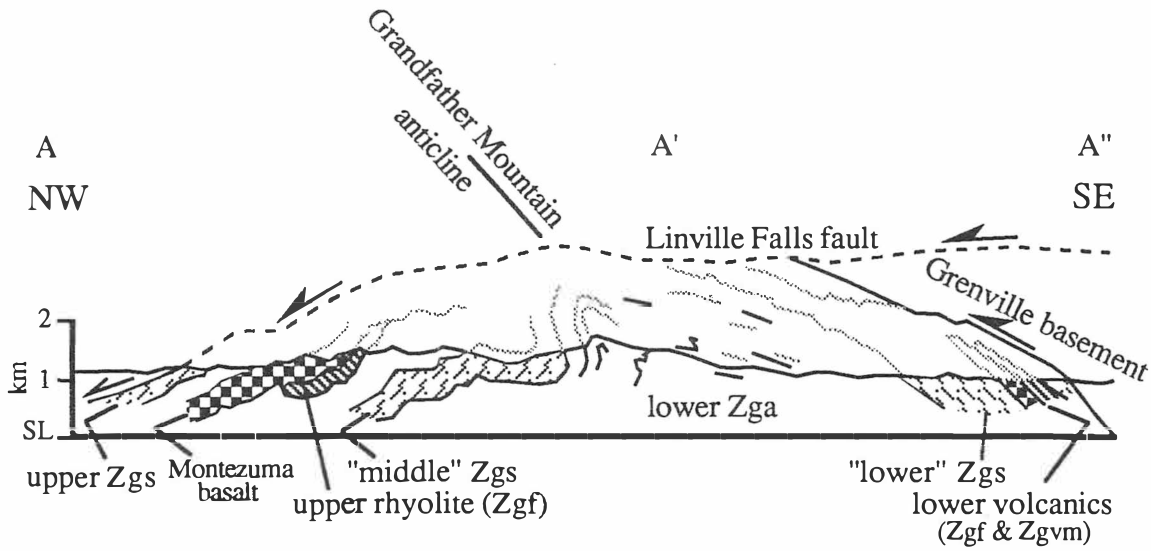


Figure 2-3. Schematic cross-section (A-A'-A") through Grandfather Mountain Formation showing Grandfather Mountain anticline and "lower" and "middle" siltstone units as the same unit. Arkose and Grenville map units not shaded. Upper arkose not labeled. Modified after down-plunge projection of Boyer (1978; 1984).

any measured-section data of single outcrops. Consequently, no formal GMF internal stratigraphy exists. In spite of the depositional and structural complexities, Bryant and Reed (1970), after Keith (1903, 1905, 1907), defined an informal stratigraphy for use as map units (Figs. 2-1 and 2-2).

Bryant and Reed (1970) maintained that no part of the section is entirely repeated and that the GMF youngs to the northwest from the nonconformity at the base. This paper accepts their informal stratigraphy (modifying it only slightly - see discussions which follow) because of the existence of distinctive (texturally and compositionally) units which are not repeated, some of which can be traced (discontinuously to continuously) for up to 36 km along structural strike (data of Bryant and Reed, 1970; Boyer, 1978; Neton and others, 1990; Neton and Driese, 1992). The observations which follow are especially significant (Figs. 2-1 and 2-2). New names of the conglomerate units and their areas of exposure will be delineated in later discussion of lateral clast size and composition.

1) Both the lower rhyolite and lower basalt are compositionally and texturally different from the upper rhyolite and Montezuma basalt member, repectively. The Montezuma is a thick, relatively homogeneous basalt that persists along strike for 28 km.

2) The lower, middle, and upper siltstone units are compositionally different and the middle and upper siltstone units are continuous along strike for 36 km and 31 km, respectively. The middle siltstone contains laminated limestone lenses near its top, whereas limestone in the lower and upper siltstone units is rare. The lower siltstone is siltier and contains more mica, chlorite, and opaque minerals than the others. In addition, the upper siltstone contains a distinctive, laterally extensive diamictite unit (here informally named the Broadstone Lodge diamictite) rich in basalt clasts, whereas the lower and middle siltstone contain very sparse gravel. Boyer (1978; 1984), however, maintained from structural data, that the lower and middle siltstone units are the same siltstone unit folded about a northeast-trending anticlinal axis (Grandfather Mountain anticline: Figs. 2-1 and 2-3). He explained the above-described lithologic differences between the two siltstone units as proximal to distal facies changes. Boyers' (1978; 1984)

stratigraphy is corroborated in this paper by similar clast composition of conglomerate successions on both limbs of the anticline (Poplar Grove conglomerate; see discussions which follow).

3) The lower arkose (base of GMF) is finer grained, more massive and thicker than either the middle or upper arkose and interfingers laterally with the lower siltstone unit (Figs. 2-1 and 2-2). Both the lower and upper arkose units appear to coarsen upward to conglomerate units (Fall Hollow and Banner Elk conglomerates respectively), and are discontinuously mappable along strike for 12 to 19 km, each with a unique clast composition. The middle arkose also contains a major, discontinuously mappable conglomerate unit (Snakeden Ridge conglomerate) with a unique clast composition that can be traced along strike for approximately 20 km.

GENERAL CONGLOMERATE DESCRIPTION: GRANDFATHER MOUNTAIN FORMATION

Bryant and Reed (1970) and Schwab (1977, 1986a) noted the wide range of clast lithologies, but collected no quantitative data. Traditionally, GMF conglomerate has been qualitatively characterized as being dominated by granite and gneiss clasts (Schwab, 1977, 1986a; Hatcher and Goldberg, 1991). Quantitative data (Fig. 2-4), however, contradict this conception. Volcanic clasts are clearly dominant. In fact, Bryant and Reed (1970) stated that in many conglomerate units, felsic volcanic clasts are most prevalent. Despite being dominated by felsite and basalt clasts, GMF conglomerate is strikingly polymictic and contains white (vein?) quartz, granitoid/gneiss, metaquartzite, chert, sandstone and siltstone clasts. This polymictic character contrasts markedly with the near monomictic nature of conglomerate within the correlative Upper Proterozoic Mechum River Formation of Virginia which contains only granitoid/gneiss and felsite clasts (Hutson and Tollo, 1991, 1992). Blue quartz and limestone clasts, prevalent within conglomerate in parts of the correlative Ocoee Supergroup (Hadley and Goldsmith, 1963; Walker and Rast, 1991), are not present within GMF conglomerate. Granitoid/gneiss clasts and quartzofeldspathic detritus of the GMF have been generally assumed to have been derived from the

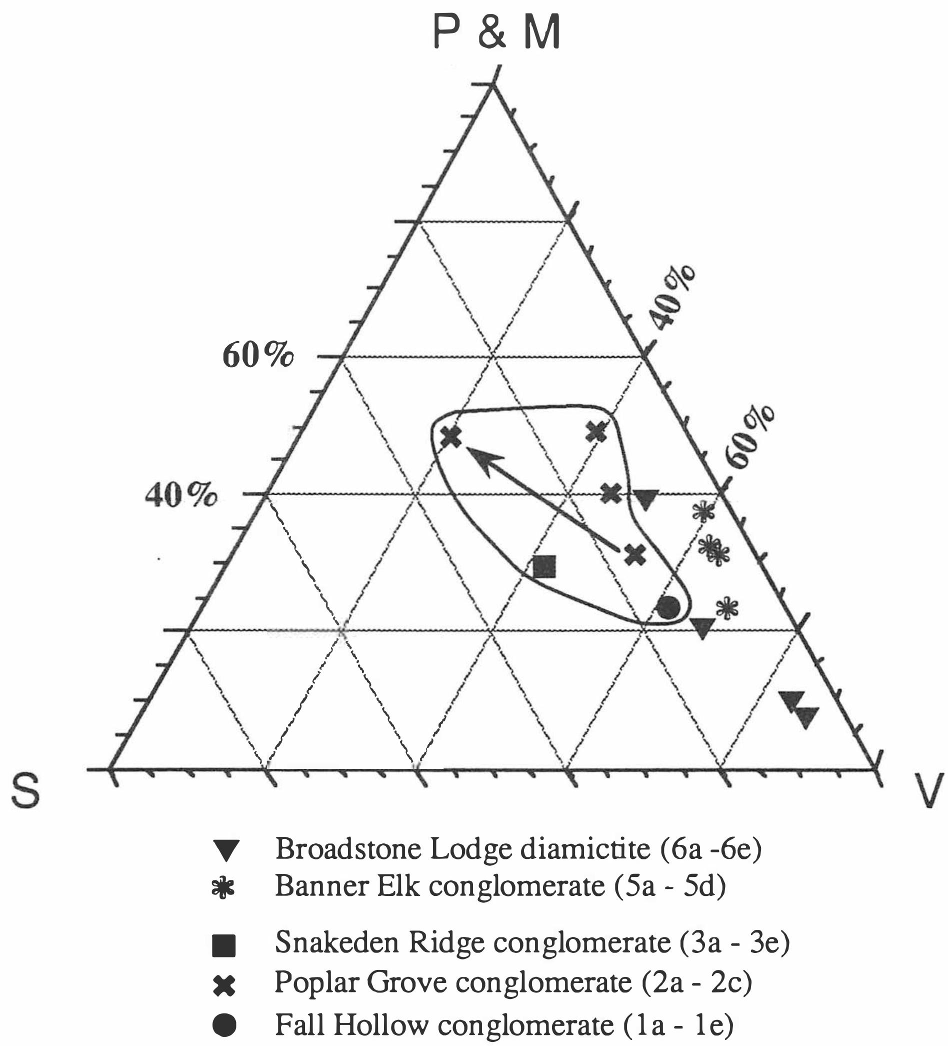


Figure 2-4. P-M/S/V ternary plot of clast composition of major conglomerate bodies of the Grandfather Mountain Formation. Conglomerate bodies arranged vertically in stratigraphic order. Frequency percent data recalculated to 100%. P & M = plutonic and metamorphic crystalline basement; S = sedimentary/metasedimentary; V = volcanic. Note that volcanically-derived conglomerate is dominant. Circled region represents lower sequence. Arrow denotes the upward increase in sedimentary and crystalline clasts at Locality 2c and is representative of the transition within the lower sequence. Fall Hollow conglomerate: clast counts at Localities 1b and 1c were combined. Snakeden Ridge conglomerate: clast counts at Localities 3a and 3b were combined. Broadstone Lodge diamictite: no clasts present at Locality 6b.

nonconformably underlying crystalline basement (Bryant and Reed, 1970; Schwab, 1977, 1986a; Boyer, 1978; Thomas, 1991). No clast, however, has been *unambiguously matched* to any of the underlying basement units, in contrast to granitoid clasts within the broadly correlatable Fauquier Formation (Kline and others, 1991) and Mechum River Formation (Hutson and Tollo, 1991, 1992). The assumption of derivation from the underlying crystalline basement is generally supported in this paper by petrologic data, although proof of clast-to-source matches must await geochemical study.

Schwab (1977, 1986a) interpreted the GMF as having been deposited largely in alluvial fan/braided fluvial environments. Detailed facies analysis of the GMF (Neton and others, 1990; Neton and Driese, 1992) is summarized in Table 2-1 and generalized depositional environments of each of the five conglomerate units are summarized in Table 2-2. Conglomerate (matrix- and clast-supported) and diamictite are most prevalent in the northern half of the exposed GMF, whereas they are virtually nonexistent in the southern half of the GMF. The five stratigraphically and compositionally distinct conglomerate units crop out as successions of lenses and as more laterally extensive horizons (Figs. 2-1 and 2-2). Conglomerate bed thickness is highly variable and ranges from stringers one pebble/cobble thick to 7 m-thick, fining-upward successions. A conglomerate succession, however, at Fall Hollow (Locality 1b) reaches approximately 100 m thick with only one intervening sandstone bed (Fig. 2-5). Cross-stratified conglomerate does not occur, but interbedded cross-stratified pebbly and granule-bearing sandstone is quite common. Cross-strata sets range up to approximately 1 m thick, but most commonly are 10 to 30 cm thick. Clast imbrication may have been present locally, especially in the Banner Elk conglomerate, but is now generally indecipherable and obscured by cleavage. Beds range from unsorted and ungraded to moderately-sorted, normal, and inversely-graded (Fig. 2-6). Matrix texture ranges from sandy mudstone to granule-bearing sandstone, with some matrix-supported conglomerate containing relatively clean medium-grained sandstone as matrix. Clasts in the GMF range from small pebble

TABLE 2-1. LITHOFACIES, SEDIMENTARY STRUCTURES AND INTERPRETED PALEOENVIRONMENTS OF FLUVIAL - ?GLACIAL? - DEEP WATER DEPOSITS OF THE GRANDFATHER MOUNTAIN FORMATION. (SCHEME MODIFIED AFTER MIALL, 1977, 1978; WARESBACK AND TURBEVILLE, 1990; NETON AND OTHERS, 1990).

Facies Code	Lithofacies	Sedimentary Structures	Interpretation
Gcsu	Conglomerate, clast-supported, non-stratified, fair to very poorly sorted, granular to bouldery, minor gravel/sand/silt matrix and as diffuse lenses	generally massive, very crude grading, ?imbrication?	cohesionless grain flow/ liquefied sediment flow types: modified grain flow, sieve deposits, gravelly sheetflood
Gcsmh	Conglomerate, clast-supported, usually as lenses, interbeds of sand/silt lenses and/or filling interstices	massive to horizontal stratification, some grading, commonly broadly undulose base ?imbrication?	longitudinal bar
Gmsi	Conglomerate, matrix-supported, non-stratified, graded, may be clast-supported in upper part	inverse grading, ?basal shear zone?	debris/mud flow, (high μ, high yield strength matrix) density modified grain flow
Gmsu	Conglomerate, matrix-supported, non-stratified, ungraded	massive	debris/mud flow (intermediate μ)
Gmsn	Conglomerate, matrix-supported, non-stratified, graded	normal grading	debris/mud flow (low μ, low yield strength)
D	Diamictite, unstratified to stratified, mud to sand matrix with granules to boulders (tr. to ~ 35 %)	massive to thin/thick bedding, wavy laminations, disrupted/diffuse laminations, normal grading, load structures, outsized clasts (?dropstones?)	subaerial mud/debris flows, subaqueous mud/debris flows, ?ice rafting?
Sln	Sandstone, fine to coarse-grained, some silt, sparse granules/pebbles	horizontal lamination/bedding, locally normal graded, load structures, rare ripple cross-laminations	subaqueous fluidal flows
Smh	Sandstone, fine to very coarse-grained, sparse to common granules and pebbles	massive to horizontal bedding/lamination local pebble stringers	sheetflood, streamflow in broad shallow-relief channels, diffuse sand and gravel sheets, sheetflood over longitudinal bars (lower and upper flow regime)
St	Sandstone, fine to very coarse-grained, sparse to common granules to small cobbles	small scale trough cross-strata, purple laminations/wisps/lens, large scale trough cross-strata	3-D dunes (lower flow regime) channel fills
Sp	Sandstone, fine to very coarse-grained, sparse to common granules and small pebbles	small scale planar tabular/tangential cross-strata large scale planar tabular/tangential cross-strata	2-D dunes transverse bars (large 2-D dunes)
Sr	Sandstone, coarse silt to fine-grained sand	symmetric ripples, ripple and climbing ripple cross-lamination, small scale trough cross-lamination	overbank deposition in ponds, sloughs, cut-off/inactive/avulsed channels superimposed bedforms
Flm	Claystone to very fine-grained sandstone, very sparse coarse sand/granules (< 1%)	planar lamination to very thin beds, wavy lamination, ripple cross-lamination, loads, flames, soft sediment folds/faults, sometimes massive	1 deep-water deposits (suspension settling) & subaqueous fluidal flows, 2 overbank deposition in ponds, inactive/avulsed channels
Ll	Limestone	thin laminations	lacustrine (playa?) carbonates, algal mats?

subaerial and subaqueous

TABLE 2-2. CLAST POPULATION, CLAST SIZE, AND INTERPRETED DEPOSITIONAL ENVIRONMENTS FROM FACIES ANALYSIS OF FIVE DISTINCT CONGLOMERATE BODIES OF THE GMF. Q = QUARTZ, VQ = ?VEIN? QUARTZ, P = PERTHITE.

Conglomerate Unit	Depositional Environment	Clast Population Characteristics	Lateral Clast Size Chars.
Broadstone Lodge diamictite	debris flows on subaqueous slope (fan-deltas) of ?deep lake? ?proglacial ice rafting?	**basalt dominant** basalt increases to SW Q/Q&P felsite decrease to SW VQ/Granite decrease to SW	**fining toward center of outcrop pattern**
Banner Elk conglomerate	mid to lower alluvial fan or ?glacial outwash plain?	**Q porph felsite dominant** vein quartz high minor granite, x-bedded purple metaquartzite, red chert basalt absent Q&P porphyritic felsite absent constant composition along strike	**fining to SW**
Snakeden Ridge conglomerate	mid/upper alluvial fan/fan-delta/deep laketo braidplain/playa lake	**Subequal Q&P porph felsite, granite/gneiss, SS/qtzt** minor basalt, VQ Q porphyritic felsite absent	**fining to SW**
Poplar Grove conglomerate	fan delta/subaqueous channel	**Q&P porphyritic felsite and granite/gneiss dominant** secondary basalt, VQ, and sedimentary clasts Q porphyritic felsite absent	**fining to SW?**
Fall Hollow conglomerate	water-flow dominated mid/upper to lower alluvial fan and between-fan pond	**Q&P porph felsite dominant** secondary granite, sandstone/qtzt minor andesite/basalt, VQ, siltstone	**fining to SW**

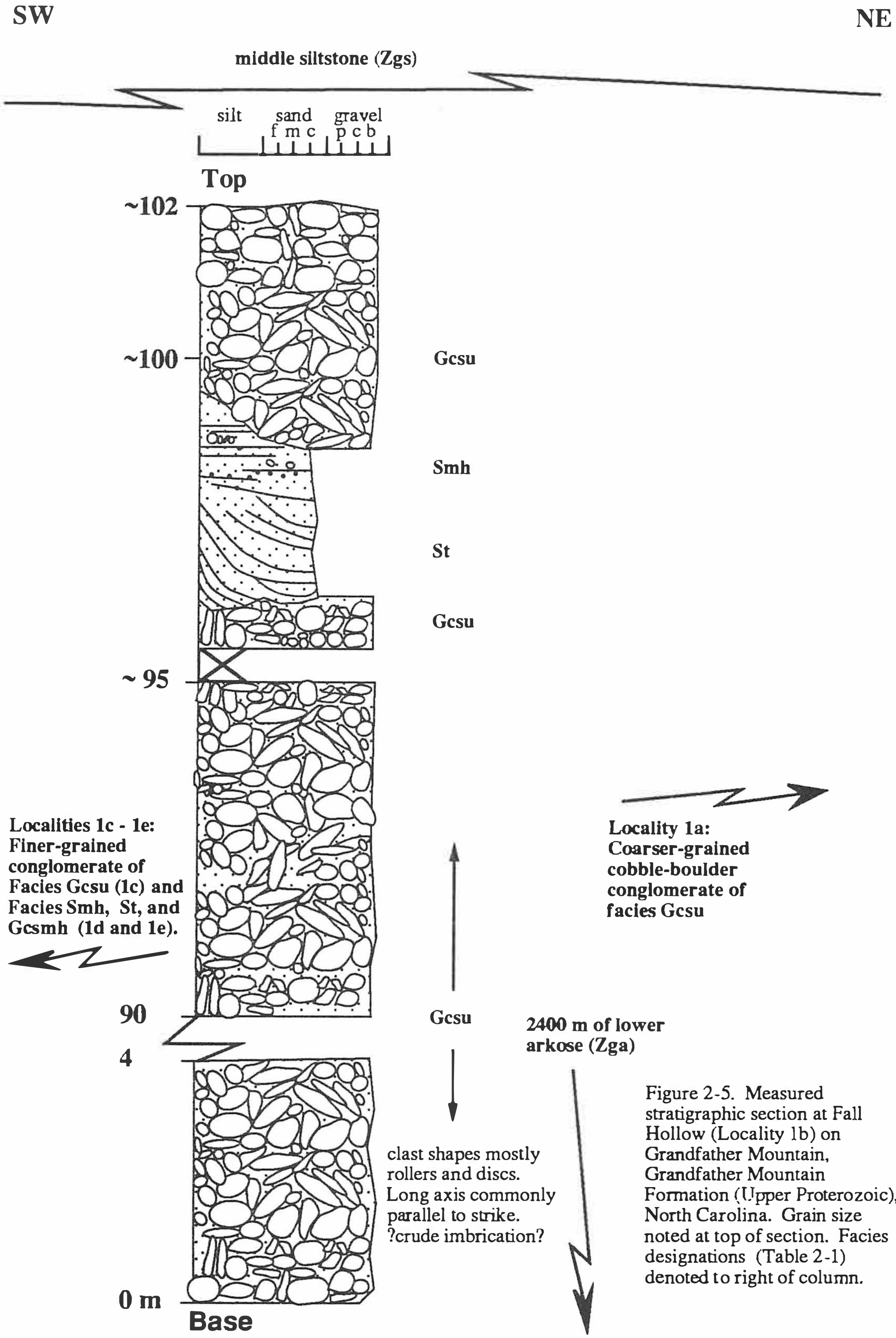


Figure 2-5. Measured stratigraphic section at Fall Hollow (Locality 1b) on Grandfather Mountain, Grandfather Mountain Formation (Upper Proterozoic), North Carolina. Grain size noted at top of section. Facies designations (Table 2-1) denoted to right of column.

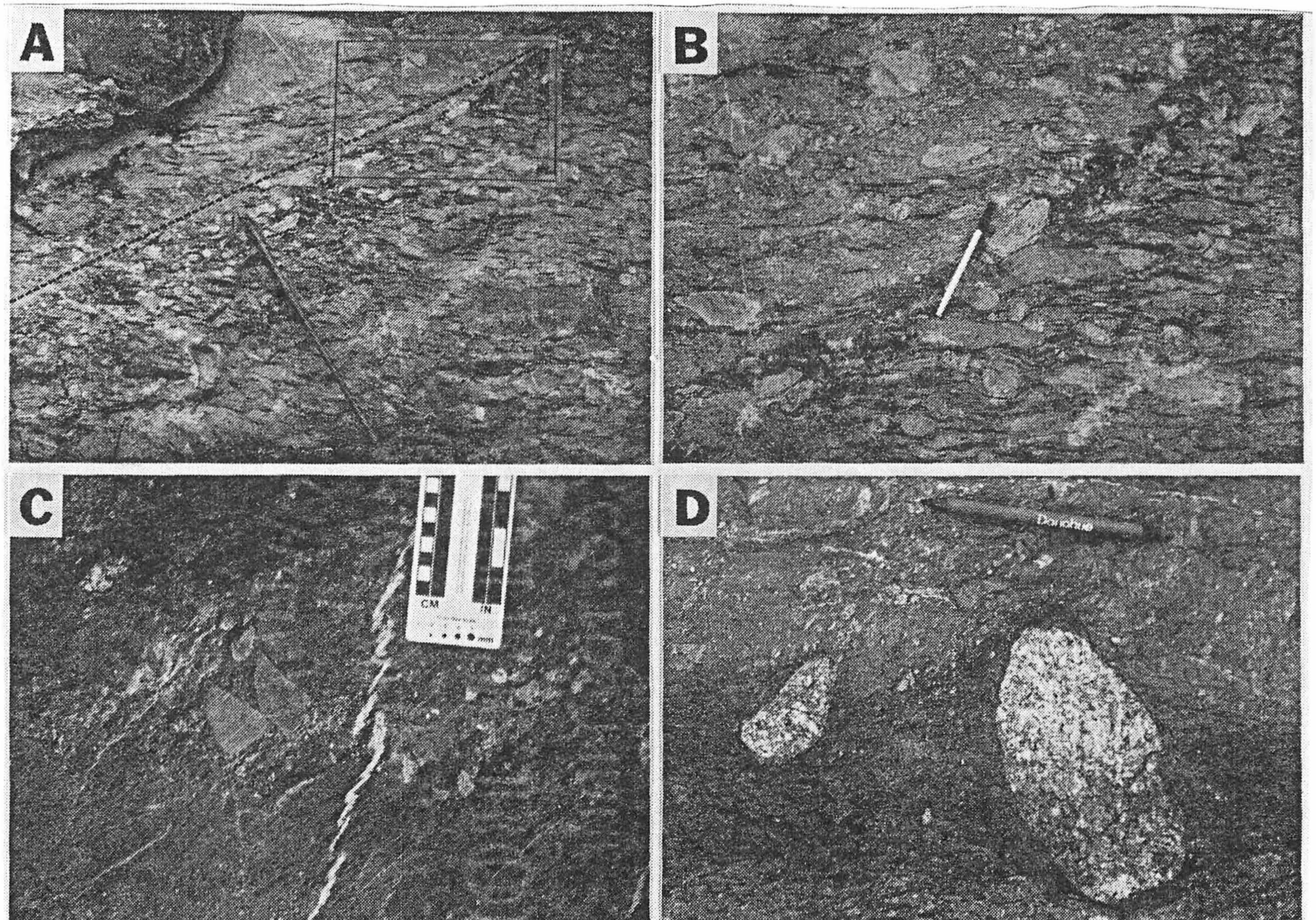


Figure 2-6. Outcrop photos of conglomerate and diamictite of the GMF. a) Three inversely-graded beds (Facies Gmsi) near base of Poplar Grove conglomerate (Locality 2c). Top of middle bed (dashed line) approaches clast support (see Fig. 2-6b). Jacob-staff (90 cm) oriented perpendicular to bedding. Felsite boulder at top of photo measures 100 x 55 cm. b) Area enclosed by box in Fig. 2-6a. Clasts flattened into cleavage plane. Pen equals 15 cm. c) Angular basalt clasts in diamictite (Facies D) of Broadstone Lodge diamictite (Locality 6a). d) Angular and rounded granitoid clasts (Facies D; Locality 6a). Pencil equals 14.5 cm.

up to boulders 1 m in diameter. The two largest measured clasts are boulders with dimensions of 100 cm x 45 cm (at Locality 2c; Fig. 2-6a) and 100 cm x 55 cm (at Locality 6a).

CONGLOMERATE UNITS AND SEQUENCES

Introduction

The five conglomerate units each have a unique clast composition verifying their apparent stratigraphic uniqueness (Fig. 2-4 and Table 2-2). Two sequences (lower and upper) are defined based on stratigraphy and clast composition, as well as vertical clast size trends. Not only are vertical clast composition trends present, but systematic, lateral changes in clast composition occur within the Snakeden Ridge conglomerate and the Broadstone Lodge diamictite.

Lateral clast size variation is also present to varying degrees in each of the conglomerate units. Three of the five distinct conglomerate units clearly fine to the southwest along strike (Fall Hollow, Snakeden Ridge and Banner Elk), whereas the other two (Poplar Grove and Broadstone Lodge) exhibit more ambiguous lateral clast size trends due to sedimentological and structural complications.

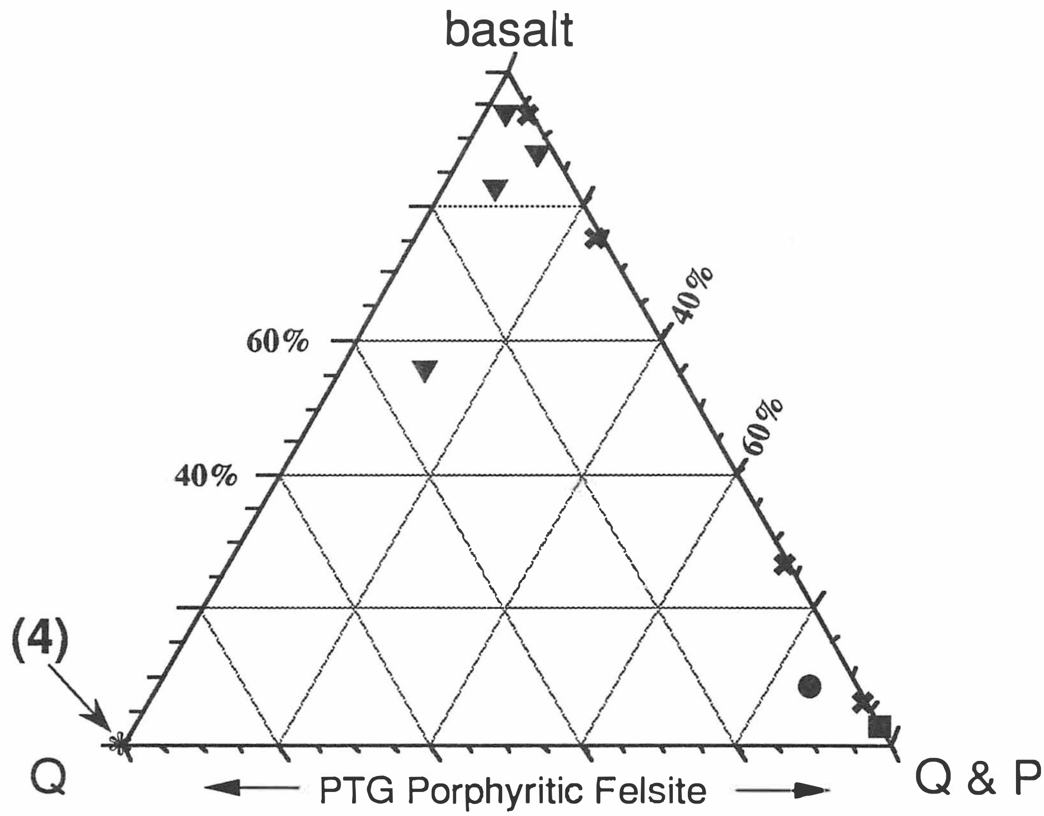
Two loosely grouped sequences are evident in Figure 2-4. The first is composed of the lowest three conglomerate units (Fall Hollow, Poplar Grove and Snakeden Ridge conglomerates), whereas, the second (above the Montezuma basalt) is composed of the upper two units (Banner Elk conglomerate and Broadstone Lodge diamictite). The lower sequence exhibits a gradual change from the felsite-dominated Fall Hollow conglomerate upward into conglomerate dominated by plutonic and sedimentary clasts (Poplar Grove and Snakeden Ridge conglomerate units).

The upper sequence contains two units of very dissimilar composition, both with respect to each other as well as to any other conglomerate unit in the lower sequence. The Banner Elk conglomerate (traceable along strike for 19 km) is remarkably constant in composition. It is dominated by felsite clasts, but contains minor amounts of very unique clasts (Table 2-2). The Broadstone Lodge diamictite is dominated by basalt clasts, but shows systematic, along-strike clast composition changes (discussed later). Each of the five conglomerate units are described in stratigraphic order on the basis of their individual clast composition and clast size characteristics.

Lower Sequence (Fall Hollow, Poplar Grove, and Snakeden Ridge conglomerate)

Fall Hollow conglomerate. The Fall Hollow conglomerate (stratigraphically lowest conglomerate; Localities 1a-1e) crops out along the crest and flanks of Grandfather Mountain Ridge and is named for a particularly massive exposure at 4200 ft. elevation in Fall Hollow (Locality 1b). The Fall Hollow conglomerate is clast-supported and is composed of crude beds of subrounded to angular pebbles, cobbles, and boulders. It is dominated by dark purple and maroon felsite clasts containing *both quartz and perthite* phenocrysts (Fig. 2-7), but also contains secondary amounts of granitoid, white pegmatitic (vein?) quartz, and tan fine- to medium-grained sandstone clasts (Fig. 2-8a and Table 2-2) .

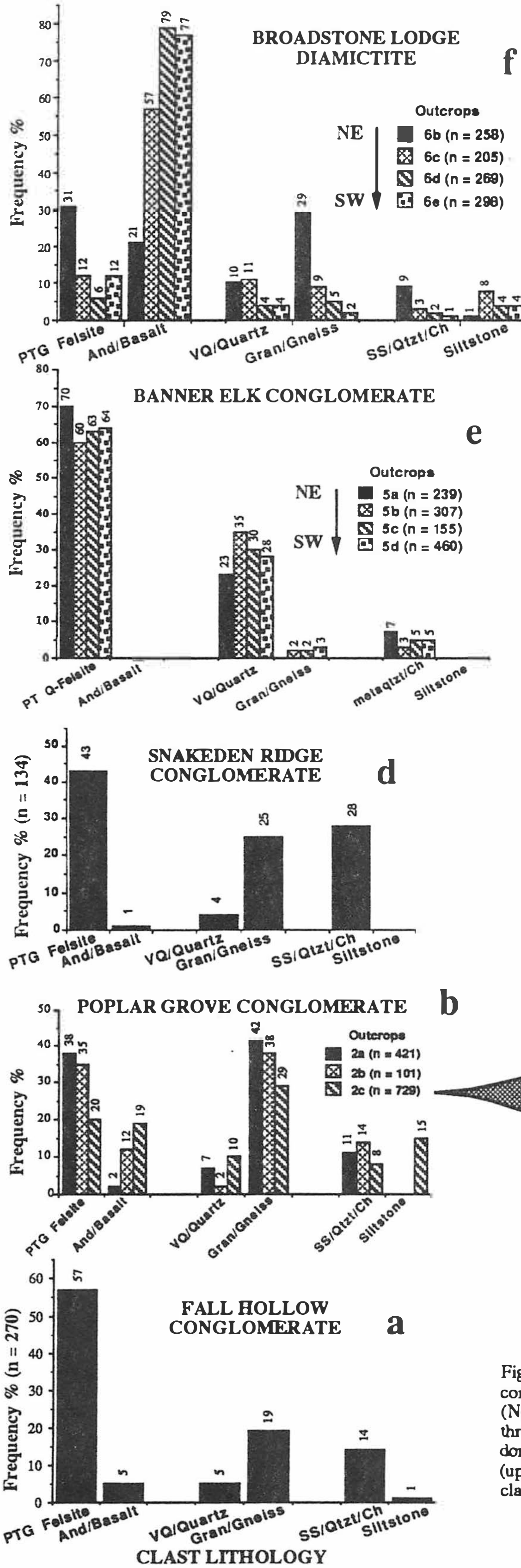
The Fall Hollow conglomerate fines from boulder conglomerate in the northeast (Locality 1a) to pebbly sandstone/pebble conglomerate in the southwest (Locality 1e) over a distance of approximately 12 km. Two localities (1b and 1c) where AMCS data were collected are indicative of this trend (Fig. 2-9a). In addition, Bryant and Reed (1970) noted clast-supported cobble-to-boulder conglomerate within the lower arkose to the northeast of Locality 1b along the flanks of Grandfather Mountain ridge. The largest clast they observed at Locality 1a is a purple felsic volcanic rock with a long axis of 60 cm. The largest clast measured at Locality 1b is a purple felsite measuring 40 x 22 x 22 cm. Assuming the conglomerate at Locality 1a is of similar nature as that at Locality 1b, the AMCS at Locality 1a is probably larger than that at 1b. Southwest of Locality 1c (Facies Gcsu dominated), the Fall Hollow unit fines to a pebbly sandstone, such as that at Locality 1d (Grandfather Mountain visitors center; Facies Smh and St). It is sparsely



▼ Broadstone Lodge diamictite (6a - 6e)
❋ Banner Elk conglomerate (5a - 5d)

■ Snakeden Ridge conglomerate (3a - 3e)
✖ Poplar Grove conglomerate (2a - 2c)
● Fall Hollow conglomerate (1a - 1e)

Figure 2-7. Volcanic clast ternary plot of major conglomerate bodies of the Grandfather Mountain Formation. Note dominance of Q & P felsite clasts in lower sequence in contrast to upper sequence which is dominated by Q felsite and basalt clasts. Legend arranged vertically in stratigraphic order. Frequency percent data of volcanic clasts recalculated to 100 percent. Q = quartz porphyritic felsite; Q & P = quartz and perthite porphyritic felsite. PTG = purple/tan/green. Clast count data same as for Figure 2-4. Point at Q felsite endpoint represents four data points (Localities 5a through 5d).



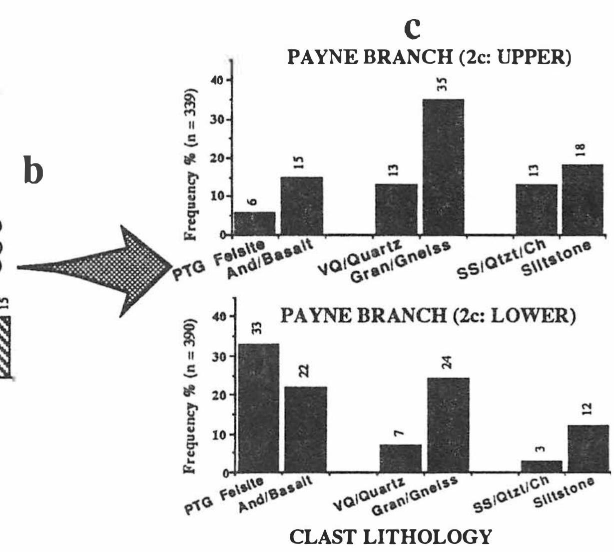


Figure 2-8. Histograms of clast composition of five distinct conglomerate bodies of the Grandfather Mountain Formation (North Carolina). Graphs arranged in stratigraphic order (a through f). c) Vertical clast changes at Locality 2c from volcanic dominated (lower) to crystalline and sedimentary dominated (upper). f) Broadstone Lodge diamictite containing systematic clast composition changes from northeast to southwest.

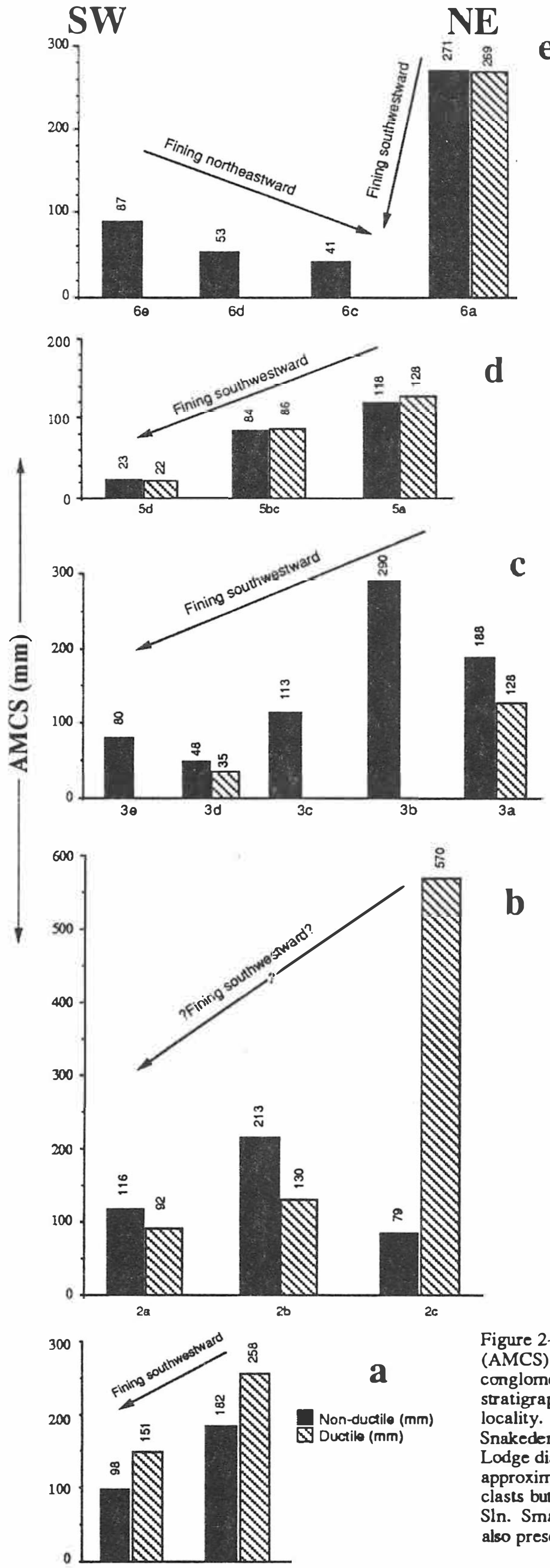


Figure 2-9. Lateral (southwest to northeast) average maximum clast size (AMCS) data of ductile and non-ductile clasts within five distinct conglomerate bodies of the Upper Proterozoic GMF. Graphs arranged in stratigraphic order (a through e). See Figure 2-1 for lateral exposure locality. a) Fall Hollow conglomerate. b) Poplar Grove conglomerate. c) Snakeden Ridge conglomerate. d) Banner Elk conglomerate. e) Broadstone Lodge diamictite: Fining toward Locality 6b (Figures 2-1 and 2-2; situated approximately halfway between Localities 6a and 6c) which contains no clasts but laminated siltstone and fine-grained sandstone of facies Flm and Sln. Small load structures and very small-scale ripple cross-lamination are also present.

intercalated with pebble, clast-supported conglomerate containing some cobbles (Facies Gcsmh), such as that exposed at Linville Gorge overlook (Locality 1e). The Fall Hollow conglomerate clearly fines from boulder-sized in the northeast to pebble-sized in the southwest.

Poplar Grove conglomerate. The Poplar Grove conglomerate is exposed on both limbs (northwest and southeast) of Boyer's (1978) Grandfather Mountain anticline (GMA; Figs. 2-1 and 2-3), and is named for a locality (2b) near the crossroads of Poplar Grove (Jct. SR 1551/1552) where it is intercalated with basalt. Both granitoid and sedimentary clasts are more abundant than in the Fall Hollow conglomerate. The increased influx of crystalline basement and sedimentary clasts is particularly evident at Locality 2c, as shown in Figure 2-4 by the arrow connecting conglomerate compositions from the lower and upper parts of the 120 m section. The upward change in clast dominance from volcanic to sedimentary and plutonic/metamorphic at Locality 2c is also evident in Figure 2-8b.

Evidence supporting the presence of the GMA within the lower sequence is contained within the Poplar Grove conglomerate. Figure 2-8c shows clast compositions from the Poplar Grove conglomerate. Despite ranges up to 18 frequency percent within any one clast lithology, abundances are similar on each limb. Specific clast lithologies are also similar. Both limbs contain purple, black and green, porphyritic *quartz and perthite* felsite; tannish pink, equigranular granitoid; biotite gneiss; tan/green, fine-grained sandstone; and metaquartzite. In addition to clast composition, the similar sedimentologic and stratigraphic character of the conglomerate units (Localities 2a,2b,2c) also suggests that the respective siltstone units (lower and middle siltstone of Bryant and Reed (1970)) are correlative: both limbs contain matrix-supported pebble to boulder conglomerate which approaches clast support locally (Fig. 2-6a and b), as well as diamictite beds. Localities 2b and 2c are both mapped as small arkose bodies totally encased in laminated to massive siltstone (Bryant and Reed, 1970) and contain, or are associated with, thin interbeds of siltstone and basalt. Locality 2a is gradational from thin-bedded, normally- graded sandstone

(Facies Sln) upward into matrix-supported pebble/cobble conglomerate (Facies Gms), into massive, granule-bearing siltstone (Facies D and Flm), and into laminated siltstone (Facies Flm). This succession is not unlike that at Locality 2c. From these observations and their respective positions within the siltstone units, Locality 2a overlies Locality 1 and underlies localities 2b and 2c, which are equivalent (Fig. 2-2).

AMCS trends within the Poplar Grove conglomerate are somewhat more ambiguous (Fig. 2-9b), because nonductile clast types do not show a fining trend, whereas ductile clast types do. At Locality 2c, ductile clasts (rhyolite and rhyolitic breccia; Table 1-2) are noticeably flattened into the cleavage plane, whereas non-ductile clasts are relatively unaffected. Many nonductile, as well as some ductile clasts even exhibit long axes and internal foliation or bedding oriented obliquely to both primary bedding and cleavage. Though ductile clasts are flattened, they are definitely larger depositionally than the non-ductile clasts because their AMCS short-axis is much longer than the AMCS long-axis of the non-ductile clast types (57 x 17.2 cm compared to 6.9 x 7.9 cm, respectively).

These relationships suggest the general validity of the southwestward fining trend for the Poplar Grove conglomerate. Localities 2b and 2c, however, are interpreted as correlative on respective limbs of the GMA, based on similar clast composition and general facies sequence relationships, and overlie Locality 2a. Because Locality 2a is stratigraphically below 2b and 2c, the grain size data cannot be compared directly. The position further southwest and finer grain size, however, may only in a very general way suggest fining to the southwest within the Poplar Grove unit. Data in Figure 2-9b are therefore presented only for the sake of completeness. Southwestward fining for this unit is presented as only one possibility. In fact, AMCS data for the Poplar Grove conglomerate are probably more significant as a vertical, rather than a lateral trend (discussed later).

Snakeden Ridge conglomerate. The Snakeden Ridge conglomerate, uppermost in the lower sequence, is a clast-supported to sandy, matrix-supported conglomerate traceable along strike for approximately 20 km (Localities 3a-3e). It is named for Snakeden Ridge (north of Foscoe, NC), along which it is best exposed (Localities 3a-3c). It contains higher quantities of granitoid, green fine-grained sandstone, and metaquartzite clasts than that of the underlying Poplar Grove conglomerate (Fig. 2-8d), yet *quartz-perthite* porphyritic felsite clasts are most abundant. Granitoid and sandstone clasts are sedimentologically much less durable than felsite (Table 2-3; Abbott and Peterson, 1978; Sadler and others, 1989) and may have been even more abundant in the source area than the concentrations in the Snakeden Ridge conglomerate would suggest. Indicative of this durability contrast, the southwesternmost two exposures of the Snakeden Ridge conglomerate (3d and 3e) are pebbly sandstone containing feldspar, white (vein?) quartz, quartz-perthite porphyritic felsite, and rare granitoid clasts. No sandstone or metaquartzite clasts were identified at these localities. Presumably, increased transport distance and abrasion had largely reduced granitoid and sandstone clasts to the constituent mineral grains.

An overall fining-to-the-southwest pattern is present in the Snakeden Ridge conglomerate (Fig. 2-9c). Cobble-to-boulder conglomerate at Locality 3a is matrix- to clast-supported in nature with a muddy sandstone matrix. Conglomerate along Pine and Snakeden Ridges (localities 3b and 3c) is present as thin horizons of angular cobbles and boulders intercalated with thickly laminated to thin bedded, fine- to coarse-grained sandstone horizons. Minor amounts of thin, muddy matrix-supported conglomerate beds are also present (Fig. 2-10). Localities 3d and 3e, located further southwest, are dominated by trough and planar tabular cross-stratified pebbly sandstone containing sparse, discontinous, granule/pebble horizons and stringers, some only one pebble thick. At Locality 3e, the largest clasts rest at the base of troughs with maximum erosional relief of approximately 0.5 m.

TABLE 2-3. RELATIVE CLAST DURABILITY. MODIFIED FROM ABBOTT AND PETERSON (1978).

increasing durability (↑)		
	Chert	
	Quartzite	ultra durable
	Rhyolite	
	Andesitic breccia	
	Obsidian	durable
	Metasandstone	
	Gneiss	
	Granodiorite	
	Gabbro	moderately durable
	Basalt	
	Marble	
	Schist	
	Limestone	weakly durable
	Shale/siltstone	

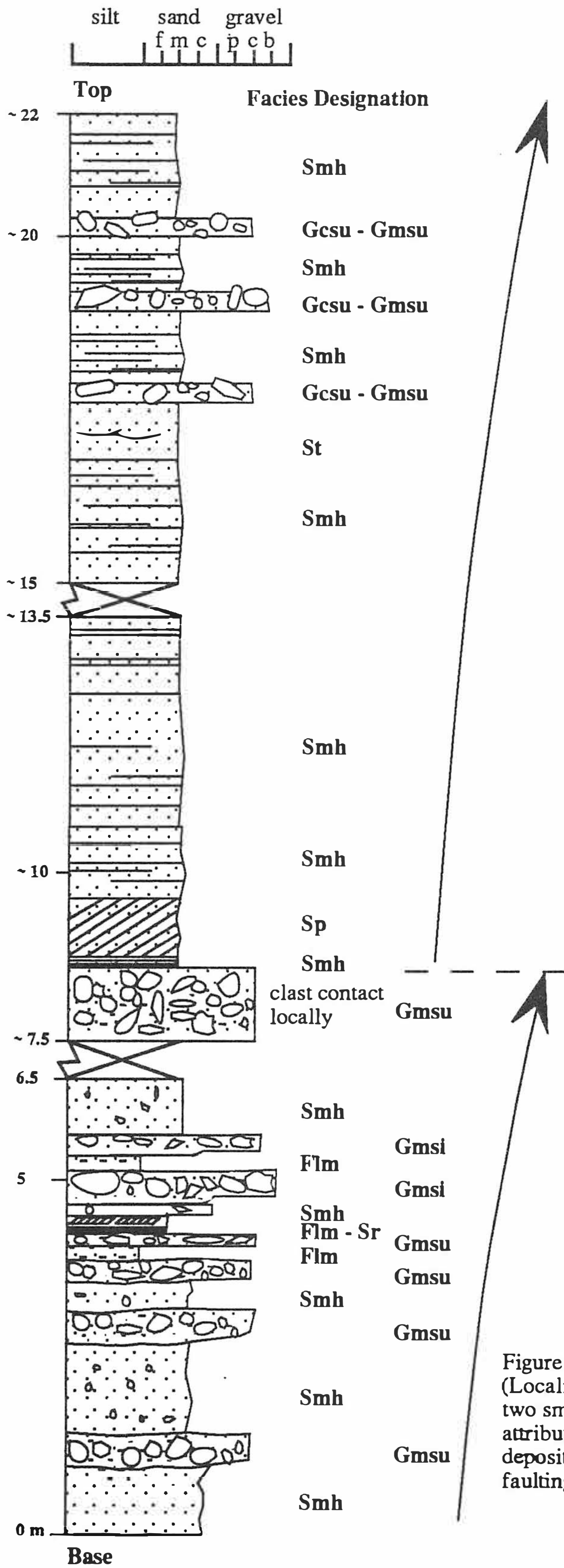


Figure 2-10. Townsend Gap - Snakeden Ridge (Locality 3bc) composite stratigraphic section denoting two small-scale coarsening-upward sequences: attributed to localized faulting events and switching of depositional locus on alluvial fan as a result of the faulting or fan trench filling and plugging.

Upper Sequence (Banner Elk conglomerate and Broadstone Lodge diamictite)

Banner Elk conglomerate. Perhaps the most significant feature of the lower sequence is the abundance of porphyritic felsite clasts containing *both quartz and perthite* phenocrysts (Fig. 2-7). In sharp contrast to the lower sequence is the clast-supported Banner Elk conglomerate of the upper sequence, which is dominated by purple and cream-colored felsite clasts containing *only quartz* phenocrysts (Fig. 2-7). It is best exposed along the crest of Horse Bottom Ridge northeast of Banner Elk, NC and is named for exposures (Localities 5b and 5c) on and near NC Highway 184, in the town of Banner Elk. Clasts typical of these distinct felsite types are shown in Figure 2-11. In addition to the dominant porphyritic quartz felsite clasts, the Banner Elk conglomerate also contains between 23 and 35 percent white (vein?) quartz and minor amounts of purple laminated and cross-stratified metaquartzite, granitoid clasts, and red, purple and white chert (Fig. 2-8e). None of the other four conglomerate units contain more than 13 percent white (vein?) quartz. The purple metaquartzite and red/purple chert clasts are unique to the Banner Elk conglomerate. In addition, basalt clasts are absent, even within the coarsest portions of the Banner Elk conglomerate (that is, Locality 5a) despite the fact that the Banner Elk conglomerate overlies the Montezuma basalt (Fig. 2-2).

Clast composition within the Banner Elk unit is remarkably consistent despite overall fining to the southwest (compare Figs. 2-8e and 2-9d). The unit fines from cobble clast-supported conglomerate (Locality 5a) to small pebble clast-supported conglomerate in the southwest near the town of Newland (Locality 5d). The resistant, ridge-forming conglomerate is particularly traceable along Horse Bottom Ridge (between localities 5a and 5bc) where undulatory conglomerate/sandstone contacts larger than outcrop scale are evident from inconsistent and reversing strike and dip data (Fig. 2-12a). The bedding data center about an axis of 41° at N33E (Fig. 2-12b). These undulations (0.5λ = approximately 70-350 m) are interpreted as either: a)

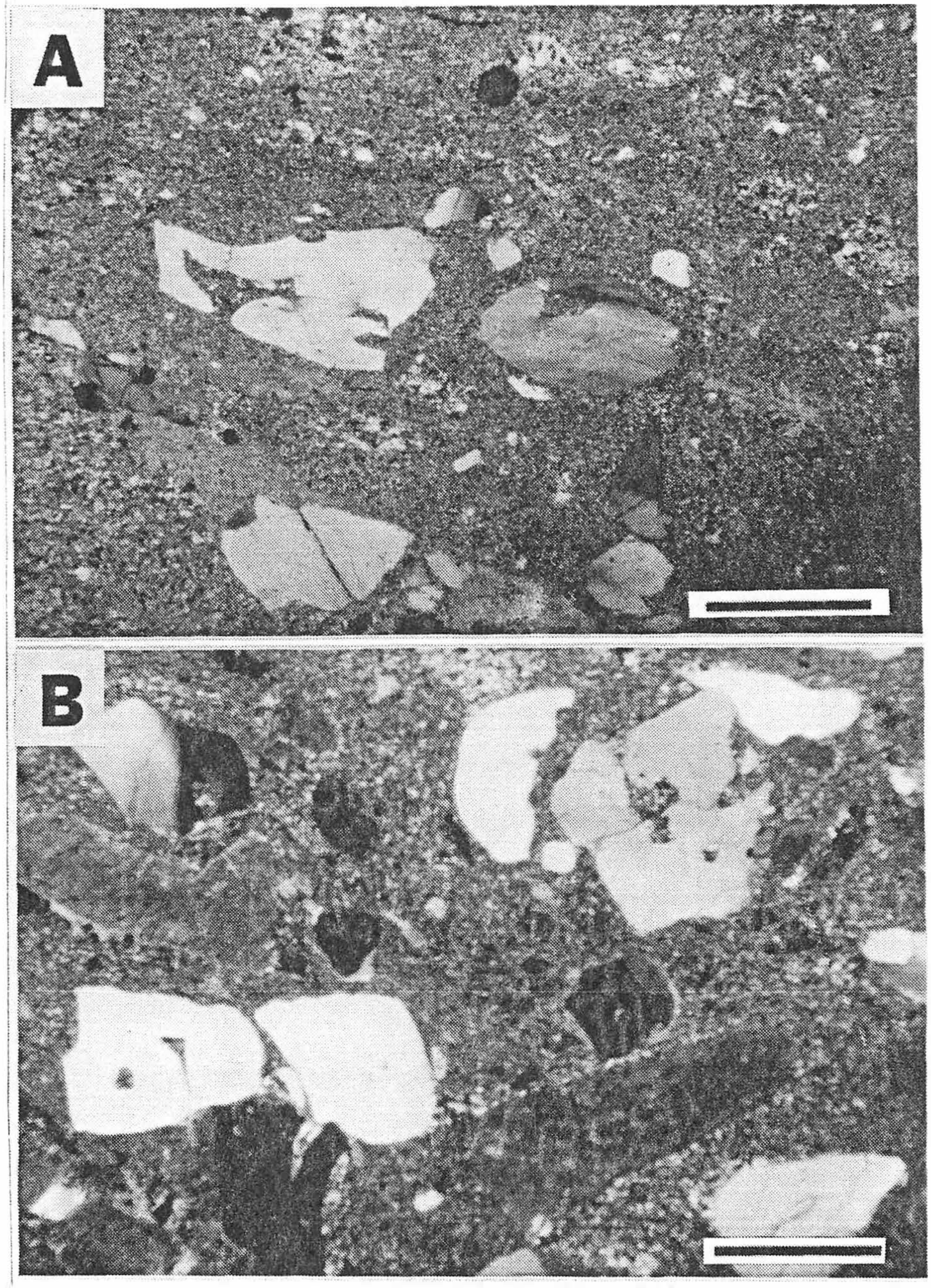
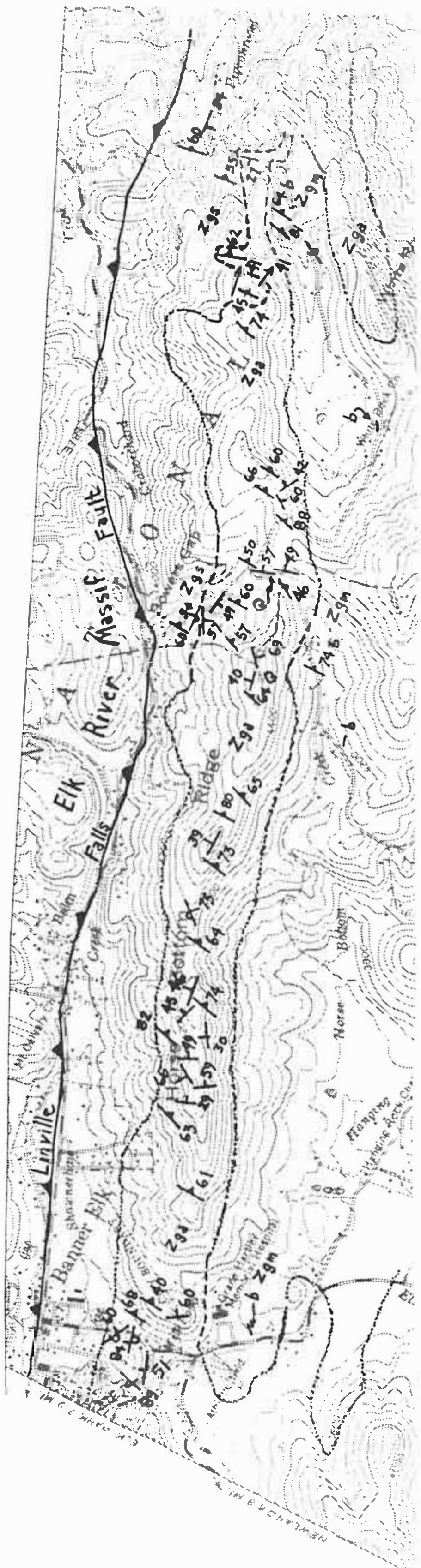
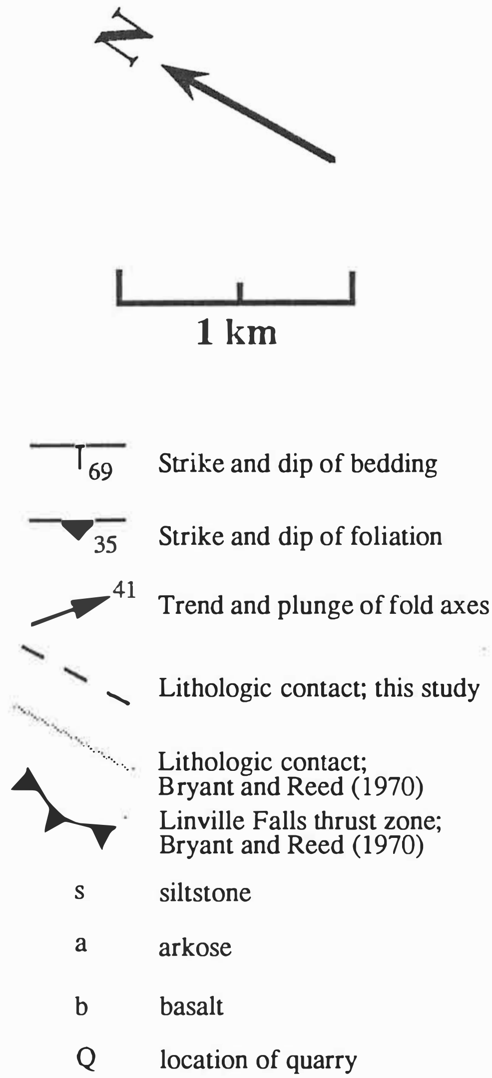


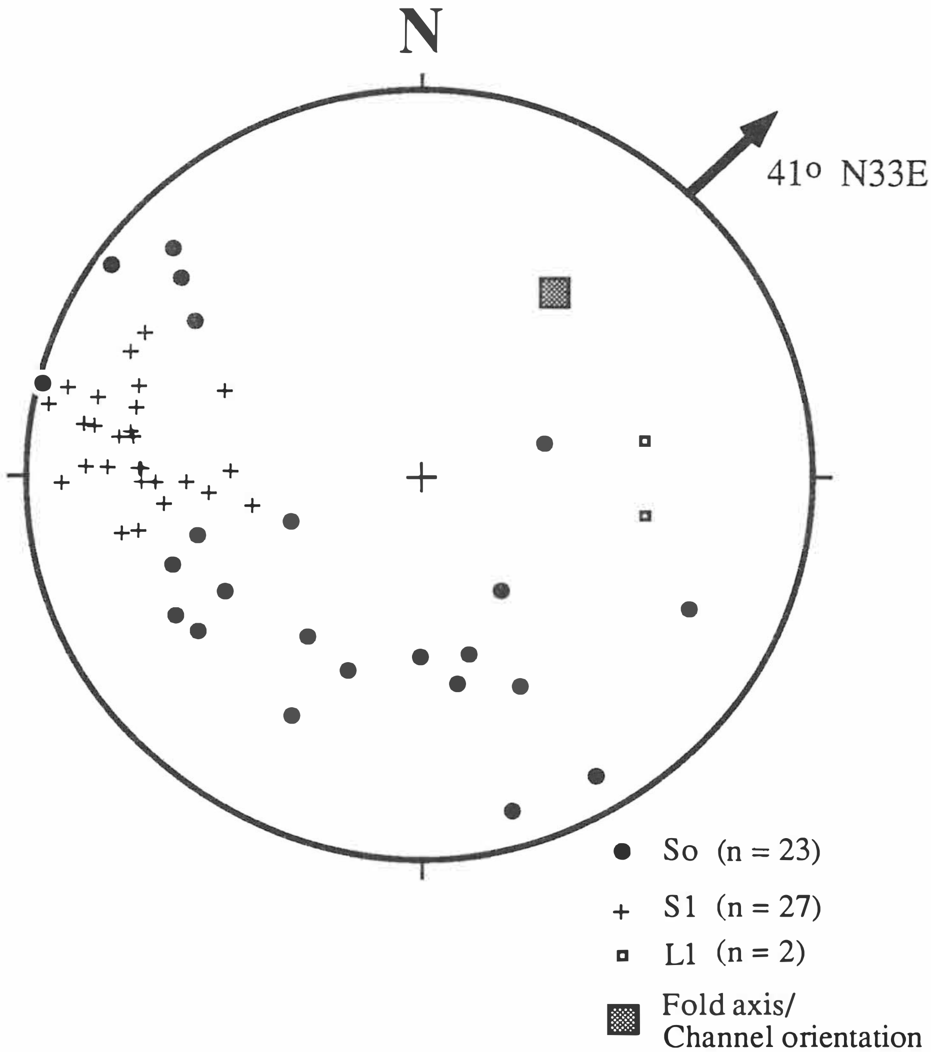
Figure 2-11. Photomicrographs of felsite clasts from distinctive lower and upper compositional sequences of the GMF. a) Felsite clast containing only quartz phenocrysts dominant in the upper sequence and indicative of the Banner Elk conglomerate. b) Porphyritic quartz and perthite felsite typical of conglomerate in the lower sequence. Bars equal 3.0 mm.





a. Geologic strip map. Rock unit designations on Fig. 2-1.

Figure 2-12. Geologic strip map and equal area diagram of Horse Bottom Ridge, northeast of Banner Elk, NC.



b. Equal-area diagram of poles to bedding, poles to cleavage, and fold axes.

Figure 2-12 continued.

folds that interfere with a box fold that trends N60W through the northwest corner of the GMW (Boyer, 1978) which are also not aligned with the N60E trend of the major rock units in the northern half of the window; b) mullions formed between lithologies of differing competence; c) random measurements taken on the flanks of fold-interference structures, such as domes and basins; or d) the bases of large-scale compound channels (for example, Williams and Rust, 1969) which represent fifth-order bounding surfaces commonly present in braided river systems (Miall, 1988). They may also be fourth-order bounding surfaces (Miall, 1988) produced as bars and smaller channels (facies-scale) migrated within the larger-scale channels. The N33E trend of the undulations and the difference from other known structural orientations suggests they are indeed relict channels. The northeast orientation permissively supports the southwestward fining trends (Fig. 2-9). The possible southwestward-plunging channels may have been subsequently tilted to the present northeasterly plunge during thrusting on the Linville Falls fault.

Broadstone Lodge diamictite. The youngest exposed unit (upper siltstone) of the GMF contains a diamictite unit (Broadstone Lodge diamictite) that is discontinuously exposed along strike for 27 km. The Broadstone Lodge diamictite is named for an exposure (Locality 6a) near the Broadstone Lodge, along NC Highway 1112, just south of the town of Valle Crucis. It is dominated by dark green, grey to black, very fine-grained basalt clasts (21-79 percent; Figs. 2-8f and 2-7). Alhough it is dominated by basalt clasts, systematic clast composition changes occur to the southwest along strike. Felsite and granitoid clast abundances decrease from northeast to southwest; concomitantly, basalt clast abundance increases rapidly to the southwest (Fig. 2-8f).

The Broadstone Lodge diamictite possesses somewhat ambiguous along-strike clast size trends. The unit shows an overall fining toward the southwest, although AMCS data at Localities 6b through 6d indicate an apparent fining to the northeast. Together with Locality 6a the unit fines toward the center of the 27 km outcrop belt (Fig. 2-9e). The Broadstone Lodge diamictite is composed of interbedded diamictite (Facies D), ungraded to normally graded matrix-supported conglomerate (Facies Gms), laminated mudstone (Facies Flm) and fine-grained sandstone (Facies Sln). Many clasts within Facies D and Gms are very angular (Fig. 2-6c and d). At and around Localities 6a, 6b and 6c the following sedimentary structures are particularly evident: millimeter-scale laminae, loads, flames, ball-and-pillow, mm- to cm-scale soft sediment normal faults, upcurled/detached laminae and slumps, as well as outsized clasts. No outsized clasts can be documented as truncating thinly laminated mudstone. A basalt boulder (1 m x 0.55 m) at Locality 6a appears to truncate cm- to dm-scale diamictite beds. Boyer (1978) documented a large crystalline basement boulder encased in weathered siltstone just north of Locality 6c (near Blevins Creek church). Upon detailed inspection of this locality, other pebbles and cobbles were discovered (Boyer's boulder has since been eroded away) encased in a very cryptic and diffusely-bedded matrix of sandy, granule-bearing mudstone. Distinct mm- to cm-scale laminae are not present at this outcrop and bed contacts are generally indiscernable.

Three interpretations are possible for the deposition of these outsized clasts: 1) the boulders are dropstones derived from the melting of debris-laden, floating glaciers or icebergs, 2) the boulders were able to be supported by a relatively thin, muddy, subaqueous debris flow or fluidal flow and after deposition, depending upon matrix strength, either protruded above the sediment-water interface to be covered by succeeding beds, or 3) may have foundered into the underlying soupy substrate. All three processes would produce apparent or actual deformation or truncation of surrounding beds. It is very difficult to substantiate the existence of a dropstone when it is encased in immature diamictite instead of laminite where laminae are truncated or deformed by the clast (see Harland and others, 1966; Thomas and Connell, 1985). Within the Broadstone Lodge diamictite no unambiguous dropstones have been discovered, although, outsized clasts are prevalent (compare to Schwab, 1981; Rankin and others, 1989).

The extreme angularity of some clasts at Locality 6a is *permissive evidence* for glacial derivation (basal zone to supraglacial transport entirely) allowing for no fluvial abrasion. Sub-glacial planing can also create extremely angular, striated clasts (for example, Anderson, 1989), but striations on clasts have never been documented in the GMF. Extremely angular clasts can also be produced as blocks from rockfalls into lake mud which are then transported by debris flows into the basin. The lack of unambiguous dropstones in the Broadstone Lodge diamictite argues against *direct* glacial influence. Unambiguous dropstones and other glacial features have been documented, however, in the uppermost member of the Mount Rogers Formation (Upper Proterozoic) of southwestern Virginia (Blondeau and Lowe, 1972; Schwab, 1976; Miller, 1986).

From the above discussion, the upper siltstone unit is interpreted as having been deposited in a relatively deep lake or marine basin by suspension settling processes, with fluidal flows and debris flows periodically moving downslope and onto the basin floor. The water body may have formed due to rifting and extrusion of the underlying Montezuma basalt which may have dammed rift-axial drainage creating a lake. Additional water may have been added to the lake from springs emanating from uplifted rift shoulders (for example, Blair, 1987; Blair and Bilodeau, 1988), from thermal lake bottom springs, one source of which is volcanic vents (for example, Shanks and Callender, 1992), or from glacial meltwater. Alternatively, marine incursion forming a large embayment or inland sea is possible.

Clast composition and lateral clast size trends of the five conglomerate units are summarized in Table 2-2. Note, in particular, the vertical changes in clast composition.

VERTICAL GRAIN SIZE TRENDS

In addition to lateral clast size trends within each compositionally distinct conglomerate unit, vertical grain size trends are also evident (Fig. 2-13). AMCS data of the five conglomerate units as well as the Norwood Hollow sandstone (Locality 4; Figs. 2-1 and 2-2) are integrated with GMF stratigraphy of Bryant and Reed (1970), as modified by Boyer (1978) and substantiated here. The ranges of the bars are a general reflection of the southwestward fining in each conglomerate unit. Coarsening-upward sequences present are of megasequence (10's to 100's m

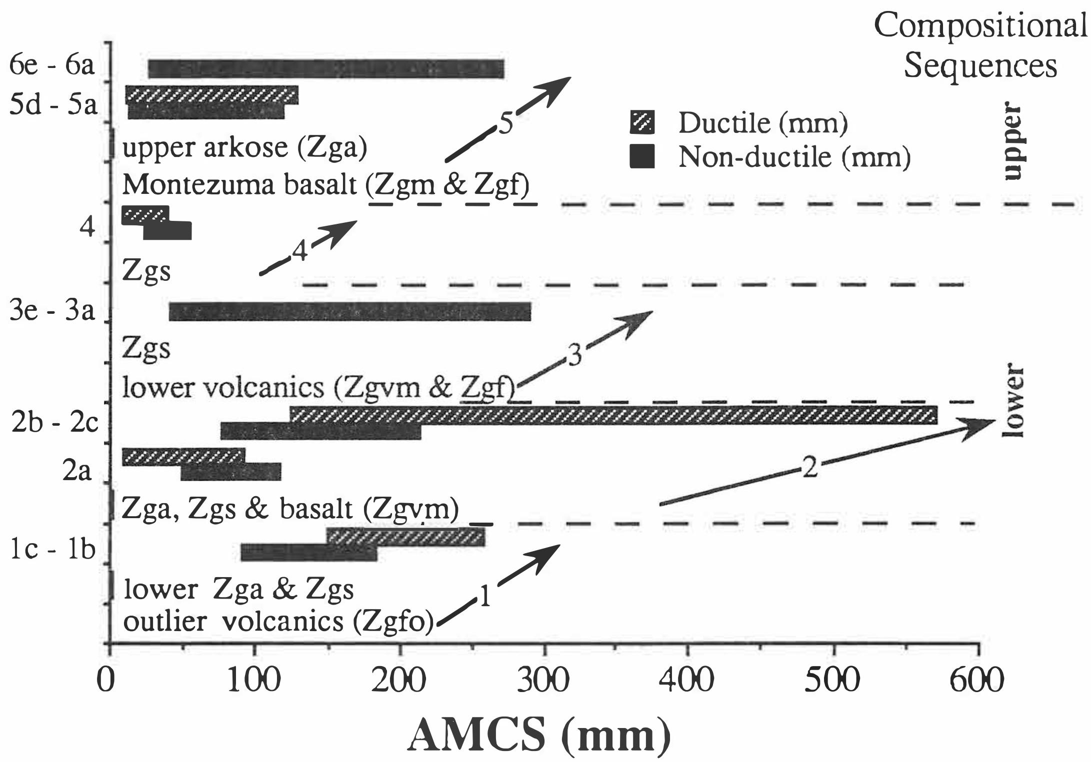


Figure 2-13. Coarsening-upward basin-fill sequences. Approximate thicknesses: 1) 2500 m, 2) 500 m, 3) 1000 m, 4) 200 m, 5) 2250 m. Bars represent a range from the lowest to the highest AMCS value from all outcrops within each particular conglomerate unit. Bars with data from only one locality (that is, 2a and 4) are plotted as the AMCS of the short and long axes. Dashed lines indicate major rifting events or clusters of events. Volcanic units (basalt and rhyolite) form the base of four of the five sequences. Compositional sequences are denoted in Figures 2-4 and 2-7.

thick) to basin-fill sequence scale (100's to 1000's m thick) after the usage of Heward (1978) and are interpreted as the basic response to an episode of basin-floor lowering (Steel, 1976; Blair and Bilodeau, 1988). Climatic changes are deemed not to be the dominant cause of these basin-fill sequences, because cycles controlled by climatic changes are commonly less than 100 m thick (for example, Koltermann and Gorelick, 1992). Smaller-scale coarsening- and/or fining-upward sequences (m to 10's m thick) are present in some sections (for example, Locality 3bc; Fig. 2-10). They are attributed to autocyclic processes (for example, lobe aggradation and avulsion) possibly due to localized faulting (Steel and others, 1977; Wilson, 1980; Bøe and Sturt, 1991) or channel plugging. Complete delineation of these smaller-scale sequences, internal to megasequences and basin-fill sequences, is generally not possible in the GMF because intervening thick sandstone, and especially siltstone, units are poorly exposed to unexposed.

Five coarsening-upward sequences ranging between 200 m and 2500 m thick (averaging approximately 1300 m thick) are present in the GMF. Each sequence is generally composed of the following succession: volcanic units (rhyolite/basalt) and/or siltstone followed by sandstone, capped by pebbly sandstone or conglomerate/diamictite of the five conglomerate units (Fig. 2-13). In each case, the deposits of coarse-grained proximal environments (fan/fan-delta/braidplain) of Facies Gms, Gcs, and D, prograde over those of finer-grained distal basin-axis environments (braidplain, floodplain, lacustrine/marine) of Facies Gcsmh, S, Flm, and Ll. Each coarsening-upward sequence represents progradation in response to a major faulting event or series of closely spaced faulting events of increasing intensity, a relationship similar to that documented by Steel and Wilson (1975), Steel (1976), Steel and others (1977), and Wilson (1980) for some Devonian rift basins in Scotland as well as by Hamblin and Rust (1989) for Devono-Carboniferous half grabens of Nova Scotia. Time of faulting events is interpreted to be at the onset of braidplain, lacustrine/marine and floodplain sedimentation at or near the basin-margin fault. Coarse-grained sediment is trapped or ponded close to the margin until faulting subsides and the trap or pond is filled. Coarse clastic wedges then prograde far out into the basin over fine-grained deposits during relatively tectonically quiescent phases (Blair, 1987; Blair and Bilodeau, 1988; Heller and others, 1988; DiGuiseppi and Bartley, 1991). In fact, during faulting, coarse-grained sediment may not even be deposited immediately in the trap or pond due to several reasons discussed by Blair and Bilodeau (1988) and Hamblin and Rust (1989), two of which follow. 1) Longitudinal fluvial and lacustrine systems react more quickly to subsidence because their water volumes are derived from drainage basins which are orders of magnitude greater in size than upland drainage basins feeding individual fans. They are therefore more quickly deposited directly adjacent to the basin margin fault after a faulting event than is coarse clastic debris despite 1000's m of relief (for example, Death Valley; Blair, 1987). 2) Average tectonic uplift rates in modern orogenic belts are 8 to 117 times higher (depending on annual precipitation) than average denudation rates (Schumm, 1963). Only after a lag time (possibly after basin-margin faulting ceases or significantly slows) can the denudation rate exceed basin subsidence to allow widespread clastic wedge progradation (Blair and Bilodeau, 1988). In contrast, fining-upward megasequences are also attributed to waning tectonism and progressive lowering of relief (for example, Steel and Wilson, 1975; Pivnik, 1990). Fining-upward megasequences have not been observed in the GMF. Coarse clastic wedge progradation is undoubtedly attributable to tectonism, and relief formation, but the actual faulting events occurred at the onset of fine-grained deposition as pre-existing alluvial fans were downfaulted along the basin margin and buried under longitudinal fluvial and lacustrine sediment which migrate quickly to cover the fan.

Volcanic rocks are present at or near the base of four of the five GMF coarsening-upward sequences (Figs. 2-2 and 2-13). This basal position also suggests that these are times of faulting and coeval extrusion of magma through fault systems and other fractures (plumbing systems) created during a rifting event. The GMF was therefore deposited largely in response to five major rifting events or clusters of events. Large amounts of relief were created followed by eventual unroofing of the sourceland rift shoulders after rifting waned.

CLAST - SOURCE MATCHES

Delineating sources of detritus in Precambrian successions, especially within the internides of mountain belts (for example, the Blue Ridge), is exceedingly difficult because commonly they are: a) no longer present, b) metamorphosed beyond recognition, or c) unexposed. In the case of the GMF, scenarios "a" and "c" are the most probable, simply because of the age of the GMF and its occurrence in a window (GMW). Regarding "c", the most likely source rocks may be present under the Blue Ridge thrust sheet. More elaborate modelling and reconstruction of source terrane geometry and characteristics (for example, Graham and others, 1986; Pivnik, 1990) cannot generally be applied to these Late Proterozoic successions, because the models require a fully exposed, preserved, and well-known sourceland stratigraphy. The most probable source rock possibilities and their characteristics are shown in Table 2-4. Grenvillian and Crossnore-type crystalline rocks within the overlying Blue Ridge thrust sheet (Elk River massif) are not deemed as probable source rocks because during Late Proterozoic rifting these massifs lay far to the southeast of the Grandfather Mountain basin. In addition, typical lithologies of the Grenvillian crystalline rocks of the Elk River massif (that is, garnet, pyroxene, and sillimanite-bearing; Bartholomew and Lewis, 1984; Gulley, 1985) are not present in granitoid/gneissic clasts or as sand-sized grains (except garnet) of the GMF.

Three relatively definitive clast-source matches have been made based on petrologic and petrographic criteria.

1) porphyroblastic granite-syenite cobble (Poplar Grove conglomerate: Locality 2b) -

Blowing Rock Gneiss

2) andesitic basalt boulder (Broadstone Lodge diamictite: Locality 6a) -

Montezuma basalt: Locality 6a

3) red, fine-grained feldspathic wacke pebble (Broadstone Lodge diamictite: Locality 6c) -

TABLE 2-4. CHARACTERISTICS OF POSSIBLE IGNEOUS SOURCE ROCKS. UNITS ARRANGED IN GENERAL STRATIGRAPHIC ORDER. INTERCALATED SEDIMENTARY UNITS NOT INCLUDED. DATA COMPILED FROM NETON (THIS PAPER), BRYANT AND REED (1970), AND RANKIN (1967). PERTHITE TEXTURE DESCRIPTIVE TERMS FROM EYAL AND SHIMSHILASHVILI (1988).

Unit				Diagnostic Characteristics
Grandfather Mountain Formation Volcanics	Montezuma Basalt Member			Generally nonporphyritic, lower albite content than other basalts, higher quartz-orthoclase content, contains rare amphibole, amygdaloidal
Grandfather Mountain Formation Volcanics	upper rhyolite			Plagioclase phenocrysts common to abundant
Grandfather Mountain Formation Volcanics	Poplar Grove basalt			Same as lower basalt
Grandfather Mountain Formation Volcanics	lower basalt			Finer-grained plagioclase (0.1-0.3 mm in groundmass; tr. plagioclase phenocrysts 0.5-0.9 mm) not bimodally sized except where albite fills amygdules (0.5-1.75 mm)
Grandfather Mountain Formation Volcanics	lower rhyolite			No plagioclase phenocrysts
Grandfather Mountain Formation Volcanics	outlier basalt			Coarser-grained, bimodal plagioclase: groundmass (0.02-0.5 mm), phenocrysts (2 mm-2 cm)
Grandfather Mountain Formation Volcanics	outlier rhyolite			Little to no plagioclase phenocrysts
Grandfather Mountain Formation Volcanics	GMF rhyolite (outlier, lower, and upper)			Additional description All GMF rhyolite contains perthite phenocrysts: fine to medium vein, patch and string varieties dominant. Generally contain 1:1 or 1: < 1 perthite to quartz phenocryst ratios.
Mount Rogers Formation Rhyolite	Middle Member	A	Wilburn Rhyolite	Ash flow tuff: quartz & perthite phenocrysts (>30%), pumice lumps, glass shards
Mount Rogers Formation Rhyolite	Middle Member	B	White Top Rhyolite	Ash and rhyolite flows: quartz & perthite phenocrysts (<5%), flow layering
Mount Rogers Formation Rhyolite	Middle Member	C	Quartz Latite	Plagioclase and perthite phenocrysts
Mount Rogers Formation Rhyolite				Additional description: MRF Perthite phenocrysts of medium to coarse vein, patch and string varieties
GMW basement (Globe Massif)	Brown Mountain Granite			Perthite:Quartz = ~ 1:1, perthite of medium to coarse patch/vein patch varieties with quartz inclusions, very low mafic content, very little plagioclase, very little microcline, contains fluorite and apatite
GMW basement (Globe Massif)	Blowing Rock Gneiss			White microcline porphyroclasts in black biotitic matrix, little to no perthite (coarse patch/vein patch varieties), low plagioclase content, high microcline content
GMW basement (Globe Massif)	Wilson Creek Gneiss			Low perthite (fine to coarse strip/string varieties), high plagioclase content, high microcline content with quartz, orthoclase, and plagioclase inclusions

red sandstone intercalated with MRF rhyolite

These are discussed below along with other more speculative derivations for clast types with presently exposed and unexposed possible source rocks.

Lower Sequence Clast Petrography

Greenish-tan to deep purple, porphyritic, quartz and perthite felsite clasts of the lower sequence (Fig. 2-11), most abundant in the Fall Hollow conglomerate, exhibit highly variable grain size, texture, and proportion of phenocrysts. Subhedral perthite phenocrysts (0.1 - 16 mm) are dominantly of medium to coarse patch variety (usage of Eyal and Shimshilashvili, 1988). Glomeroporphyritic perthite is also common. Anhedral to euhedral quartz phenocrysts (0.1 - 6 mm) are commonly deeply embayed and some contain perlitic cracks. Perthite to quartz ratio ranges between 1:1 and 3 : 1. Untwinned plagioclase, fine-grained zircon, and biotite phenocrysts are present in trace amounts as well as pumice lumps and granitoid xenocrysts. Groundmass is composed of microcrystalline quartz of varying grain size and texture, sericite, and opaques (Fig. 2-11). Groundmass sericite commonly defines a lamination. A cryptic shard texture is uncommon. Opaque minerals control the darkness of purple hue.

Particular felsite clasts of the lower sequence most strongly resemble those of the Wilburn Rhyolite and Quartz Latite units of the MRF (Table 2-4), as well as some of the rhyolite flows present in the outlier rhyolite of the GMF (Zgfo). Commonly, a clast will match one of these source units in a certain respect (for example, proportion and/or size of phenocrysts), but possesses a much different groundmass color and/or texture than the possible source rock, or vice versa. This clast - source ambiguity suggests that felsite clasts of the lower sequence could have been derived from flows within the MRF or GMF, which are now completely eroded away. Minor amounts of basalt clasts (especially in the Poplar Grove conglomerate) are probably derived from basaltic flows interbedded with the above-named felsite units. Confident, definitive clast-source matching must await further sampling, petrography, and trace element geochemistry.

Tan to pink granitoid/gneiss clasts of the lower sequence, most abundant in the Poplar Grove and Snakeden Ridge conglomerates, contain variable amounts of quartz, orthoclase, perthite, plagioclase, and trace micas. A few clasts were identified as containing characteristics unique to one of the three units in the Globe massif (Table 2-4). A granite-syenite cobble from the Poplar Grove conglomerate (Locality 2b) contains large microcline/orthoclase (up to 8 mm) and quartz (up to 5 mm) phenocrysts within a black chlorite/biotite-quartz-plagioclase matrix. The distinctive mineralogy and texture of this clast suggest derivation from the Blowing Rock Gneiss (Fig. 2-14). Several granitoid clasts and granules in thin-section contain a perthitic texture unique to the Wilson Creek Gneiss, namely, a fine to coarse strip/string variety. In addition, many of these clasts contain very similar high abundances of plagioclase and microcline indicative of the Wilson Creek Gneiss. Clasts containing subequal amounts of perthite and quartz, perthite textures similar to the Brown Mountain Granite, and containing apatite grains were possibly derived from the Brown Mountain Granite (Table 2-4). No granitoid clasts, however, contain fluorite, rendering the Brown Mountain Granite source unlikely. White pegmatitic quartz veins, which do not extend beyond clast boundaries, are common within large granitoid and gneiss cobbles and boulders, especially within the Poplar Grove and Snakeden Ridge conglomerates. These veins clearly were present before the clast was eroded. The fact that the clast did not split along these planes during transport suggests a proximal alluvial environment.

Some crystalline clasts within the lower sequence can be relatively unambiguously matched to a particular unit within the Globe massif on the basis of similar mineralogical abundances and perthite textures. Many other clasts, however, contain similar perthite textures to a certain basement unit, but quite different mineralogical abundances, or vice versa. The three major units of the Globe massif (Table 2-4), therefore, probably only composed a portion of the crystalline units exposed to erosion during Late Proterozoic time. The far-traveled, overlying Elk

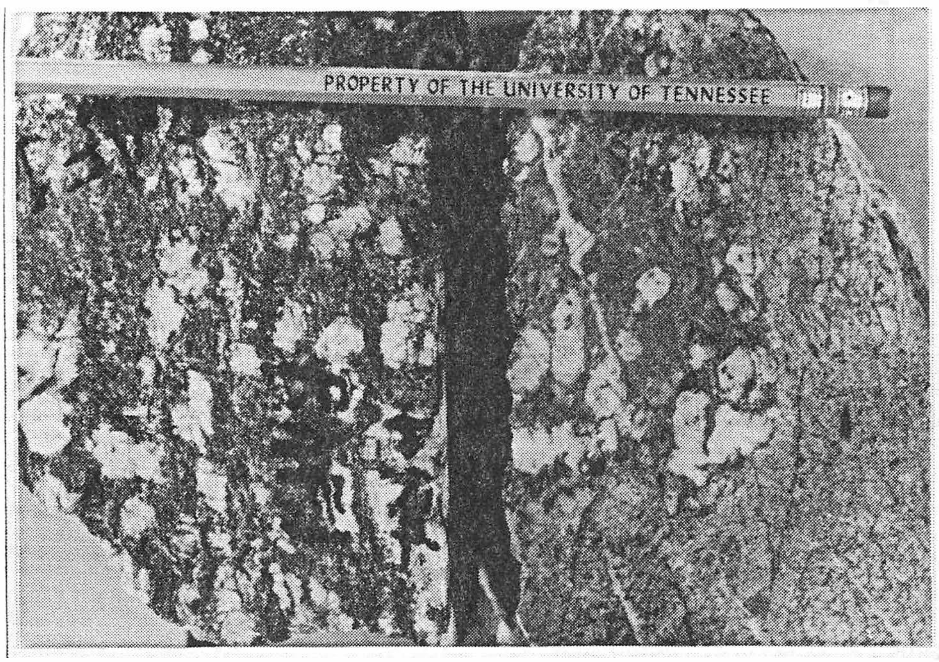


Figure 2-14. Photograph of Blowing Rock Gneiss (Ybr) sample on left compared to granite-syenite cobble in Poplar Grove conglomerate (Locality 2b) on right, possibly derived from Blowing Rock Gneiss. Pencil for scale equals 19 cm.

River massif of the Blue Ridge thrust sheet was not a source of GMF detritus because of the lack of any high grade metamorphic minerals in conglomerate clasts or sandstone (except garnet).

Tannish-pink to green sandstone and metaquartzite clasts of the lower sequence, most abundant in the Poplar Grove and Snakeden Ridge conglomerates, contain variable amounts of quartz (both mono- and polycrystalline), orthoclase, plagioclase, perthite, opaques, detrital muscovite, and apatite. Embayed quartz and abraded quartz overgrowths are present, but uncommon. A significant amount of mud matrix is present in some sandstone clasts. These clasts generally contain much less feldspar and little to no lithic fragments, whereas, most presently exposed sandstone units of the GMF are much higher in these constituents (Schwab, 1977). The clasts are moderately to well sorted and are very fine- to medium-grained, in contrast to GMF sandstones, which are poorly sorted and medium- to coarse-grained. This difference in grain size, however, no doubt contributes to the compositional differences between the clasts and presently exposed GMF sandstone. The presence of embayed quartz and detrital apatite suggests a volcanic derivation for at least some of the sand within the clasts. Uncommon abraded quartz overgrowths in the sandstone clasts suggest third-generation recycling. The relative maturity of the sandstone clasts, the presence of abraded overgrowths and the fact that some of these clasts are metaquartzite argues against them being recycled GMF rift sandstone. Purple, green and yellow laminated mudstone clasts, however, occur with these sandstone clasts (especially at Locality 2c). The mudstone clasts are very similar to siltstone units within the GMF and MRF. The occurrence with laminated mudstone clasts may instead suggest that the sandstone and metaquartzite clasts are indeed recycled rift sandstone, possibly derived from a distal floodplain/lacustrine environment (to achieve relative maturity). Laminite, however, occurs in many depositional environments (overbank, lacustrine, marine) of diverse tectonic settings and its apparent similarity to presently exposed rift laminite does not preclude other origins.

These sedimentary clasts may in fact have more than one source, ranging from rift-deposited sediment to remnant, uplifted Grenvillian clastic wedge of many types. These varied sources were then eroded into the Grandfather Mountain basin during rifting.

Upper Sequence Clast Petrography

Unlike the conglomerate of the lower sequence, the Banner Elk conglomerate contains a very enigmatic clast suite that cannot even be conditionally matched to any presently exposed possible source rocks (Table 2-4). Porphyritic quartz felsite clasts contain *no feldspar phenocrysts*, which are so common in presently exposed GMF and MRF rhyolite as well as in lower sequence felsite clasts (Fig. 2-11). Cream-colored porphyritic, quartz felsite/tuff clasts bear no resemblance to any GMF or MRF rhyolite bodies, which are purplish tan to deep purple. Some very dark purple clasts are composed dominantly of microcrystalline quartz with minor amounts of sericite (some laminae) and 1 to 2 percent opaque minerals. Protoliths of these clasts may have been obsidian, now devitrified and recrystallized. Alternatively, they may have been lacustrine chert or iron-rich laminite deposited coevally with rhyolitic volcanic rocks. Unique red jasper and white chert clasts may also have a volcanic-lacustrine origin. Abundant white and pink coarse-grained quartz clasts are ultradurable (Table 2-3) and may have been derived from a number of sources – thick quartz segregations, or quartz veins in crystalline basement, or as clasts in preexisting conglomerate (rift or Grenville clastic-wedge related). The last exotic clast type within the Banner Elk conglomerate is purple-laminated to cross-stratified metaquartzite. The fact that it is a quartzite argues against a rift-sandstone derivation as there probably was not sufficient time and burial depth between deposition and re-erosion to produce a quartzite. None of the GMF or MRF sandstone units are metaquartzite presently, and most probably were not metaquartzite in the Late Proterozoic when they may have been uplifted on rift shoulders. The metaquartzite clasts may represent pieces of a hypothesized Grenville clastic wedge (sandstone). Metaquartzite and rhyolite are ultradurable clast types (Abbott and Peterson, 1978; Sadler and others, 1989). Much of the Banner Elk conglomerate may therefore be eroded from previously deposited rift basin conglomerate units (but apparently not from any similar to the lower sequence), although no clasts of conglomerate were observed. Alternatively, the felsite clasts may have been derived from a felsite unit once present in the GMF or MRF, but now completely eroded away. If this is the case, an intraformational unconformity may be present within these units. None has been mapped or described within the GMF, but one possibility is discussed later. All three members of the MRF, however, are known to rest nonconformably upon Grenville basement (Rankin, 1967, 1970). This suggests repeated uplift and erosion of parts of the MRF and adjacent areas, which may have supplied the exotic detritus to the Banner Elk conglomerate. In the extreme northern end of the GMF at Locality 6a, Broadstone Lodge diamictite of the upper siltstone unit rests ?unconformably? on Montezuma basalt. The contact is an irregular surface overlain by muddy sandstone containing basalt pebbles. The intervening upper arkose, containing the Banner Elk conglomerate, is not present here suggesting a hiatus (Figs. 2-1 and 2-2). The felsite in question may have been derived from this locality and localities further northeast in the Mount Rogers basin. Furthermore, southwestward fining and the possible N33E trending channel axes of the Banner Elk conglomerate (Figs. 2-9d and 2-12b) are consistent with a northeasterly source.

The highly polymictic Broadstone Lodge diamictite, in contrast to the Banner Elk conglomerate, contains clasts for which sources can be more reliably interpreted. The dominant basalt and andesitic basalt clasts are of two types: 1) nonporphyritic, trachytic-textured, plagioclase basalt to nonporphyritic, more quartz-rich, andesite with lower plagioclase content, and 2) porphyritic plagioclase (0.2 - 2 mm) basalt with a trachytic-textured plagioclase groundmass. Both types contain opaque minerals, sericite flecks, chlorite, and traces of epidote, and sphene. These grey to black basalt clasts are petrographically similar to the underlying Montezuma basalt, perhaps the most logical possible source. An andesitic basalt boulder at Locality 6a is very similar to a sample from below the ?hiatus? also at 6a (Fig. 2-15). Type 2 basalt is very similar

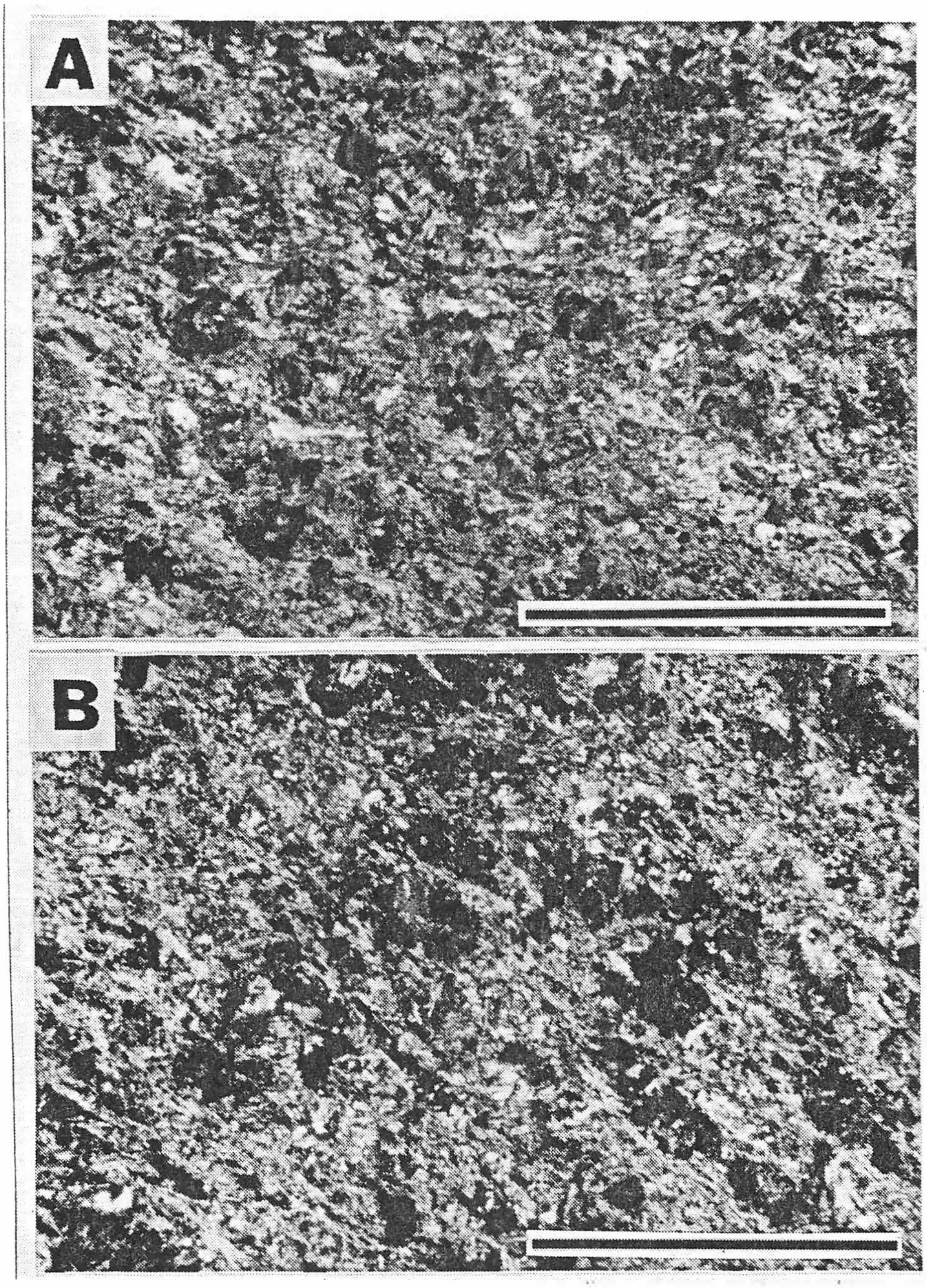


Figure 2-15. Photomicrographs of possible clast - source match in GMF. a) Andesitic basalt boulder in Broadstone Lodge diamictite (Locality 6a). b) Underlying Montezuma basalt. Both contain quartz, albite, white mica, opaque minerals, and sphene. Bar equals 3 mm.

petrographically to some Montezuma basalt described by Bryant and Reed (1970). The similarity of the two basalt clast types to the Montezuma basalt and its stratigraphic position below the Broadstone Lodge diamictite, as well as the presence of the ?hiatus? at Locality 6a, suggest the Montezuma basalt was at least partially uplifted and eroded after its deposition, which is not uncommon in rift basins (for example, Froelich and others, 1982; Tanner and Hubert, 1991). The relationships at Locality 6a also suggest that uplift of the Montezuma basalt occurred after deposition of the upper arkose (and Banner Elk conglomerate). The Montezuma basalt may also have been erupted onto rift shoulders as well as into the basin (common in rift basins: for example, Ellis and King, 1991) and subsequently eroded off the shoulders. The above petrographic similarities, however, do not preclude other origins for the basalt clasts.

The felsite clasts are of two types: 1) quartz and perthite porphyritic, and 2) quartz porphyritic, and are similar to those of the lower sequence and Banner Elk conglomerate respectively. These may have been derived from the upper rhyolite of the GMF, but they contain only traces of plagioclase, unlike the upper rhyolite (Table 2-4). Alternatively, recycling of the Banner Elk conglomerate is a possibility, but the Broadstone Lodge diamictite contains none of the other exotic clast types of the Banner Elk conglomerate and no clasts of conglomerate.

Granitoid clasts are dominantly composed of perthite, quartz, and muscovite, with lesser amounts of plagioclase and microcline. They are very similar mineralogically and texturally (relatively equigranular and medium-grained) to the Brown Mountain Granite, but fluorite and apatite (Table 2-4) were not observed in any Broadstone Lodge diamictite granitoid clasts.

A red, fine-grained, feldspathic wacke clast is mineralogically and texturally similar to a red sandstone interbedded with rhyolite of the MRF. Their similar feldspathic nature and angular grains may suggest an MRF derivation, but do not preclude other origins. Red, silty sandstone units do not exist within the GMF. During the Late Proterozoic, however, much of the GMF sandstone may have been red as are many younger terrestrial sandstone units. The prevalent

Fe_2O_3 and clays were probably metamorphosed to green, Fe-rich sericite (Bryant and Reed, 1970; Boyer, 1978) during Paleozoic orogenesis.

PALEOGEOGRAPHY: GRANDFATHER MOUNTAIN AND MOUNT ROGERS BASINS

To achieve a rift geometry that might have created the observed patterns of lateral clast size and composition data, the MRF (within the Blue Ridge thrust sheet) may be retrodeformed a distance of 55 km to reveal an approximate along-strike alignment with the GMF. Boyer (1978) and Schwab (1986b) also noted this alignment and concluded the existence of one basin. In addition, Boyer (1978) maintained from structural data that the GMF thins to the southeast. Rankin (1970) stated that the MRF thins to the northwest. Combining these interpretations (thickness changes), data presented here (lateral clast size and clast provenance) and knowledge of modern rift geometries demonstrated by Rosendahl (1987) for the East African rift system as well as by Manspeizer and others (1988) for the eastern North America Triassic-Jurassic rift basins, it is proposed here that the two basins (GMF and MRF) may have developed as an asymmetric, alternating half-graben pair (Fig. 2-16). D. Walker (1988) first suggested geometries similar to those of Rosendahl (1987; east African rifts) as a generalized large-scale framework for the Late Proterozoic Laurentian breakup.

The clear southwestward fining of three of the five conglomerate units (Fall Hollow, Snakeden Ridge, and Banner Elk) suggests two possibilities for their derivation: 1) paleodispersal was from northeast to southwest, with rhyolitic debris shed from either the MRF directly (one basin) or from a topographic high between the two basins (that is, an accomodation zone, Fig. 2-16), or 2) paleodispersal was from northwest to southeast and the southwestward fining was created by more extensive basinward progradation of fans and fan-deltas in the northern half of the basin. The southern half of the Grandfather Mountain basin was overall more tectonically

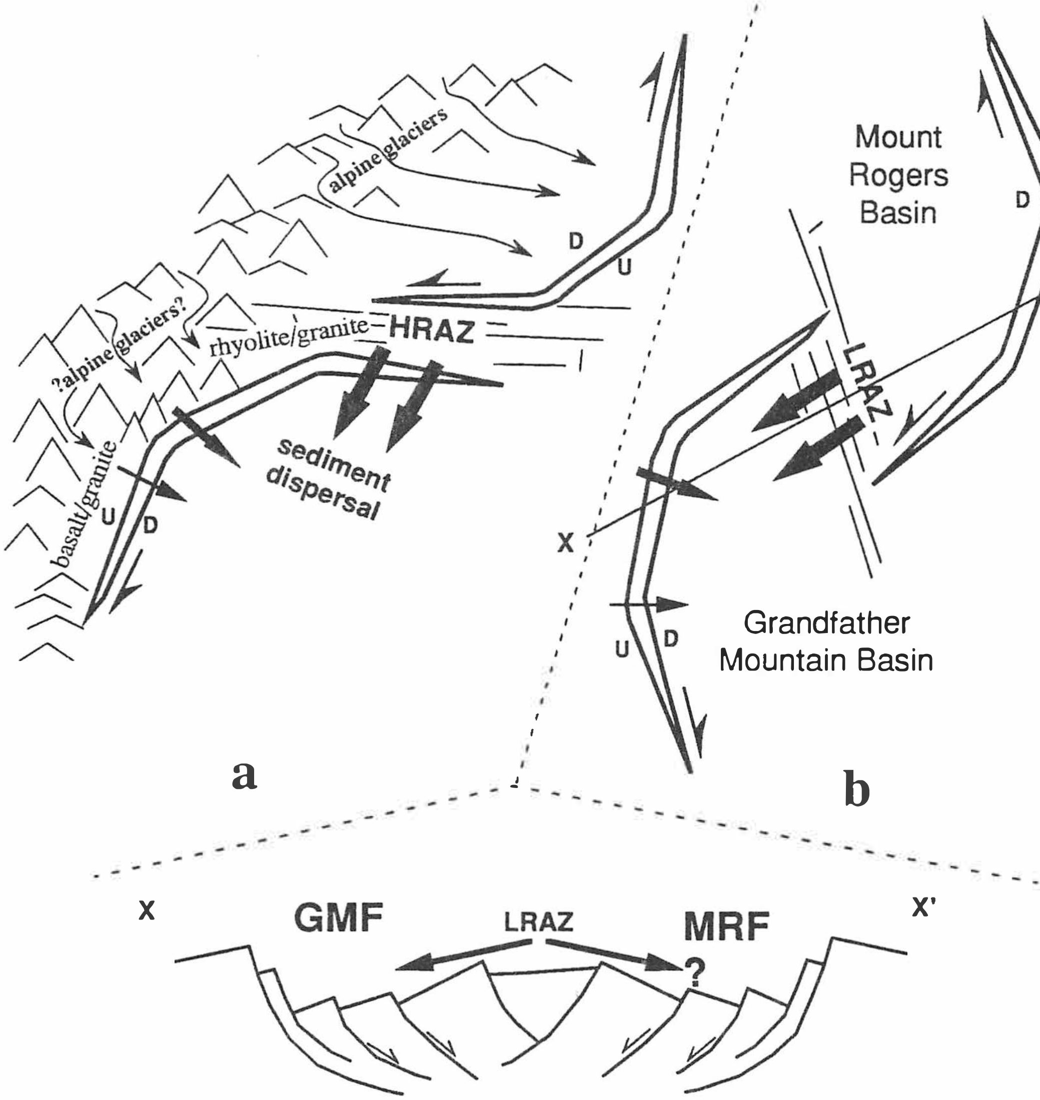


Figure 2-16. Paleogeography of two possible alternating half-graben geometries (a and b) for development of the Grandfather Mountain and Mount Rogers basins. Arrows of different thicknesses represent dispersal of fan deltas/alluvial fans in different scenarios to create observed stratigraphic patterns. See text. HRAZ = high relief accomodation zone; LRAZ = low relief accomodation zone; U and D denote relative movement on basin margin normal faults. In cross-section X-X', erosion off LRAZ into MRF is conjectural. Elements labeled in either "a" or "b" are valid for both configurations.

quiescent with less flank relief created over time. A lower volume of debris was therefore produced in the southern half of the basin, which led to smaller fan radii and less progradation. Alternatively, progradation distances may have been similar, but the basin shoulder rocks of the southern half were more deeply weathered granitoid rocks than those in the north, therefore producing finer-grained sediment. In this latter case, rocks that tend to weather and are eroded as large, durable clasts and blocks (for example, rhyolite and metaquartzite) may have been uncommon or even absent on the rift shoulders of the southern half of the Grandfather Mountain basin.

Scenarios 1 and 2 may both have occurred together or separately at various times during basin development in order to produce the southwestward-fining pattern. The fact that the Mount Rogers basin was an extensive volcanic center (Rankin, 1975, 1976) very near the Grandfather Mountain basin (between 4 and 25 km northeast along strike to possible accomodation zone and center of Mount Rogers basin, respectively) and the general similarity of many GMF felsite clasts to rhyolite units in the MRF, together suggest that at least some of the felsite detritus was derived from the Mount Rogers area. In addition, the fact that all three members of the MRF rest nonconformably upon Grenvillian basement (Rankin, 1967; 1970; Rankin and others, 1989) introduces the possibility that great volumes of rhyolite and granitoid/gneiss were periodically uplifted and eroded after rhyolite was extruded into the Mount Rogers basin or onto the crystalline-cored accomodation zone. Much of the debris could have been transported to the southwest into the Grandfather Mountain basin. The systematic southwestward decrease in frequency percent of felsite (31 to 12 percent) and granitoid rock (29 to 2 percent) clasts within the Broadstone Lodge diamictite is consistent with this interpretation, at least for Broadstone Lodge diamictite time.

The more ambiguous clast size trends within the Poplar Grove conglomerate and the Broadstone Lodge diamictite cannot be easily attributed to a northeast source. Both units are interpreted as subaqueous slope/large-scale channel deposits prograding into a deep basin with dominant transport and deposition by subaqueous debris flow and sediment gravity flow mechanisms. Debris flows, in particular, do not sort sediment and in a subaqueous environment can travel many kilometers, in contrast to most subaerial debris flows. Determination of paleodispersal direction solely from clast size data in these deposits is therefore inconclusive. Other directional features common in fan-delta and submarine fan environments, such as channel orientation, clast orientation, sole marks, and unambiguous cross-strata, are absent in these two units. If they were present, they have been obscured or obliterated by Paleozoic metamorphism and deformation. The Poplar Grove conglomerate and Broadstone Lodge diamictite are most simply interpreted as being composed of subaqueous slope deposits which were derived from the steep, northwest margin of the Grandfather Mountain basin. The lateral clast size data of the Broadstone Lodge diamictite (fining from northeast *and* southwest (Fig. 2-9e) is interpreted as representing the downgradient portion of two non-coalescent fan-deltas on a subaqueous slope. Finer-grained laminite and thin grain flows dominate the sequence between the fan-delta loci, which were centered approximately at Localities 6a and 6e. In addition, clast composition data of the Broadstone Lodge diamictite (Fig. 2-8f) indicate that the more northern fan-delta (centered near Locality 6a) was derived from a more felsite and granitoid-rich sourceland, whereas, to the south basalt was dominant on the rift shoulders, thereby creating a fan-delta rich in basalt clasts. This paleosource geography (felsite/rhyolite more prevalent to north and northeast) is in agreement with earlier stated conclusions for the three conglomerate units which unambiguously fine to the southwest. The lack of any definite glacial features in either of these two siltstone units and their included conglomerate/diamictite suggests that glaciation either did not occur in or near the Grandfather Mountain basin, or that during upper siltstone (Broadstone Lodge diamictite) time alpine glaciers may have been present in the highlands to the northwest but never advanced into or near the basin proper. The sediment preserved in the two fan-deltas then would represent immature debris derived from meltwater of these high mountain glaciers. In contrast, alpine glaciers did advance into the Mount Rogers basin, because well-preserved glacial features are present (including unambiguous dropstones and till pellets) within the uppermost member of the

MRF (Blondeau and Lowe, 1972; Schwab, 1976; Miller, 1986). Still further northeast, Wehr (1986) documented unambiguous dropstones and other glacial deposits in the broadly correlative Rockfish Conglomerate. To the southwest of the GMF, Lowe (1980) suggested that much of the sandstone of the Great Smoky Group of the Ocoee Supergroup may be of proglacial origin.

The rift geometry shown in Figure 2-16 is proposed to be the case for the length of the Late Proterozoic Blue Ridge trend. Relationships to the south may reflect this geometry. Hadley and Goldsmith (1963) noted coarse-grained, granitoid conglomerate beds in the northern extent of the Great Smoky Group which pinch-out to the southwest. They concluded a northern source during Great Smoky depositional time. This northern source may in fact be an accomodationzone between the Grandfather Mountain and Ocoee basins.

CONCLUSIONS

1) GMF conglomerate units were deposited in alluvial fan, fan-delta/subaqueous slope, and braidplain environments which prograded basinward over braidplain, playa lake and deep lake/marine environments.

2) Five conglomerate/diamictite units and one pebbly sandstone unit cap five coarsening-upward basin-fill sequences averaging 1300 m thick.

3) Three of the five conglomerate units unambiguously fine toward the southwest. Southwest-fining along strike suggests derivation from a sourceland to the NE (?low-relief or high-relief accomodation zone?) or a higher sediment supply in the northern half of the basin, that ultimately produced more extensive, northwest-to-southeast progradation than in the southern half of the basin.

4) The Broadstone Lodge diamictite appears to fine toward the middle of the outcrop belt, suggesting southeastward progradation of two noncoalescent fan-deltas with fanheads positioned on the northeast and southwest ends of the present-day exposure belt.

5) GMF conglomerate is strikingly polymictic, but dominated by greenish purple to black felsite and greyish black basalt clasts, NOT by crystalline basement clasts.

6) The rift shoulders in the northern half of the Grandfather Mountain basin were dominated by rhyolitic volcanic lithologies as well as by crystalline and sedimentary rocks, whereas the rift shoulders in the southern half of the basin were dominated by crystalline basement rocks, until Broadstone Lodge diamictite time when a basaltic terrane was exposed.

7) Basin history/unroofing sequence. Five major rifting events or clusters of rifting events created relief which eventually produced five coarsening-upward sequences.

1) Rifting - extrusion of outlier rhyolite and basalt (Zgfo)

Unroofing of rhyolite/felsite terrane (quartz and perthite porphyritic)

2) Rifting - extrusion of basalt (Zgvm)

Unroofing of sedimentary terrane (sandstone, siltstone, and metaquartzite)

3) Rifting - extrusion of lower basalt (Zgvm) and rhyolite (Zgf)

Unroofing of crystalline basement (Blowing Rock Gneiss and Wilson Creek Gneiss, ?Brown Mountain Granite)

4) Rifting - deposition of siltstone and Norwood Hollow sandstone

5) Rifting - extrusion of upper rhyolite (Zgf) and Montezuma basalt (Zgm)

Unroofing of another felsite terrane (quartz porphyritic)

Unroofing of basalt terrane (also quartz and perthite porphyritic felsite)

The first three sequences exhibit the characteristics of a progressive unroofing through rhyolitic volcanic units, sedimentary units and finally down into crystalline basement. None of these conglomerate units are monomictic, indicating that all three source units (volcanic, sedimentary, and crystalline basement) were exposed at the same time. Crystalline basement (Globe massif and unknown basement lithologies) exposure, erosion and clast availability, however, increased with time into the Poplar Grove and Snakeden Ridge conglomerates.

Crystalline basement of the overlying Blue Ridge thrust sheet most probably did not provide sediment to the Grandfather Mountain basin.

8) Felsite was derived from MRF and/or GMF rhyolite bodies. MRF and GMF basins may have developed as an asymmetric, alternating half graben pair, and probably were at various times joined or separated by an accomodation zone. Felsite and crystalline basement detritus may have been shed from the accomodation zone (low relief or high relief) or from rift shoulders to the northwest.

9) The two most reliably matched sources for debris deposited in the Grandfather Mountain basin are the Grenvillian Blowing Rock Gneiss and the intraformational Montezuma basalt. These and other possible clast-source matches must be confirmed by further petrographic study and geochemical and chronological methods.

ACKNOWLEDGMENTS

Grants supporting this research were from the University of Tennessee - Knoxville Department of Geological Sciences Professors Honor Fund, North Carolina Geological Survey, Geological Society of America - Southeastern Section, and the American Association of Petroleum Geologists. Discussion with Dan Walker (Kentucky Geological Survey), D. W. Rankin (USGS), J. M. G. Miller (Vanderbilt University), L. Raymond (Appalachian State University), S. E. Boyer (University of Washington-Seattle), E. Simpson (Kutztown State University), and UT- Knoxville colleagues Brent Couzens, Robert D. Hatcher, Jr., Harry McSween, and William M. Dunne, among others, were instrumental in the formulation of many of the above stated ideas. R. D. Hatcher, Jr., is thanked for use of his Macintosh™ computer facilities. Many observations regarding the Fall Hollow and Snakeden Ridge conglomerates could not have been made without the company and rapelling gear of James Berry (UT - Knoxville).

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3. Alluvial fan and subaqueous conglomerate deposition in an asymmetric half graben of the Laurentian continent: Grandfather Mountain Formation (Upper Proterozoic) of North Carolina

ABSTRACT

Rifting of Laurentia during the Late Proterozoic resulted in formation of a northeast-trending system of half graben basins. Thick accumulations of sandstone, siltstone, bimodal volcanic rocks, conglomerate, diamictite, and minor limestone were deposited largely in response to rifting and relief formation on the basin margins. Five basin-fill scale, coarsening-upward sequences formed in the Grandfather Mountain basin and each is capped by a major conglomerate/sandstone unit. Deposition of the sequences followed five major basin subsidence events.

Four facies associations are composed of thirteen descriptive facies. Lateral and vertical changes in facies and facies associations of the conglomerate units of the Grandfather Mountain Formation indicate that coarse-grained alluvial fans, fan-deltas/subaqueous slopes, and braidplains prograded from the basin margins, displacing finer-grained braidplain and marine or lake deposits back toward the basin center. Subaqueous (marine or lake?) slope and large-scale subaqueous channel deposits are more significant basin-fill environments in the Grandfather Mountain Formation than previously thought. Their presence is particularly indicative of high relief due to basin-margin faulting. Smaller-scale coarsening-upward sequences are attributed to avulsion and lobe progradation due to inherent fan/fan-delta/subaqueous slope processes as well as to progradation following a localized faulting event.

Differing clast composition and grain size between conglomerate units as well as interpreted hydrodynamics produce heterogeneous longitudinal bar sequences, braidplain and fan styles. The heterogeneous styles are due to heterogeneous fluvial processes and the complex interplay between proximal and distal environments such as at the alluvial fan to braidplain transition. Evidence in support of a glacial or proglacial origin for deposits in the upper part of the Grandfather Mountain Formation is either absent or ambiguous at best.

INTRODUCTION

Alluvial fans and fan-deltas develop along high relief basin margins. Finer-grained lacustrine or marine and low-gradient fluvial systems occupy the basin center and after basin subsidence rapidly migrate toward the margin, covering proximal fans/fan-deltas. After basin-margin tectonism wanes, fans and fan-deltas can prograde over and displace finer-grained environments basinward during relative tectonic quiescence. Blair (1987), Blair and Bilodeau (1988), and DiGuiseppi and Bartley (1991) documented this stratigraphic style in Tertiary and younger basins. Facies analysis allows reconstruction of depositional environments, paleogeography, paleohydraulics, and delineation of stratigraphic style due to tectonism on basin margins.

Detailed facies analyses and stratigraphic studies in the Grandfather Mountain Formation (GMF: Upper Proterozoic, North Carolina) and in correlative rift-related units along the Blue Ridge axis have been sparse. Because of this, the internal stratigraphy of these units is generally poorly constrained. Facies analysis of these units, such as those of Blondeau and Lowe (1972), Schwab (1976), and Miller (1986), all in the Mount Rogers Formation, as well as those of Wehr (1986; Rockfish Conglomerate), Neton and others (1990) and Neton and Driese (1992; GMF) will lead to a much better understanding of temporal changes in depositional environments within each basin. Additional work of this nature (this paper and see Raymond and others, 1992; Whisonant and Tso, 1992), when synthesized, will aid tectonic reconstruction of the rift system; it will also help delineate the depositionally and structurally complex, rift stratigraphies as well as give insight into interconnectedness of the now disparate basin fills.

Presented here are results of detailed sedimentologic study of conglomerate/diamictite and sandstone of the GMF. Fan-delta and deep subaqueous (lake?) sedimentation are seen as more important basin-fill environments than previous investigators (that is, Bryant and Reed, 1970; Schwab, 1977, 1981, 1986a, 1986b) recognized. Four facies associations (defined by thirteen lithofacies) are described and integrated with a GMF stratigraphy which agrees with that of Bryant and Reed (1970) as modified by Boyer (1978) and corroborated by Neton (see Part 2). Temporal development of sedimentology and paleogeography of the GMF basin is delineated. Possible sedimentological relationships between the GMF and the Mount Rogers Formation are discussed.

TECTONIC SETTING

See Part 1 for details regarding correlative Upper Proterozoic units (Fig. 1-1), large-scale Late Proterozoic rift geometry and stratigraphy, and comparisons to the Mesozoic rift system of eastern North America.

REGIONAL GEOLOGY

See Part 1 for details of Grandfather Mountain window (GMW) location, stratigraphy and age relationships (Table 1-1 and Figs. 3-1 and 3-2).

STRUCTURAL RELATIONSHIPS

See Part 1 for details regarding GMW and GMF structural style (Figs. 1-1 and 1-4 and Figs. 2-3 and 3-1) and clast deformation (Table 1-2).

METHODS

See Part 1 for detailed discussion of methods (measured sections and facies analysis) as well as conglomerate and diamictite definition (Fig. 1-5).

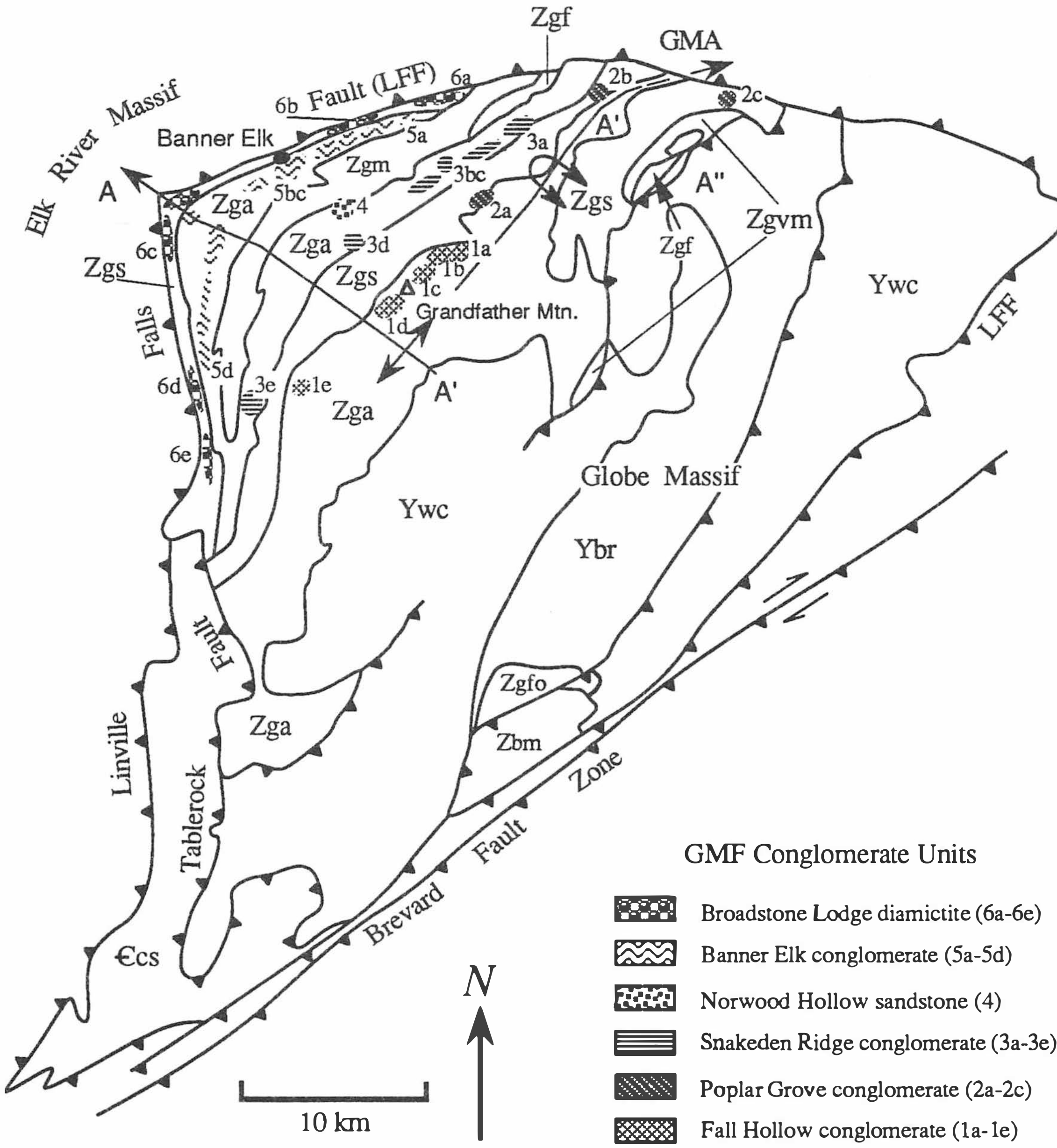

Figure 3-1. Generalized geologic map of the GMW and GMF showing distribution of major conglomerate units. Numbers 1a through 6e denote outcrops within discontinuously mappable units (see Figure 3-2). A-A'-A" denotes trend of cross section (Figure 2-3). GMA = Grandfather Mountain anticline. Map units: GMF: Zga = lower, middle, and upper arkose; Zgs = lower and upper siltstone; Zgf = felsic volcanics (lower and upper rhyolite); Zgfo = outlier rhyolite; Zgvm = lower mafic volcanic rocks; Zgm = Montezuma basalt. Crystalline basement (Globe massif): Ywc = Wilson Creek Gneiss; Ybr = Blowing Rock Gneiss; Zbm = Brown Mountain Granite. Other: €cs = Chilhowee Group and Shady Dolomite in Tablerock thrust sheet; Zl = Linville Metadiabase (not shown). Modified from Bryant and Reed (1970), Boyer (1978), Bartholomew and Lewis (1984), and Brown and many others (1985).

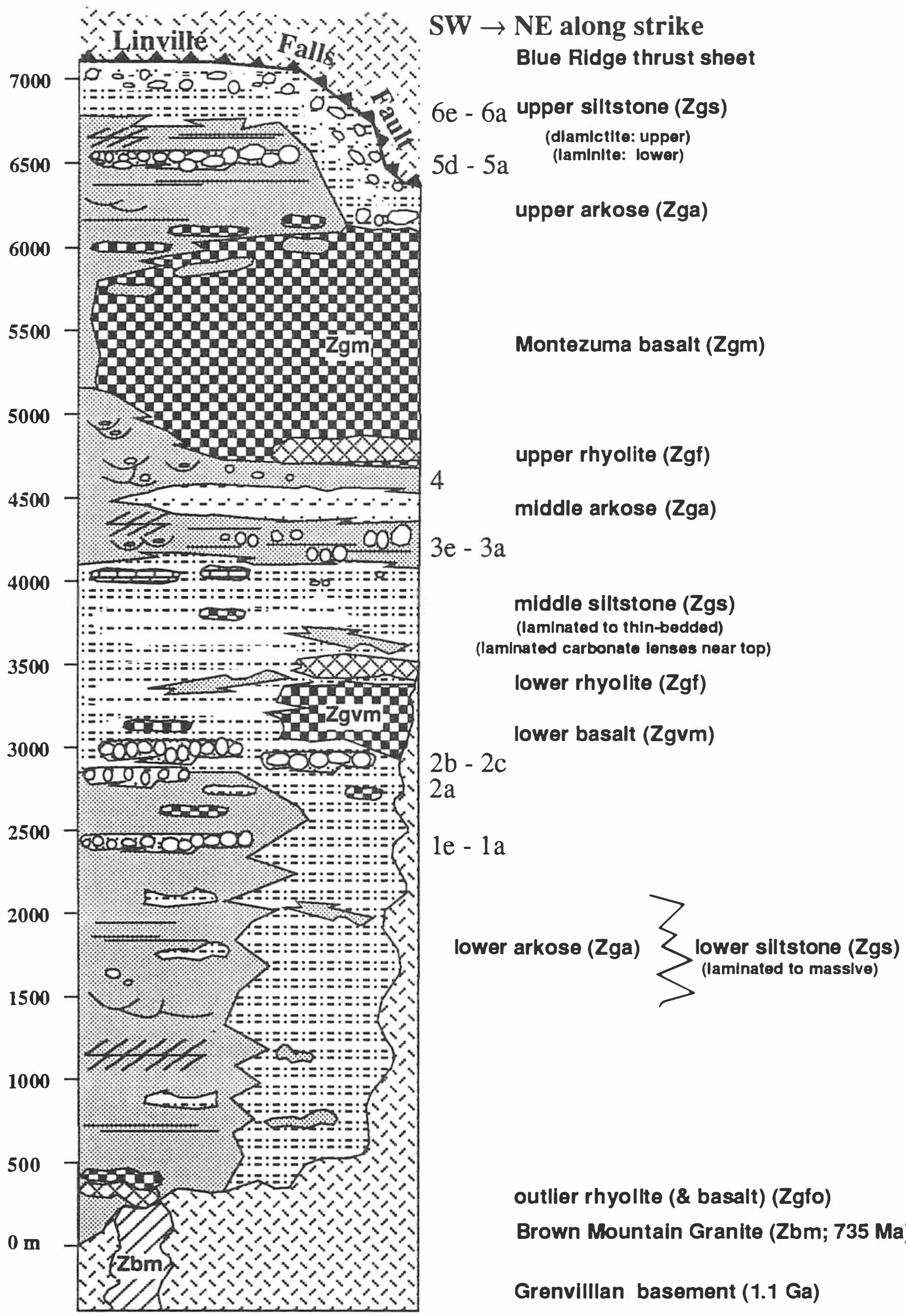

Figure 3-2. Generalized GMF stratigraphy constructed from map thickness data. Rock unit designations of Bryant and Reed (1970). Lower and middle siltstones of Bryant and Reed (1970) interpreted as same unit repeated on limbs of Granfather Mountain anticline after Boyer (1978; 1984) and data of this study and Neton and Driese (1992). Numbers denote conglomerate sections and bodies defined in Figure 3-1. Linville Metadiabase dikes and sills not pictured. Column not intended to show all variability across and along strike. Depiction of basal nonconformity does not imply true depositional relief, but merely depicts units which are known to rest nonconformably upon basement.

STRATIGRAPHY: GRANDFATHER MOUNTAIN FORMATION

The GMF youngs toward the northwest from the nonconformity at the base (Figs. 3-1 and 3-2). The lower and middle siltstone are the same unit repeated on respective flanks of the northeast-plunging Grandfather Mountain anticline (GMA, Fig. 2-3; Boyer, 1978, 1984). The Fall Hollow conglomerate is the oldest of the conglomerate units. The Broadstone Lodge diamictite is the youngest and is contained within the uppermost siltstone unit. Part 2 defines each unique conglomerate unit stratigraphically and compositionally (Figs. 2-4 and 2-7).

GENERAL CONGLOMERATE DESCRIPTION: GRANDFATHER MOUNTAIN FORMATION

Bryant and Reed (1970) described conglomerate bodies as ranging in thickness from several centimeters to over 30 m, with an average thickness of 3 m and clast size ranging up to 60 cm. They, however, did not map conglomerate bodies, instead grouping them with other units (arkose and siltstone). Schwab (1977, 1986b) studied the sandstone strata primarily through petrography and paleocurrents of the GMF as a whole. Schwab also noted that the average clast size, rounding and sorting of conglomerate bodies which he observed are: small cobble, rounded to subangular, and moderate to poor, respectively. Bryant and Reed (1970) and Schwab (1977, 1986b) also noted the occurrence of a wide range of clast lithologies, including rhyolite, basalt, vein quartz, granite, gneiss, metaquartzite, sandstone, and siltstone, but collected no quantitative data concerning them (see Neton, Part 2). Bryant and Reed (1970) and Schwab (1977; 1986b) interpreted the unit as having been deposited in alluvial fan/braided fluvial environments.

Neton and others (1990), Neton and Driese (1992) and this study document both matrix and clast-supported conglomerate as well as diamictite within the GMF. These bodies crop out as successions of lenses and as more laterally extensive horizons. Major units occur as shown in Figures 3-1 and 3-2. Immediately surrounding lithologies include feldspatholithic sandstone, laminated and massive siltstone, laminated carbonate, and basalt. Conglomerate bed thickness is highly variable and ranges from stringers one pebble/cobble thick to 7 m-thick, fining-upward successions. A 100 m-thick massive cobble-boulder conglomerate no doubt contains more than one bed. Clasts rarely protrude and cannot generally be plucked from the outcrop face. The two largest measured clasts are boulders with dimensions of 100 cm x 45 cm (Locality 2c) and 100 cm x 55 cm (Locality 6a).

FACIES/FACIES ASSOCIATIONS

The five conglomerate units (and overlying and underlying strata) of the GMF consist of thirteen lithofacies (Table 3-1), which together comprise four facies associations (A, B, C, D): A) laminite, diamictite, pebble to boulder matrix-supported conglomerate and minor clast-supported conglomerate of Facies Flm1, D, Gms (i,u,n) and Gcsu; B) planar-laminated to massive claystone, siltstone, sandstone and limestone containing various types of ripples and ripple cross-laminae of Facies Sr, Flm2, and Ll; C) cross-stratified to pebbly, planar stratified sandstone and lenticular, planar-stratified to massive, pebble to cobble clast-supported conglomerate of Facies Sp, St, Smh, and Gcsmh; and, D) massive to graded, pebble to boulder, clast-and matrix-supported conglomerate and planar-stratified pebbly sandstone of Facies Gcsu, Gms (i,u,n) and Smh. Volcanic bodies also occur, both as lenses/pods and as thick laterally extensive units (for example, Montezuma basalt; Figs. 3-1 and 3-2).

The inferred depositional environments represented by these facies associations were determined by examination of: 1) the individual facies and sedimentary structures, 2) the stacking pattern of these facies, and presence of coarsening- and fining-upward sequences forming the five conglomerate units, 3) the relationship of the five conglomerate units laterally and vertically to the surrounding stratigraphy, and 4) by comparison to modern and ancient analogues.

TABLE 3-1. LITHOFACIES, SEDIMENTARY STRUCTURES AND INTERPRETED PALEOENVIRONMENTS OF FLUVIAL - ?GLACIAL? - DEEP WATER DEPOSITS OF THE GRANDFATHER MOUNTAIN FORMATION. (SCHEME MODIFIED AFTER MIALL, 1977,1978; WARESBACK AND TURBEVILLE, 1990; NETON AND OTHERS, 1990).

Facies Code	Lithofacies	Sedimentary Structures	Interpretation
Gcsu	Conglomerate, clast-supported, non-stratified, fair to very poorly sorted, granular to bouldery, minor gravel/sand/silt matrix and as diffuse lenses	generally massive, very crude grading, ?imbrication?	cohesionless grain flow/ liquefied sediment flow types: modified grain flow, sieve deposits, gravelly sheetflood
Gcsmh	Conglomerate, clast-supported, usually as lenses, interbeds of sand/silt lenses and/or filling interstices	massive to horizontal stratification, some grading, commonly broadly undulose base ?imbrication?	longitudinal bar
Gmsi	Conglomerate, matrix-supported, non-stratified, graded, may be clast-supported in upper part	inverse grading, ?basal shear zone?	debris/mud flow, (high μ, high yield strength matrix) density modified grain flow
Gmsu	Conglomerate, matrix-supported, non-stratified, ungraded	massive	debris/mud flow (intermediate μ)
Gmsn	Conglomerate, matrix-supported, non-stratified, graded	normal grading	debris/mud flow (low μ, low yield strength)
D	Diamictite, unstratified to stratified, mud to sand matrix with granules to boulders (tr. to ~ 35 %)	massive to thin/thick bedding, wavy laminations, disrupted/diffuse laminations, normal grading, load structures, outsized clasts (?dropstones?)	subaerial mud/debris flows, subaqueous mud/debris flows, ?ice rafting?
Sln	Sandstone, fine to coarse-grained, some silt, sparse granules/pebbles	horizontal lamination/bedding, locally normal graded, load structures, rare ripple cross-laminations	subaqueous fluidal flows
Smh	Sandstone, fine to very coarse-grained, sparse to common granules and pebbles	massive to horizontal bedding/lamination local pebble stringers	sheetflood, streamflow in broad shallow-relief channels, diffuse sand and gravel sheets, sheetflood over longitudinal bars (lower and upper flow regime)
St	Sandstone, fine to very coarse-grained, sparse to common granules to small cobbles	small scale trough cross-strata, purple laminations/wisps/lens, large scale trough cross-strata	3-D dunes (lower flow regime) channel fills
Sp	Sandstone, fine to very coarse-grained, sparse to common granules and small pebbles	small scale planar tabular/tangential cross-strata large scale planar tabular/tangential cross-strata	2-D dunes transverse bars (large 2-D dunes)
Sr	Sandstone, coarse silt to fine-grained sand	symmetric ripples, ripple and climbing ripple cross-lamination, small scale trough cross-lamination	overbank deposition in ponds, sloughs, cut-off/inactive/avulsed channels superimposed bedforms
Flm	Claystone to very fine-grained sandstone, very sparse coarse sand/granules (< 1%)	planar lamination to very thin beds, wavy lamination, ripple cross-lamination, loads, flames, soft sediment folds/faults, sometimes massive	1 deep water deposits (suspension settling) & subaqueous fluidal flows, 2 overbank deposition in ponds, inactive/avulsed channels
Ll	Limestone	thin laminations	lacustrine (playa?) carbonates, algal mats?

subaerial and subaqueous

Facies Association A: Subaqueous fan-delta/slope/subaqueous channel

Facies Association A is composed of Facies Gms (i,u,n), D, Sln, Flm1, and minor Gcsu, Smh, and St. The poorly-sorted and generally unorganized deposits of diamictite (D) and matrix-supported conglomerate (Gms (i,u,n)) are massive to planar-bedded. Outcrop-scale channels are absent. Clasts are subrounded to angular and range in size from granules to boulders 1.0 m long. Matrix consists of sandy mud (Broadstone Lodge diamictite) to silty sand (Poplar Grove conglomerate). Inversely-graded beds (Facies Gmsi) are locally clast-supported near bed tops (Fig. 2-6a). Where determinable, bedding of Facies Gms and D ranges between approximately 0.1 and 3.0 m thick. Locally, however, Facies Gmsu and D reach thicknesses up to approximately 20 m thick and contain no readily apparent bedding planes or fabric/grain size changes. Facies D and Gms are variably interbedded with Facies Flm1 and Sln. Muddy laminite is present in a range of colors. Black, green, and purplish maroon tints are typical of claystone and siltstone laminae, whereas, yellow and grey are typical of siltstone and sandstone. Laminae range from 0.1 mm to 3.0 cm thick and distinct couplets or other rhythmic alternations are not readily evident. "Compound laminae" or laminasets (usage of Campbell, 1967), however, are common. A typical example of a lamina set occurs at Locality 6b, where a green claystone lamina (15 mm thick) contains three yellow siltstone laminae between 0.1 and 0.5 mm thick. Facies Sln ranges between approximately 3 to 100 cm thick and is commonly interbedded with laminite (Fig. 3-3a), but also occurs in repetitous succession as at Locality 2c. Sedimentary structures occurring in Facies Association A are wavy, disrupted and diffuse laminae (commonly occurring as clast-poor areas and wisps in Facies D and Gms), ripple cross-laminae, loads, flames, small ball-and-pillow structures, soft sediment folds/faults and outsized clasts. Outsized clasts were nowhere observed encased in laminite or thin-bedded Sln, however, they are present within decimeter-scale beds of Facies D and Gms. Loading occurred most commonly where Facies Sln succeeded either Facies Flm and D, or the fine-grained top of a previous Sln bed. The most common facies

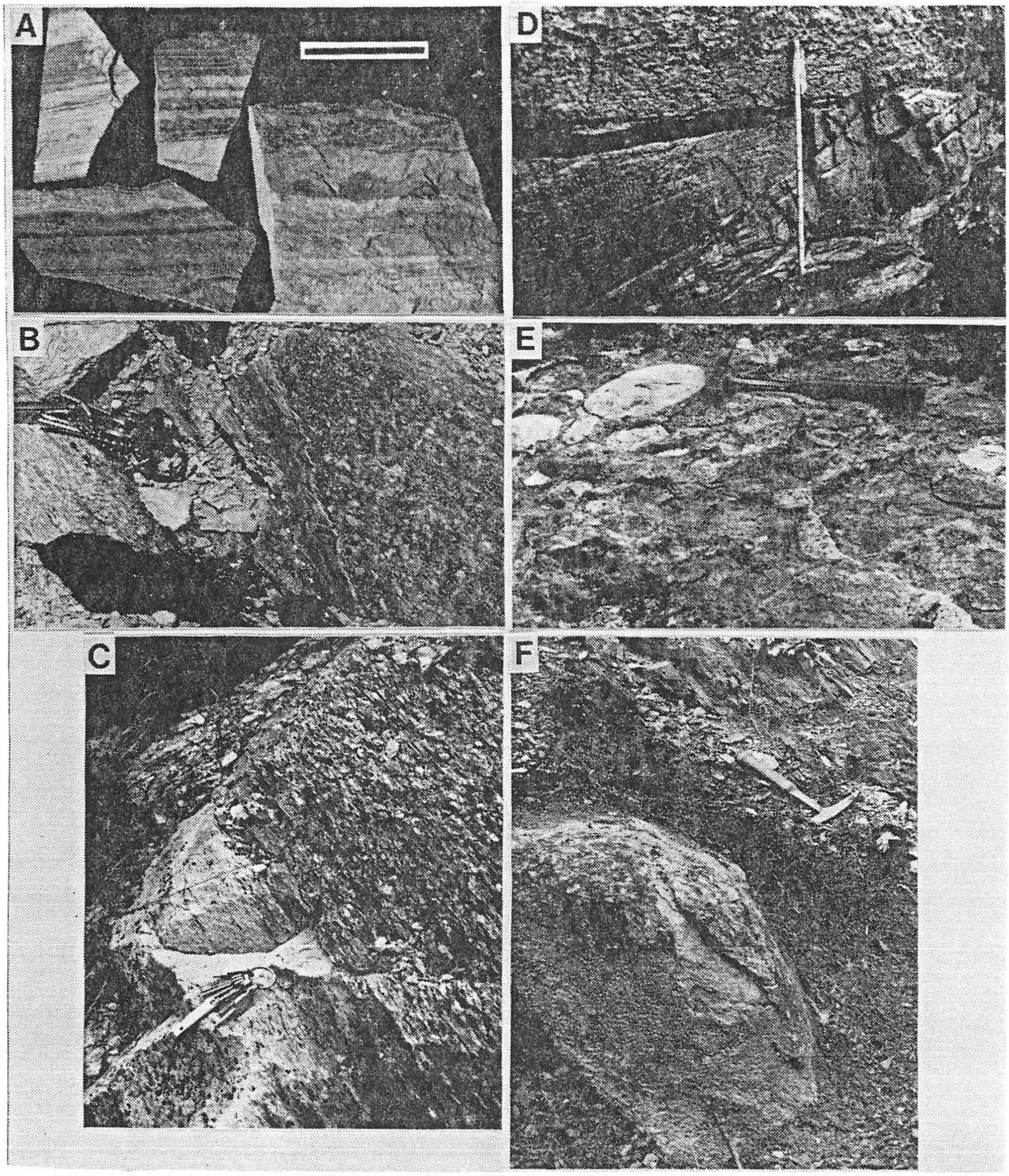

Figure 3-3. Outcrop photos of facies of the GMF. Scales (b, c: Length of single key = 5.5 cm; e, f: Hammer = 31 cm). a) Facies Sln and Flm1 of Facies Association A exposed on laminite slabs from Broadstone Lodge diamictite. Sedimentary structures: load casts, flames, and soft sediment folds and thrusts. Scale bar = 5 cm. b) Facies Flm2 overlying a fine-grained variant of Facies Gcsmh-Smh at approximately 113 m level (Locality 5d). Bedding (dashed line) overturned. Younging direction to left. Mullions present at contact between the two facies. c) Facies Smh abruptly overlying Facies Gcsmh (small pebble) at Locality 5d. Bedding overturned. Younging direction to lower left. d) Single set of large-scale Facies St overlain by Facies Gcsmh and Smh just north of Locality 1d on Grandfather Mountain. Jacob staff = 90 cm. e) Facies Gcsu composed of subrounded cobbles and boulders of purple felsite, granitoid, and metaquartzite (Locality 1c). f) Angular crystalline basement boulder in massive siltstone of the Broadstone Lodge diamictite near Locality 6c. Coarsely porphyroclastic texture suggests derivation from the Blowing Rock Gneiss. Photo courtesy of S. E. Boyer.

transition within Facies Association A forms a coarsening-upward sequence (Fig. 3-4; discussed later). Facies Smh and St substitute uncommonly in position for Facies Sln, and Facies Gcsu substitutes for Gms.

The lateral continuity of GMF siltstone units (up to 36 km along strike) as well as this facies association, the lack of dessication features, lack of evaporitic rocks (albeit greenschist metamorphism and deformation may have obliterated any evaporites once present), lack of symmetrical wave ripples, and the presence of soft sediment deformation structures suggest that this facies association was deposited in a large, relatively deep (below storm wave base), perennial rift water body. The laminite was deposited by suspension settling processes out of the water body, which periodically received mud influx after rains or glacial melting, as well as by subaqueous fluidal flows. Thin sandy horizons (Facies Sln) within Flm1 sequences were deposited by subaqueous fluidized flows and turbidites which spread out over the bottom in areas distal from the basin margin or between noncoalesced fan-deltas. Matrix-supported conglomerate and diamictite were deposited by subaqueous debris flows and density modified grain flows on prograding lobes of fan-deltas or on a broad slope in large subaqueous channels.

Facies Association B: Playa/pond/fluvial overbank

This fine-grained facies association, composed of Facies Sr, Flm2 and Ll, is sparsely present in some coarser-grained sequences. Laminated, muddy limestone containing black graphite is present only in the uppermost parts of the middle siltstone and underlies Facies Association C at Locality 3d. Facies Flm2 occurs as red to blackish-grey laminated/thin-bedded to massive mudstone with some fine-grained sandstone. It also occurs as laminated sandy mudstone sparsely intercalated with Facies Sr. Facies Sr occurs most commonly as ripple cross-lamination, but also as climbing ripple cross-lamination in siltstone lenses enveloped by Facies Smh (pebbly)

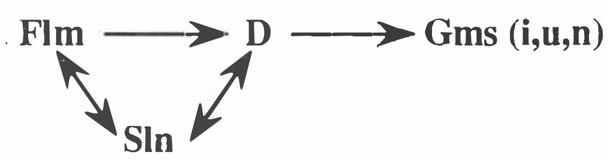

Figure 3-4. Coarsening-upward facies succession present in the Poplar Grove conglomerate and Broadstone Lodge diamictite of the Grandfather Mountain Formation (Upper Proterozoic).

and lenses of Facies Gcsmh. Symmetrical ripples occur in one locality in association with Facies Flm2 and Facies Smh, St and Sp of Facies Association C.

Facies Flm2 and Sr of Facies Association B occur most commonly within Facies Association C overlying Facies Smh-Gcsmh (Fig. 3-3b) and as part of thin, fining-upward sequences as follows: large or small-scale St → Smh → Sr → Flm. This sequence is most common within the Snakeden Ridge conglomerate and the Norwood Hollow sandstone. In one instance Facies Flm2 and Sr occur within Facies Association D.

Facies association B is interpreted to represent deposition in the lowest energy environments of the fluvial system. Facies Ll was deposited in a playa lake, possibly in conjunction with evaporites (which may have been subsequently replaced by calcite) and algal mats (now black graphite). The thin, lenticular occurrences of Facies Flm2 and Sr within Facies Associations C and D suggest that they were deposited in overbank areas in a braidplain setting or in cut-off/avulsed braid channels on top of longitudinal bars in a manner such as observed by Williams and Rust (1969).

Facies Association C: Mid to lower alluvial fan/braidplain

The clast-supported conglomerate, cross-stratified sandstone and pebbly sandstone facies association (Facies Gcsmh, Smh, St, Sp) is the most prevalent in the GMF. Bedding is lenticular (especially of Facies Gcsmh) to planar on outcrop-scale. Pebbly cross-stratified sandstone (Facies St and Sp) is common, whereas cross-stratified conglomerate (Facies Gt and Gp of Miall, 1977; 1978) is absent. Locally, Gcsmh lenses (Figs. 3-3b and 3-3c; 0.2 - 7 m thick) fine or coarsen-upward slightly, with fining-upward being more common. Tops of Gcsmh lenses are gradational to abrupt with overlying sandstone facies. Lateral boundaries of conglomerate lenses, if seen, are either abrupt throughout their thickness (up to a meter; Locality 5c) or grade into surrounding gravelly sandstone. It is likely that thin conglomerate lenses/stringers represent the fringes of a thicker conglomerate lens projected into or out of the outcrop plane. Facies Gcsmh commonly contains thin to thick lenses of pebbly Smh and interfingers with Facies Smh, St, and Sp.

Grain size of Facies St, Sp, and Smh ranges from fine-to very coarse-grained sandstone that is poorly to moderately well-sorted. Sand grains are subangular to rounded. Granules and pebbles are sparse to common, are well-rounded to subangular and generally consist of white to grey (vein?) quartz, feldspar, rhyolite, and rare quartzite, granite, siltstone and basalt. Typically, the most angular grains are feldspar sand and gravel.

Small-scale cross-strata are defined as having a thickness between 3 and 10 cm. Large-scale cross-strata are defined as being greater than 10 cm thick. The thickest sets of Facies St are 1 m and the average thickness ranges between 15 and 40 cm (Fig. 3-3d). Average set width is 1 to 4 m and adjacent troughs commonly intersect one another. Large-scale sets of Facies Sp range between 15 and 70 cm thick, with the average being 20 to 40 cm thick.

Purple (and less commonly green), fine-grained sand (heavy minerals) and silt commonly define upwardly concave, as well as upwardly convex, wavy, diffuse to distinct wisps. Whereas the geometry of these structures is locally indeterminant and complex, they are no doubt some type of cross-strata which may or may not be slightly deformed by soft-sediment deformation processes as well as tectonic deformation. These purple wisps are herein defined as small-scale trough cross-strata. They are most commonly associated with Facies Smh, forming thick vertical successions.

Sets of small and large-scale St and Sp are variably interbedded and occur singularly (Fig. 3-3d) and in successions of beds up to 5 m thick. Foresets are defined by grain size changes, as well as by heavy mineral concentrations.

Bedding thickness of Facies Smh ranges from several cm to several m, to massive successions in which bedding planes are unrecognizable and description and measurement were based on gross grain size changes. Bedding is planar, but locally gently undulose bases are evident as are large-scale, faintly lenticular geometries. Horizontal stratification is most easily observed where it is defined by pebble stringers. Pebble stringers are discontinuous horizons most commonly composed of granules and pebbles, and are rarely more than two clasts thick. The clasts within the stringer are not generally in contact with each other, except for isolated clast pairs and triplets. Isolated cobbles along stringer horizons are rare, but do occur. Contacts between other Smh bodies are generally gradational. Contacts with other facies, such as Gcsmh, are locally sharp and are best observed at Localities 5b and 5d (Fig. 3-3c).

This facies association is interpreted to have been deposited by high gradient braided streams in the mid to lower alluvial fan area and in lower gradient braidplain environments of the distal fan area such as longitudinal fluvial environments. Deposition of longitudinal bars (Facies Gcsmh) was more common in the mid to lower alluvial fan area, whereas, channels (Facies St) separated by transverse bars (Facies Sp) and sandflat complexes of Cant and Walker (1978) were more common in distal fan/braidplain environments. Facies Smh, containing pebble stringers, was also deposited in broad sheets on the braidplain as upper flow regime plane beds. The complete lack of trough and planar cross-stratified conglomerate (Facies Gt and Gp, respectively) in Facies Association C most probably indicates dominance of shallow flows (Kraus, 1984; Smith, 1985) on GMF fans and braidplains. Smith (1985) suggested as a general "rule of thumb" that the flow depth to grain size ratio must exceed 10 to produce cross-stratification of gravel.

Facies Association D: Mid to upper alluvial fan

Facies Association D (Facies Gcsu, Gms (i,u,n), Smh) is composed of pebble to boulder conglomerate of clast-supported and matrix-supported varieties, variably intercalated with massive or planar-stratified sandstone and pebbly sandstone. Facies St and Sp are sparse. Bedding is generally sheet-like or nearly indiscernable on outcrop-scale due to the massive nature of some of the clast-supported cobble to boulder conglomerate (Facies Gcsu; Fig. 3-3e), in particular. Locally, however, decimeter-scale beds of pebble-cobble Facies Gcsu are sharply interstratified with similar scale beds of Facies Smh. Uncommonly, finer-grained Facies Gcsu (granule-small pebble) beds overlie slightly undulatory to scoured surfaces (1 to 2 cm relief). Sorting of the conglomerate facies (Gcsu and Gms) is poor to moderate and gravel is subrounded to angular with clasts of highly varying degrees of roundness occurring in the same bed. Matrix of Facies Gms ranges from slightly muddy sandstone to sandy mudstone. Upper parts of Facies Gms approach clast-support. The two largest clasts measured in Facies Association D are of Facies Gcsu with dimensions of 40 x 22 x 22 cm (purple felsite) and 45 x 30 cm (angular gneiss boulder).

The massive to planar-stratified and poorly-sorted nature of the angular coarse-grained sediment, and the paucity of cross-stratified beds together suggest that Facies Association D was deposited in mid to upper alluvial fan environments in the vicinity of the intersection point. At this point the fanhead trench merges with the fan surface and flows spread and thin; lose competence, resulting in sheet-like deposition (Hooke, 1967). Hooke (1967) and Bull (1972, 1977) documented dominance of debris flow, sieve deposition and sheetflood processes in the mid to upper alluvial fan environment. Facies Gms of this facies association, however, is not prevalent and occurs only within the Snakeden Ridge conglomerate where, in fact, most of the Gmsu and Gmsi beds present contain a matrix composed of sandstone to slightly muddy sandstone. Only one bed of Gmsu at Locality 3bc contains appreciable reddish-purple mudstone. The lack of appreciable high yield strength mud in these debris flows suggests that the dominant support mechanism was interclast dispersive pressure as well as some turbulence (Naylor, 1980; Lowe, 1982). If as little as 5 percent by volume of the flow is mud - water matrix, significant buoyant support is provided and reduces the effective weight of the clasts (Rodine and Johnson, 1976). These low mud-content Gms beds, bordering on clast-support, therefore are subaerial density-modified grain flows (usage of Lowe, 1976a, 1982).

The clast population of these two conglomerate units (dominated by felsite, granite/gneiss, and metaquartzite/sandstone) is indicative of source regions where little mud is produced (Bull, 1972, 1977). Muddy debris flows and debris flows in general were therefore rare on the Fall

Hollow fan and Snakeden Ridge fans. In fact, the Fall Hollow conglomerate contains the higher amounts of purple felsite (Fig. 3-3e) and no debris-flow deposits. These fans were dominated proximally by coarse-grained sieve/sheetflood and density modified grain-flow processes and distally by sheetflood and sandy (some gravel) braided river processes. The distal reaches of the Snakeden Ridge fan were very sandy due to high amounts of granite and sandstone debris, whereas, distally the Fall Hollow fan was still gravel dominated due to the predominance of resistant purple felsite clasts. The Snakeden Ridge and Fall Hollow fans are interpreted as broad, relatively low-gradient fans as opposed to smaller radius, steeper fans dominated by cohesive, muddy debris flow deposits (for example, Blissenbach, 1954; Hooke; 1967; Harvey, 1984; Blair and McPherson, 1992).

LATERAL AND VERTICAL VARIABILITY

Delineation of lateral and vertical changes in facies associations and small-scale coarsening- and fining-upward sequences within each of the six conglomerate/sandstone units, and their integration with the overlying and underlying stratigraphy, allow for accurate characterization of depositional environments. Four of the six conglomerate/sandstone bodies are described with three or four laterally correlative measured sections. Two are described by only one measured section (Fall Hollow conglomerate and Norwood Hollow sandstone). All the units, except for the Norwood Hollow sandstone, are additionally described by observations from field reconnaissance and mapping as well as those of Bryant and Reed (1970), Schwab (1977, 1981), and Boyer (1978).

Fall Hollow conglomerate

The Fall Hollow conglomerate (stratigraphically lowest conglomerate; Localities 1a-1e) caps a coarsening-upward basin-fill sequence (usage of Heward, 1978) that is 2500 m-thick

(Neton, Part 2). It crops out along the crest and flanks of Grandfather Mountain Ridge and is named for a particularly massive exposure at 4200' elevation in Fall Hollow (Locality lb). It fines from boulder clast-supported conglomerate in the northeast to pebbly sandstone in the southwest. It is composed of Facies Associations D, C, and B in decreasing order of abundance. Regarding Facies Association D, the Fall Hollow conglomerate does not contain Facies Gms(i,u,n), in contrast to the Snakeden Ridge conglomerate, and is dominated by Facies Gcsu, Smh, Gcsmh and lesser but significant amounts of Facies St (Figs. 3-3d and 3-5) and Sp. Facies Association D (without Facies Gms) dominates in the northeast (Localities 1a-1b-1c) and grades southwest (Localities 1d-1e) to dominance of Facies Association C. Relationships at Locality 1b (Fig. 3-5) characterize Facies Association D. In addition, Bryant and Reed (1970) observed clast-supported boulder conglomerate at Locality 1a and reported a purple felsic volcanic boulder with a long axis of 60 cm. The massive cobble-boulder conglomerate is interpreted as having been deposited as successive sieve lobes (liquefied sediment flows; Middleton and Southard, 1984; or modified grain flows; Lowe, 1976a) and gravelly sheetfloods in or near the fanhead trench in the vicinity of the intersection point (Hooke, 1967). The single sandstone interval (Facies St, Smh) at Locality 1b may represent filling of the fanhead trench by migrating 3-D dunes and sandy sheetfloods. The remaining depth of the trench (approximately 1 m; Fig. 3-5) was then filled,or scoured then filled, by a succeeding sieve deposit. Subangular to subrounded, disc-and roller-shaped cobbles and boulders of purple quartz and perthite porphyritic felsite, green and tan metaquartzite, and fine-to medium-grained granite are locally arranged with long axes parallel to strike, but no preferred dip direction is present. This crude imbrication can be developed in sieve deposits due to localized clast jostling as the cohesionless grain flow moves downslope (FitzGerald and Gorsline, 1989). The fact that matrix-supported conglomerate is absent in this 102 m section, as well as throughout the Fall Hollow conglomerate, suggests that these deposits are not reworked debris flows with mud winnowed from the interstices, because some debris flow beds should remain intact.

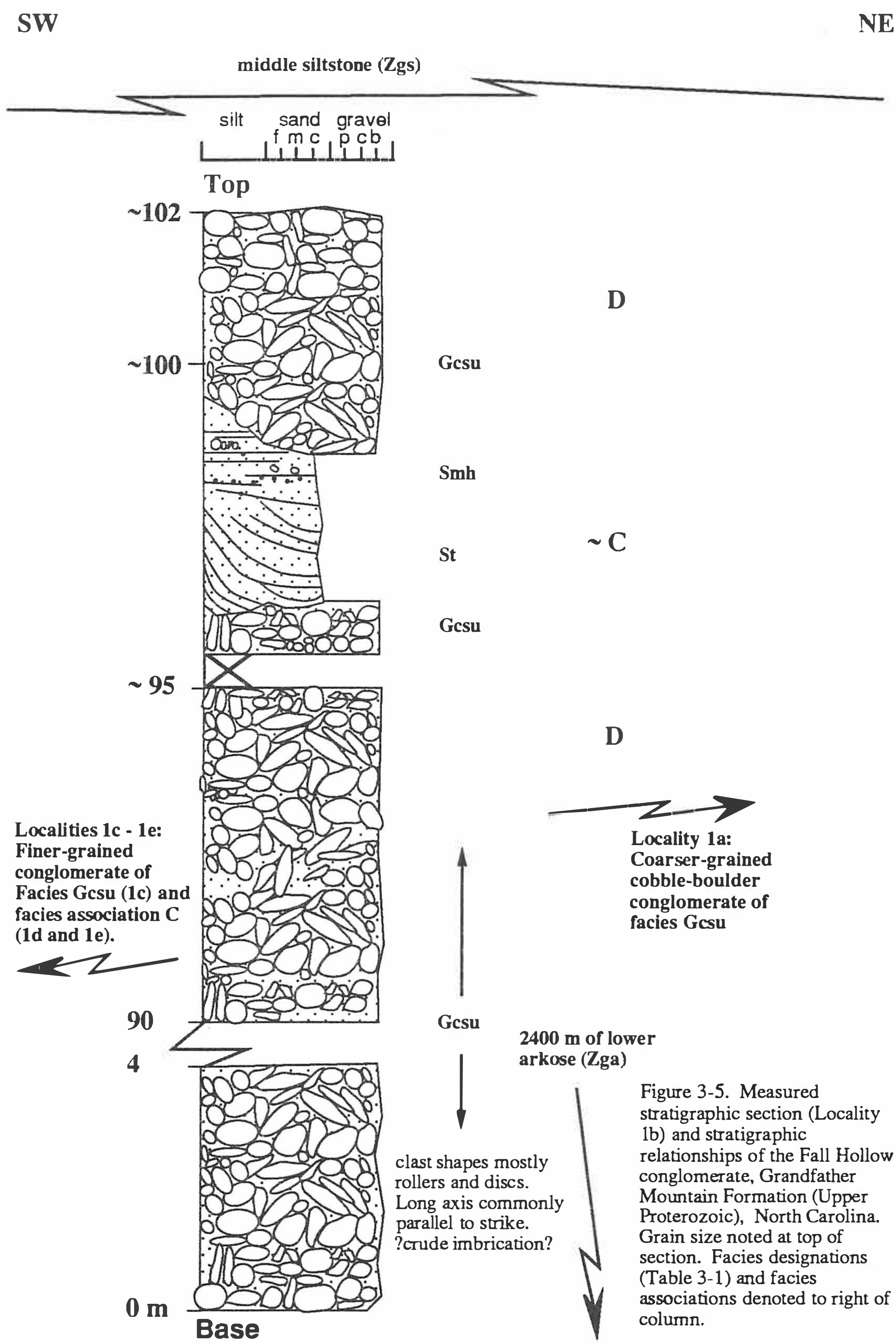

Figure 3-5. Measured stratigraphic section (Locality 1b) and stratigraphic relationships of the Fall Hollow conglomerate, Grandfather Mountain Formation (Upper Proterozoic), North Carolina. Grain size noted at top of section. Facies designations (Table 3-1) and facies associations denoted to right of column.

Southwest of Locality 1c (Facies Gcsu dominated), the Fall Hollow body fines to a gritty, pebbly sandstone of Facies Association C, such as that at Locality 1d (Grandfather Mountain visitors center; Facies Smh and St). It is sparsely intercalated with pebble clast-supported conglomerate containing some cobbles (Facies Gcsmh) such as that exposed at the Linville Gorge overlook (Locality 1e).

Facies Association B occurs approximately 0.25 km west of Locality 1b where symmetrical ripples (A = 3 m, l = 2.0 to 2.5 cm) of Facies Sr (interpreted as wave ripples) occur in association with Facies Sp and St, and thin-bedded Smh intercalated with 1 mm shale partings (Facies Smh and Flm).

The facies associations (D,C,B) of the Fall Hollow conglomerate suggest a mid to upper alluvial fan environment dominated by watery sediment gravity flows fining to the southwest into a braided, mid to lower alluvial fan that was covered by periodic sandy/gravelly sheetfloods. Bull (1972) documented fans in Death Valley, California which are dominated by these processes. The close proximity of Facies Association B to Facies Associations D and C suggests that shallow ponds and lakes dotted areas between noncoalesced alluvial fans and inactive areas of alluvial fans, such as cutoff or plugged fan head trenches. The southwestward fining suggests derivation from a felsic volcanic, quartzite/sandstone and crystalline basement terrane to the northeast (Part 2).

Poplar Grove conglomerate

The Poplar Grove conglomerate caps a 500 m-thick, coarsening-upward basin-fill sequence (Neton, Part 2). It occurs on the northwest and southeast limbs of the northwest-vergent, northeast-plunging Grandfather Mountain anticline (GMA: Figs. 3-1 and 2-3) and is named for a locality (2b) near the crossroads of Poplar Grove (Jct. SR 1551/1552) where it is intercalated with basalt. Precise correlation of strata across the GMA axis is unclear, but the similar clast composition and depositional style (Facies Association A) on respective limbs (Part 2) suggests that the lower and middle siltstone units (containing the Poplar Grove conglomerate) of Bryant and Reed (1970) are the same unit, as was concluded by Boyer (1978; 1984). From map thickness and general stratigraphy, rocks at Locality 2c are taken to underlie those exposed at Localities 2b and 2c, which are approximately correlative (Fig. 3-6).

Localities 2b and 2c are both sandy (but with some mud) conglomeratic successions of Facies Association A, which are mapped as large lenses/pods of "arkose" (Zga) by Bryant and Reed (1970). Locality 2b contains thin amygdaloidal basalt flows (Fig. 3-6), whereas, thick amygdaloidal basalt bodies occur above, below and along strike from Locality 2c (Figs. 3-1 and 3-2). Approximately 4 km southwest of Locality 2c along Flattop Mountain, intercalated siltstone of Facies Flm1 and Sln are interfingered with basalt and rhyolite units.

Matrix of pebble to cobble-bearing diamictite and matrix-supported conglomerate at Locality 2a is composed of sandy mudstone, whereas, matrix at Localities 2b and 2c is sandstone to slightly muddy sandstone. The largely ungraded deposits at Locality 2a were deposited by subaqueous debris flows in which viscous, high shear strength mud was the dominant clast support mechanism (Naylor, 1980; Lowe, 1982). In contrast, the sandier, inversely graded, matrix-to clast-support conglomerate (0.2 - 2 m thick) at Locality 2b and near the base of Locality 2c (Fig. 2-6a) was deposited by subaqueous density-modified grain flows in which interclast dispersive pressure was the dominant clast support mechanism and clast collisions led to inverse grading (Lowe, 1976a; 1982). The minor amount of mud (present throughout and locally as reworked diffuse, wavy Flm) in these deposits, however, also contributed partially to clast support by providing buoyant lift (Rodine and Johnson, 1976; Naylor, 1980) and increased flow strength, allowing the flow to travel further before freezing occurred. True grain flows contain no mud and therefore only form on slopes approaching the angle of repose (18° - 28° for subaqueous sand; Middleton and Hampton, 1976; Lowe, 1976a). In addition, because of the lack of mud, true grain flows may refreeze after traveling only a few meters and commonly are less than 5 cm thick (Lowe, 1976a, 1976b). The middle part of Locality 2c is composed of Facies Gms (u, i)

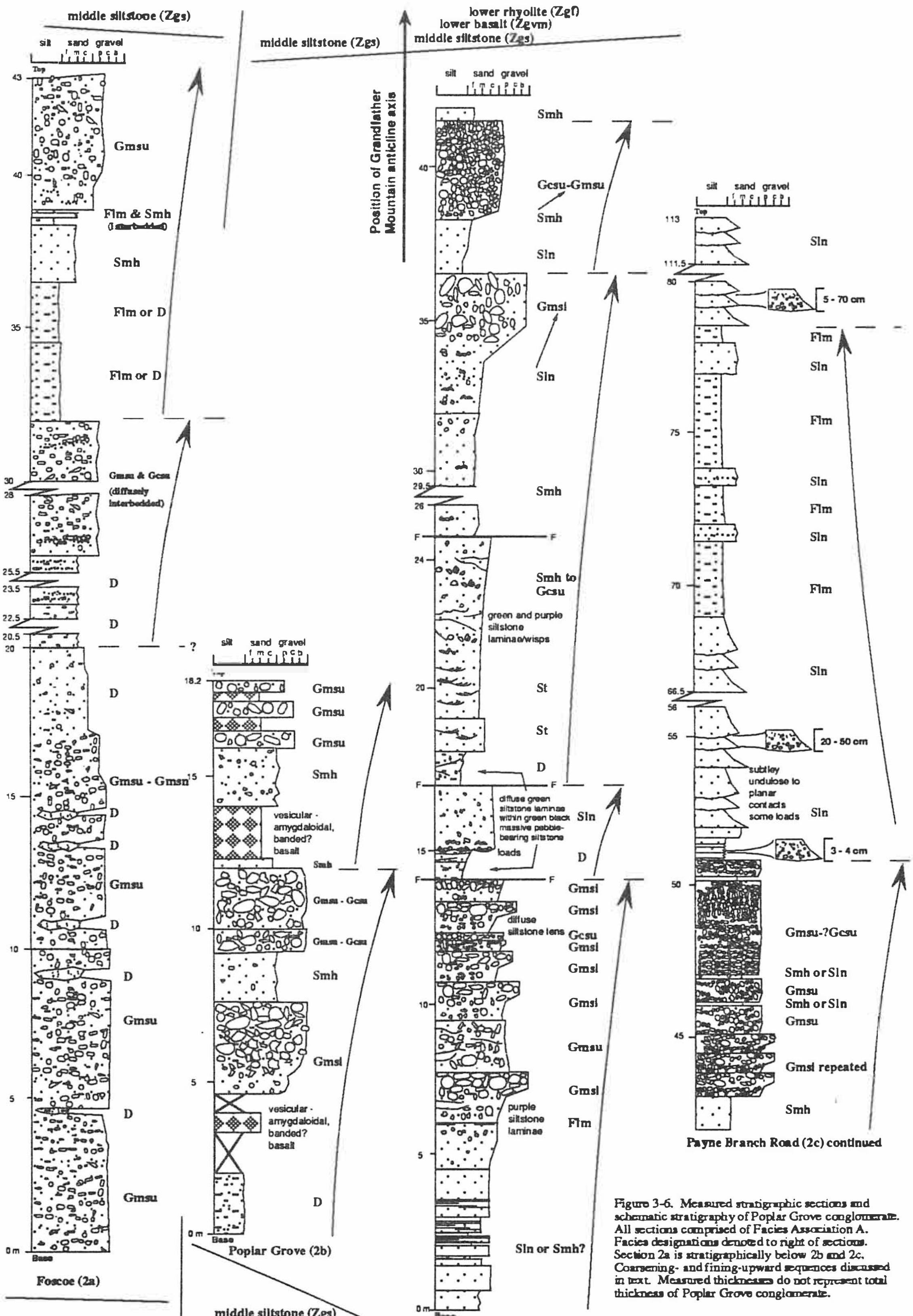

Figure 3-6. Measured stratigraphic sections and schematic stratigraphy of Poplar Grove conglomerate. All sections comprised of Facies Association A. Facies designations denoted to right of sections. Section 2a is stratigraphically below 2b and 2c. Coarsening- and fining-upward sequences discussed in text. Measured thicknesses do not represent total thickness of Poplar Grove conglomerate.

(generally with a muddier matrix than near the base of 2c), D, Sln, St, and Smh. These facies are interpreted to be deposited by subaqueous debris flows and sandy to gravelly high-density turbidity currents. Facies St (20 m level of Locality 2c) in these deposits may represent the S1 traction layer of a high density turbidity current forming trough cross-stratification (Mutti and Ricci-Lucci, 1975; Lowe, 1982). The upper part of Locality 2c is dominated by Facies Sln with undulose to planar bases and Facies Flm1. Facies Sln here contains partial Bouma sequences at different scales (Figs. 3-6 and 3-7). The upper part of Locality 2c is interpreted to have been deposited by low-density turbidity currents of various thickness and by suspension settling of mud below wave base. In addition, large load casts at the 15 m level, load casts at 51 m in Facies Sln (Fig. 3-6), the presence of wavy and diffuse muddy laminae, and irregular patches of muddier matrix locally within Facies Gms and Smh suggest a wholly subaqueous origin (Nemec and Steel, 1984) for the Poplar Grove conglomerate.

The lens and pod-like map pattern of these conglomeratic successions (Localities 2b and 2c), as well as others nearby, enveloped within laminated to massive siltstone further suggests a subaqueous origin. These pods may represent a system of subaqueous fans or subaqueous channels which transported coarse debris from the basin margin into deeper parts of a large rift water body. Dimensions of the map-scale "arkose" pods are of similar scale and dimension to three large subaqueous channels within the San Carlos submarine canyon, delineated by Morris and others (1989) in the Upper Cretaceous of Baja California (Table 3-2). These channels are filled with conglomeratic successions with very similar properties to those of the Poplar Grove conglomerate. The lens-like nature of these conglomeratic successions in the GMF may be accentuated, or alternatively, wholly caused by fold interference. Their similar dimensions and similar bounding and fill lithologies to those in the Upper Cretaceous of Baja California, however, lend credence to a sublacustrine (or marine) channel origin.

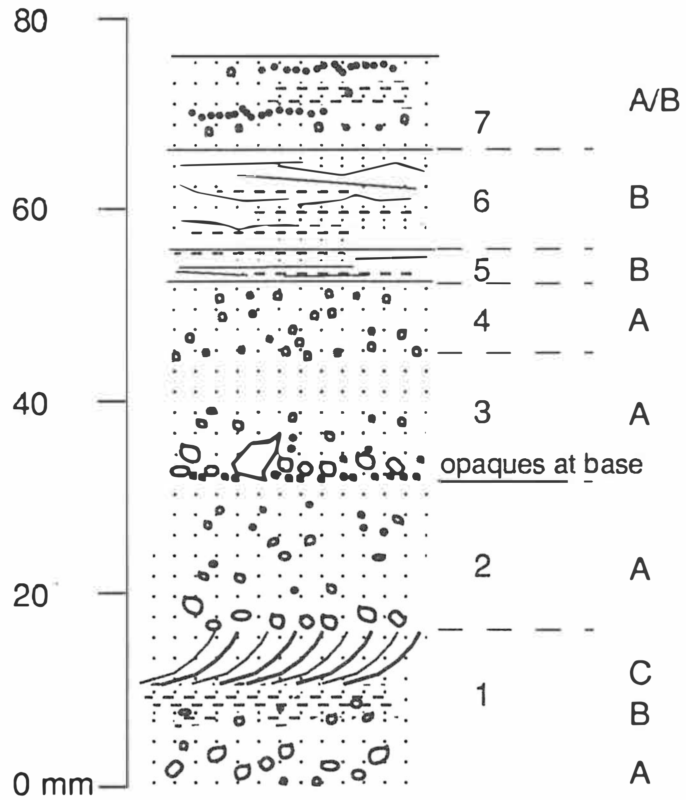

Figure 3-7. Drawing of thin-section (1018-PB-20) from 51 m level of Locality 2c. Seven laminasets and interpreted Bouma (1962) divisions are denoted. Ripple cross-laminae produced by traction current are 8 mm thick and are defined by higher quartz silt content and concentration of opaque minerals along base and foresets. Parallel laminae defined by lack of sand and higher clay content. Lowest three laminasets are normally graded.

TABLE 3-2. COMPARISON OF MAP-SCALE CONGLOMERATE BODIES OF THE GMF (POPLAR GROVE CONGLOMERATE) TO YOUNGER ROCKS DEPOSITED IN THE SAN CARLOS SUBMARINE CANYON, BAJA CALIFORNIA

channel width (km)	channel depth (km)	
1.3	0.2	Three conglomerate-filled channels surrounded by turbiditic mudstone and sandstone within San Carlos submarine canyon
2.0	0.5	
3.0	0.7	
San Carlos submarine canyon (Upper K)		
6 - 9	2.5	Morris and others (1989)
Poplar Grove conglomerate map-scale "arkose" (Zga) pods		Bryant and Reed (1970b)
0.6	0.1	Locality 2b (Poplar Grove)
0.4	0.1	
		GMA axis →
1.1	0.2	Locality 2c (Payne Branch)
1.3	0.4	
0.5	0.3	
0.9	0.1	

Snakeden Ridge conglomerate

The Snakeden Ridge conglomerate (Localities 3a-3e) caps a 1000 m-thick, coarsening-upward basin-fill sequence (Neton, Part 2). It is named for Snakeden Ridge (north of Foscoe, NC), along which it is best exposed. It is composed of Facies Associations D, B, and C, and undergoes a transition from dominantly Facies Association D in the northeast to dominantly Facies Association C in the southwest (Fig. 3-8) It is underlain by Facies Association A, especially notable around Seven Devils, NC where laminite of Facies Sln and Flm crop out, and Facies Association B just below Locality 3d. The Snakeden Ridge conglomerate is overlain by siltstone of Facies Association B (Fig. 3-8).

Beds of Facies Gms (i,u) at localities 3a and 3bc lack significant mud matrix and locally are clast-supported near bed tops. Support of cobbles and boulders, therefore was largely by interclast dispersive pressure in lieu of significant support from matrix strength or density (Naylor, 1980). These sandy, sediment gravity flows are interpreted as subaerial density-modified grain flows (Lowe, 1976a) deposited in the mid to upper alluvial fan region. Facies Smh and thin horizons of cobbly Gcsu are sharply interstratified near the top of Locality 3bc and record liquefied sediment flow processes (sheetflood and sieve deposition) in the midfan area (Fig. 3-8). Debris flows at the base of Locality 3bc contain a higher mud content, providing more buoyant support and lubrication for pebbles and cobbles, therefore allowing the debris flow to travel further downfan before freezing (Rodine and Johnson, 1976) in the midfan area, instead of in the upper fan. Despite containing more mud, these debris flows were probably of high volume or were particularly liquid and possibly had a higher water content together with the mud. It is evident that the areal extent of a debris flow is limited by its volume, viscosity, and yield strength and the slope of the fan surface (Hooke, 1967). Thin, reddish-purple horizons of Facies Flm-Sr directly overlying debris flows are interpreted as surges of mudflow/sheetflood following the debris flow during waning stages of the depositional event. As flow velocity declined into the lower flow

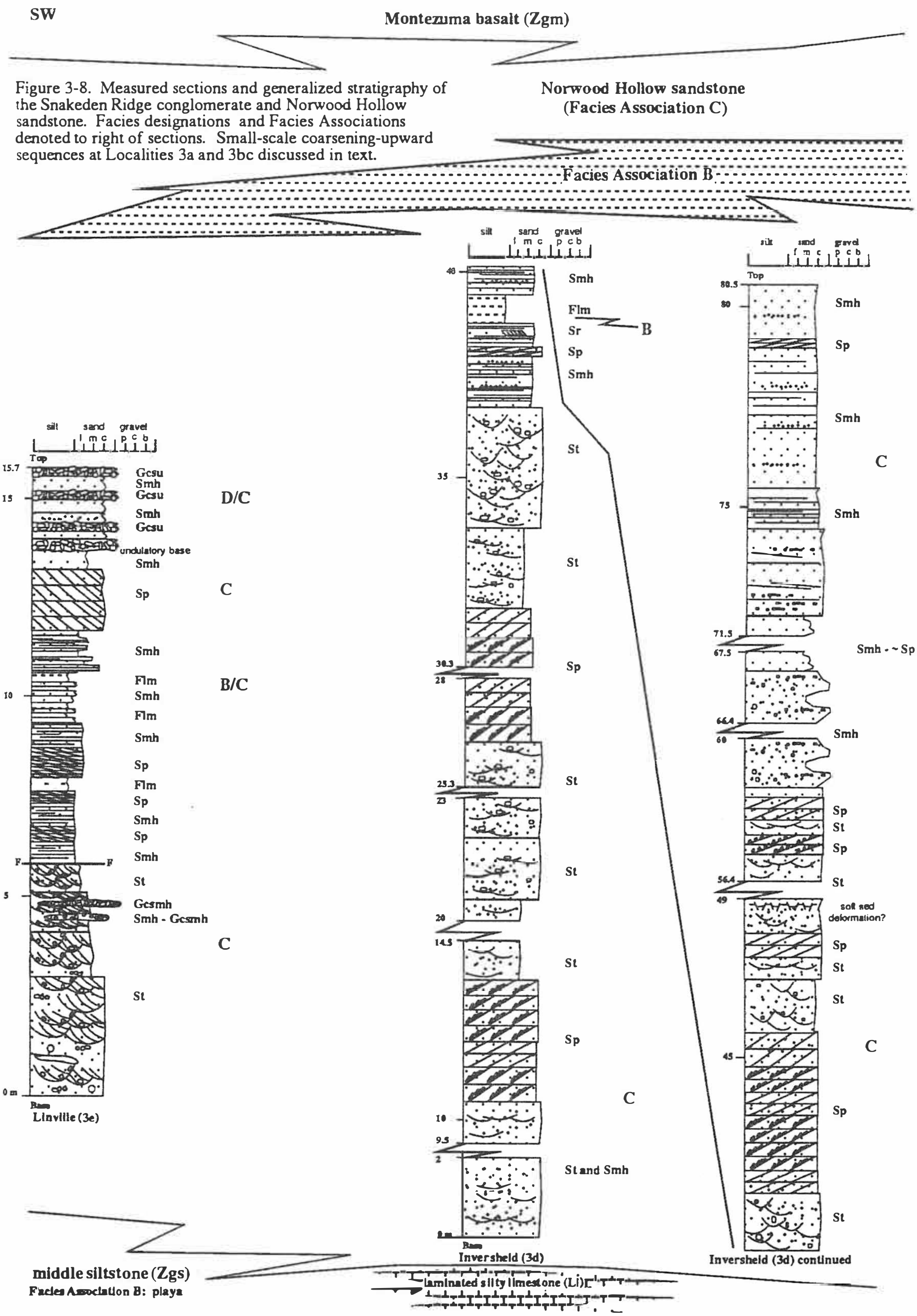

Figure 3-8. Measured sections and generalized stratigraphy of the Snakeden Ridge conglomerate and Norwood Hollow sandstone. Facies designations and Facies Associations denoted to right of sections. Small-scale coarsening-upward sequences at Localities 3a and 3bc discussed in text.

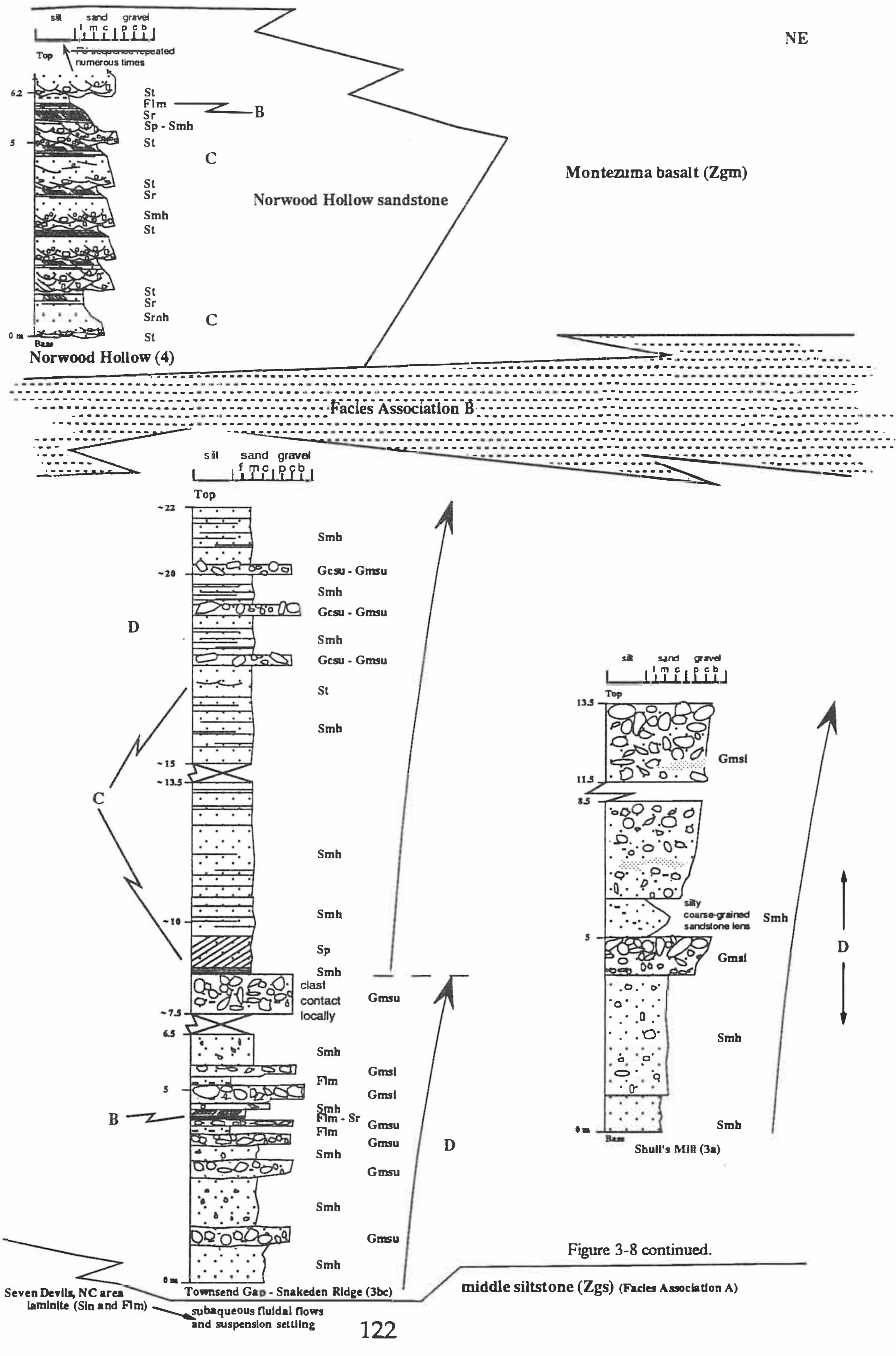

Figure 3-8 continued.

regime, the red mudflow was reworked into ripples (for example, Nemec and Steel, 1984; Bøe and Sturt, 1991). A 70 cm thick bed of Facies Sp overlies Facies Gmsu and represents the migration of a transverse bar or large 2-D dune possibly in the fanhead trench following deposition of a density modified grain flow or debris flow.

Further southwest, at Locality 3d, deposition of Facies Flm on top of crude fining-upward sequences indicates overbank deposition in an abandoned channel on a braidplain traversed by shallow channels separated by transverse bars. Thick successions of Facies Smh containing granule and pebble stringers near the top of Locality 3d indicate prolonged maintenance of upper flow-regime conditions on the braidplain, creating upper plane-bed lamination and one-pebble-thick, shifting sand and gravel sheets (Hein and Walker, 1977). The sheets never developed into longitudinal bars (Facies Gcsmh) due to the paucity of coarse gravel too large to be transported. Large clasts which are stable on the bed give rise to flow velocity shadows, which initiate aggradation (Leopold and Wolman, 1957). Alternatively, the thick Smh successions may represent thin, stacked sheetflood deposits created by remobilization of sediment by intense rains on the mid to lower alluvial fan surface, then redistributed downfan as a broad sheet (Wasson, 1977) or as a thin, fine-grained, downgradient equivalent of an upgradient gravelly sheetflood responsible for sieve lobe deposition (Hooke, 1967; Bull, 1972) that was fluid enough to undergo transport onto the braidplain. Most probably these Smh successions represent a combination of these processes. Four, thin pebbly, Gcsu beds intetercalated with Facies Smh at the top of Locality 3e (Fig. 3-8) are more probable sheetflood deposits. The lowest is underlain by an undulatory base (1-2 cm relief) indicating scouring as the turbulent sheet of gravelly flood water (Hogg, 1982) moved downfan onto the braidplain.

Facies Association C within the Snakeden Ridge conglomerate lacks the clast-supported conglomerate of Facies Gcsmh, indicating that longitudinal gravel bars were not present on the lower alluvial fan/braidplain. Commonly, however, outsized cobbles (purple felsite, white (vein?) quartz, and granite) are enveloped by sand at mid trough depth or isolated in sandy Smh beds.

The largest clast at Locality 3e measures 21.0 x 6.7 cm. Average maximum clast size at Locality 3e is 8.0 x 4.5 cm. A clast with intermediate diameter of 7 cm would have required a minimum flow velocity of between 82.3 cm/s (Owens, 1908) and 130 cm/s (Peterka and others, 1956) for initial movement over a sand bottom. Flow velocities on the Snakeden Ridge fan, therefore, were adequate to transport large quantities of coarse gravel. The coarse gravel, however, was not supplied to the lower fan/braidplain area due to in-situ weathering of the dominantly crystalline basement source terrain into its constituent minerals. The clast population of the proximal outcrops (Localities 3a, 3bc) contains subequal amounts of crystalline basement, metaquartzite/sandstone and purple felsite (Neton, Part 2). Rapid, in-situ and on-fan weathering and abrasion of crystalline basement and sandstone clasts supplied large quantities of sand- and granule-sized debris, with lesser amounts of fine gravel. The general lack of gravel favored formation of diffuse sand and gravel sheets (Leopold and Wolman, 1957; Hein and Walker, 1977) under upper flow regime conditions (Facies Smh) and sandflat complexes (Cant and Walker, 1978) under lower flow regime conditions (Facies St, Sp, Smh, Sr).

Mid to upper alluvial fan environments at Localities 3a-3bc overlie (but not directly) laminated siltstone and sandstone (Facies Flm and Sln) of Facies Association A (Fig. 3-8; middle siltstone) above the Poplar Grove conglomerate, and are interpreted as distal fan-delta deposits that accumulated in a relatively deep water body. Further southwest at Locality 3d, lower alluvial fan to braidplain strata directly overlie laminated, silty limestone (Facies Ll; Fig. 3-8). This relationship suggests that the laminated limestone represents playa-deposited carbonate and perhaps evaporite covered by progradation of a low-gradient braidplain containing transverse bars and sandflat complexes separated by channels.

The Snakeden Ridge conglomerate best documents the alluvial fan to braidplain transition. The Snakeden Ridge fan prograded across deeper water environments following faulting, after Poplar Grove depositional time. Eventually the water body was filled or its level was lowered and the area became a playa (Locality 3d). Once basin-margin subsidence slowed and accomodation space was filled, the fan then prograded over the distal playa environment during relatively tectonically quiescent times. The Snakeden Ridge conglomerate therefore documents the progradation of a sandy, broad, low-gradient fan-delta (usage of McPherson and others, 1987) dominated by sheetflood and braided river processes, and is in distinct contrast to steep, smaller-radii, muddy, debris flow-dominated fans documented by Harvey (1984). The fan-delta prograded from the basin margin forming a 1000 m-thick, coarsening-upward, basin-fill sequence. This pattern (coarsening-upward after a major faulting event or cluster of events) corroborates the tectonic and basin-filling model of Blair (1987) and Blair and Bilodeau (1988).

Norwood Hollow sandstone

Following Snakeden Ridge depositional time the fan-delta was covered by a thin, strike continuous siltstone of Facies Association B deposited in a playa or shallow perennial lake (Fig. 3-8), requiring either lake level to rise or subsidence of the fan-delta to occur due to basin margin faulting (for example, Waresback and Turbeville, 1990). The Norwood Hollow sandstone, named for exposures along NC Highway 184 in Norwood Hollow, subsequently prograded over the siltstone and consists of thin (approximately 1m thick) fining-upward sequences described by the following facies transitions: scoured base → St (commonly pebbly sandstone) → Smh → Sr → Flm (Fig. 3-8). The Norwood Hollow sandstone represents deposition on a low-gradient braidplain consisting of broad, shallow shifting channels in either very distal alluvial fan environments or more likely as a longitudinal braidplain in a rift-axial position, with depositional strike perpendicular to that of rift-bordering alluvial fans.

Banner Elk conglomerate

The Banner Elk conglomerate (Localities 5a-5d) is within a 2250 m coarsening-upward basin-fill sequence deposited following rifting and extrusion of the Montezuma basalt. It is best exposed along the crest of Horse Bottom Ridge northeast of Banner Elk, NC and is named for exposures (Localities 5b and 5c), on and near NC Highway 184, in the town of Banner Elk. The conglomerate fines from cobble to small pebble-sized, from northeast (Locality 5a) to southwest (Locality 5d). It is composed of Facies Association C, with very minor lenses of Facies Association B of overbank type (Figs. 3-3b and 3-9). Unlike the Fall Hollow conglomerate and the Snakeden Ridge conglomerate, the Banner Elk conglomerate lacks debris flows or sieve deposits of Facies Association D, even in the coarsest (that is, most proximal) locality (5a). Facies Gt and Gp are absent. There is also a general paucity of Facies St and Sp. Small-scale Facies St is poorly developed as uncommon, undulose, purple laminae and wisps within Facies Smh. Facies Sp is only well developed at the top of Locality 5c. Facies Gcsmh and lenses and thick successions of Facies Smh are predominant (Figs. 3-3c and 3-9).

Locality 5d contains a 15 cm thick, climbing ripple-laminated (Facies Sr) maroon siltstone lens (Facies Flm) of Facies Association B. Amplitudes of the ripple cross-strata are 1 cm and they are interlaminated with sand and granule stringers. The lens is wholly contained within Facies Smh and was deposited by high sediment concentration flood waters moving into abandoned channel areas or overbank areas (bartops in abandoned channels), thereby losing competence and depositing suspended sediment (Williams and Rust, 1969; Bluck, 1979; Smith, 1985)

Hydrodynamics. The predominance of Facies Gcsmh and Smh (with minor Sp) in the Banner Elk conglomerate suggests that migrating longitudinal bars, diffuse sand and gravel sheets (Leopold and Wolman, 1957; Hein and Walker, 1977) and transverse bars were the dominant sediment storage bodies, and that most sediment transport occurred within the upper flow regime. The largest clast measured within the Banner Elk conglomerate is a purple cross-stratified quartzite cobble (Locality 5a) with dimensions of 19.5 x 14 x 8.5 cm. To initiate movement of this cobble along its intermediate axis would require a flow velocity of between approximately 183 cm/s (Peterka and others, 1956) and 238 cm/s over a gravel bottom`(Gilbert, 1914). Following the

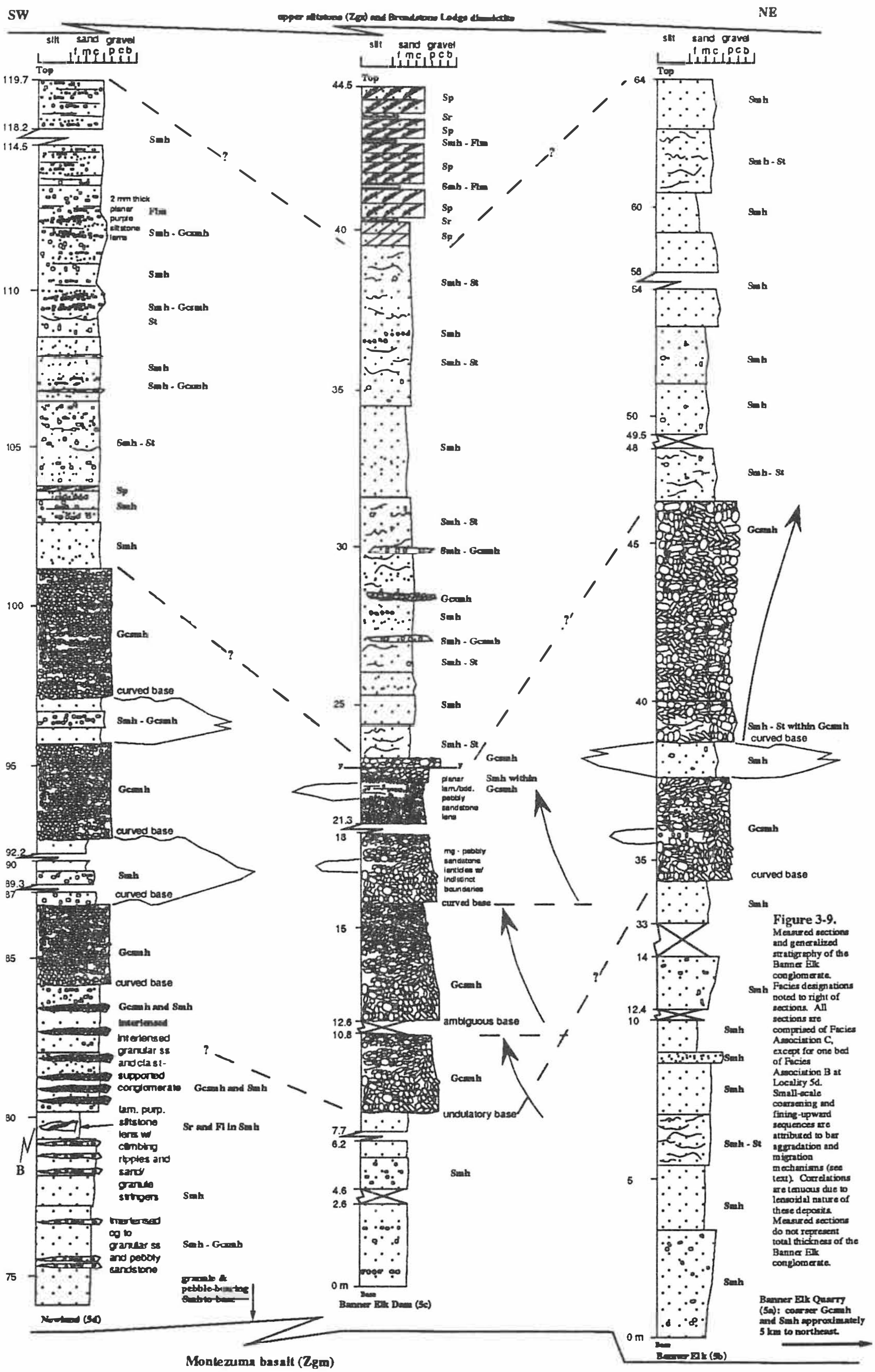

Figure 3-9. Measured sections and generalized stratigraphy of the Banner Elk conglomerate. Facies designations noted to right of sections. All sections are comprised of Facies Association C, except for one bed of Facies Association B at Locality 5d. Small-scale coarsening and fining-upward sequences are attributed to bar aggradation and migration mechanisms (see text). Correlations are tenuous due to lensoidal nature of these deposits. Measured sections do not represent total thickness of the Banner Elk conglomerate.

"rule of thumb" of Smith (1985), flow depth responsible for deposition of the Banner Elk conglomerate probably did not exceed 1.4 m because Facies Gp and Gt are absent.

Longitudinal bar sequences. Locality 5b contains a 7 m-thick, coarsening-upward sequence of pebble to small-cobble Gcsmh with a broadly curved base. Boothroyd and Ashley (1975) observed that pebbles and cobbles accrete in a clast-by-clast fashion on the bar top and that the coarsest clasts are concentrated on the central bar axis, with clast size decreasing downbar. Hein and Walker (1977) attributed coarsening-upward longitudinal bar sequences to downstream migration of the bar form causing coarser upbar gravel to migrate over finer downbar gravel. The curved base of the sequence above Facies Smh represents the base of the compound channel over which numerous longitudinal bars migrated at any one time, forming smaller-scale channels between bars (Williams and Rust, 1969). These surfaces represent fourth or fifth-order bounding surfaces of Miall (1988).

In contrast, nearby Locality 5c contains three stacked, fining-upward sequences of pebbly Gcsmh (Fig. 3-9). These have been found to arise as high energy flood surge wanes, promoting aggradation of progressively smaller pebbles on the bar top. Thin, discontinuous sandstone lenses within Facies Gcsmh were deposited as flow competency over the bar top further decreased. The stacked nature and undulose bases may reflect three successive flood events, each flood being lower in magnitude than the previous (Rust, 1972: Miall, 1977). Abrupt lateral changes from facies Gcsmh to Smh at Locality 5c indicate scouring along bar margins, and formation of up to a meter of near vertical relief similar to that documented by D.G. Smith (1973) and N.D. Smith (1985).

The close proximity (0.2 km) of Localities 5b and 5c and their apparently correlative relationship (Fig. 3-9) reveal that coarsening-upward and fining-upward sequences formed on the braidplain at approximately the same time. This apparent hydrodynamic paradox (that is, stable or increasing flow competence occurred at Locality 5b while at the same time, repeated decreases and surging of flow competence occurred 200 m away at Locality 5c) can be explained by a combination of two mechanisms. Firstly, the paradoxical sequences may have been deposited in different/adjacent compound channels that alternately became constricted, blocked or opened as coarse gravel migrated possibly during one flood event. The channel at Locality 5c may have been partially blocked by an upriver longitudinal or transverse bar three times causing discharge and competency to decrease, then rise again, forming the fining-upward sequences. Secondly, the two longitudinal bar sequences may also have been deposited during different flood events, at which time one of the channels was completely inactive (preserving a previous flood event) and the other underwent bar migration and reworking of the previously deposited sequence. These differences in nearby, apparently correlative sequences serve to elucidate the process heterogeneity inherent in braidplain deposition.

Braidplain style. The lack of Facies Association D suggests that the Banner Elk conglomerate may have been deposited as a coarse-grained braidplain that was not directly linked to upgradient alluvial fans, and possibly on a proglacial braidplain similar to that developed on the southern coast of Alaska (for example, Boothroyd and Ashley, 1975). Glaciation occurred during Late Proterozoic time approximately 20 km to the northeast in the Mount Rogers basin (Blondeau and Lowe,1972; Schwab, 1976; Miller, 1986) and glaciation is also possibly recorded in the upper siltstone of the GMF (see ahead); therefore, a proglacial braidplain origin is not precluded. Three distinctive features of glacial outwash plains are: 1) debris flows containing till (very proximal), 2) reworked till balls within downgradient fluvial sequences, and 3) very large-scale Gt and Gp (commonly up to 5 m thick; Smith, 1985) deposited by glacial lake burst floods (jokulhlaups). These three features are arranged in most common occurrence, proximally to distally. Boothroyd and Nummedal (1978) and Smith (1985) suggested that occurrence of Facies Gt and Gp may be characteristic of glacial outwash streams and Smith (1985) further suggested that thinner Gt and Gp (decimeter-scale) may represent more distal jokulhlaups. Till balls are absent in the Banner Elk conglomerate, as are debris-flow deposits. The Banner Elk conglomerate therefore does not represent a proximal outwash plain. Furthermore, the complete absence of Facies Gt and Gp of any scale argues against occurrence of very deep flows or jokulhlaups. This evidence discredits a proglacial origin for the Banner Elk conglomerate. It is instead more simply interpreted as having been deposited in the mid to lower reaches of an alluvial fan that was dominated by streamflow processes The lack of debris flows (lack of mud produced in the sourceland) is due to derivation from a source terrain dominated by purple felsite, white (vein?) quartz, metaquartzite and chert. These rocks do not weather to form significant amounts of mud (Bull, 1972, 1977). The southwestward-fining suggests that the felsite-dominated alluvial fan/braidplain system may have been derived from the northeast and prograded to the southwest over the Montezuma basalt (see discussion in Part 2).

Broadstone Lodge diamictite

Laminite and diamictite of the upper siltstone unit overlie sandstone of the Banner Elk conglomerate and Montezuma basalt in gradational to abrupt fashion. The Broadstone Lodge diamictite is named for an exposure (Locality 6a) near the Broadstone Lodge, along NC Highway 1112, just south of the town of Valle Crucis. It occurs within laminite and fines toward the center of its 27 km outcrop belt (Part 2). It is composed of Facies Association A. Facies Gms is either ungraded or rarely, normally-graded (Fig. 3-10). Matrix of Facies D and Gms is mudstone to sandy mudstone as compared to the sandier matrices of these facies in the Poplar Grove and Snakeden Ridge conglomerates. Many clasts within Facies D and Gms are very angular. At and around localities 6a, 6b and 6c the following sedimentary structures are particularly evident: millimeter-scale laminae, loads, flames, ball-and-pillow, millimeter- to centimeter-scale soft sediment normal faults, upcurled/detached laminae and slumps (Fig. 3-3a), as well as outsized clasts. No outsized clasts can be documented as truncating thinly laminated mudstone. A basalt

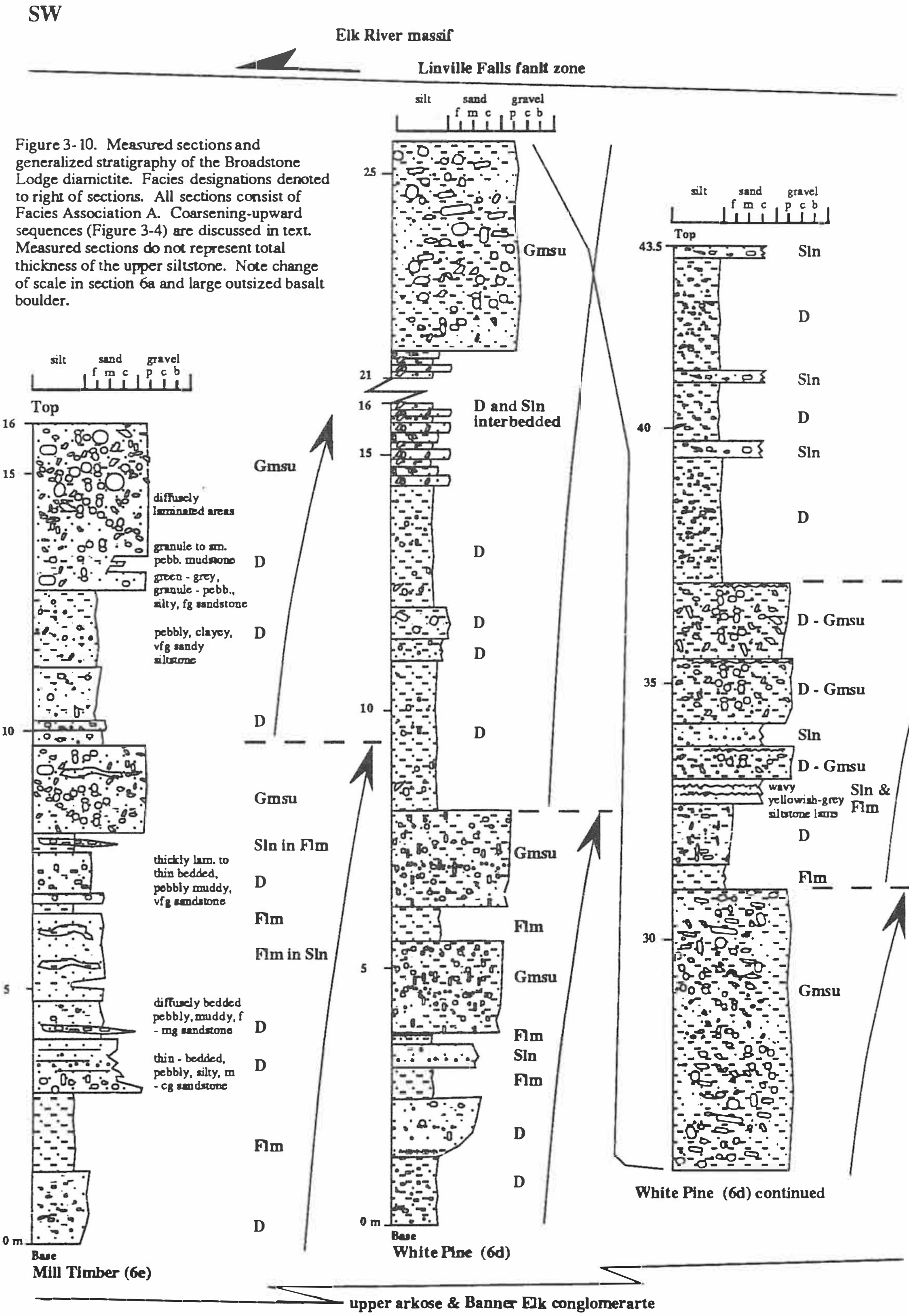

Figure 3-10. Measured sections and generalized stratigraphy of the Broadstone Lodge diamictite. Facies designations denoted to right of sections. All sections consist of Facies Association A. Coarsening-upward sequences (Figure 3-4) are discussed in text. Measured sections do not represent total thickness of the upper siltstone. Note change of scale in section 6a and large outsized basalt boulder.

NE

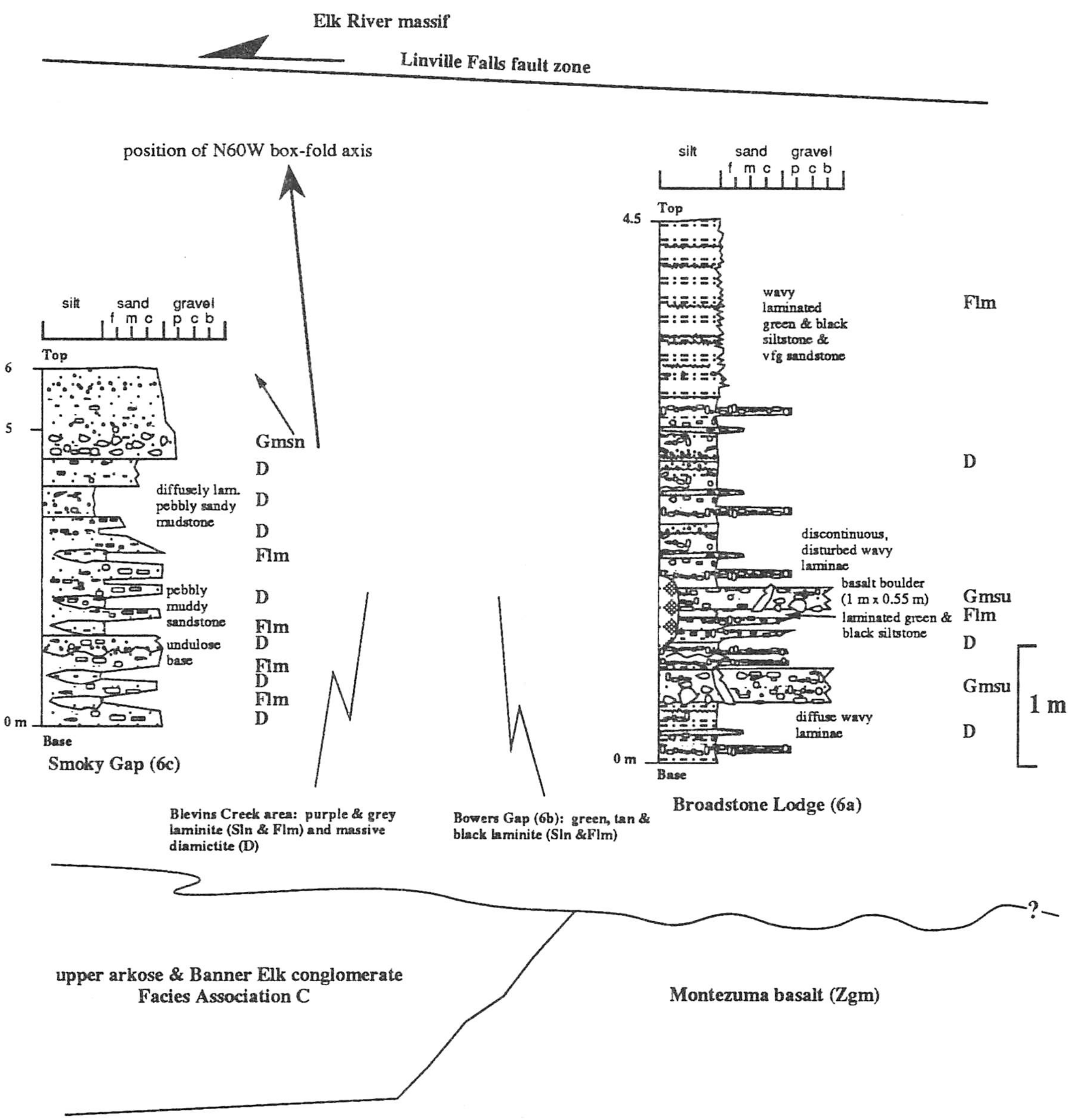

Figure 3-10 continued.

boulder (1 m x 0.55 m) at Locality 6a appears to truncate centimeter- to decimeter-scale diamictite beds (Fig. 3-10). Boyer (1978) documented a large crystalline basement boulder encased in massive, weathered siltstone (Fig. 3-3f) just north of Locality 6c (near Blevins Creek church). Upon detailed inspection of this locality, other pebbles and cobbles were discovered (Boyer's boulder has since been eroded away) encased in a very cryptic and diffusely-bedded matrix of sandy, granule-bearing mudstone. Distinct millimeter to centimeter-scale laminae are not present at this outcrop and bed contacts are generally indiscernable.

Three interpretations are possible for the deposition of these outsized clasts: 1) the boulders are dropstones derived from the melting of debris-laden, floating glaciers or icebergs, 2) the boulders were able to be supported by a relatively thin, muddy, subaqueous debris flow or fluidal flow and after deposition, depending upon matrix strength, either protruded above the sediment-water interface to be covered by succeeding beds, or 3) may have foundered into the underlying soupy substrate. All three processes would produce apparent or actual deformation or truncation of surrounding beds. It is very difficult to substantiate the existence of a dropstone when it is encased in immature diamictite instead of laminite in which laminae are truncated or deformed by the clast (see Harland and others, 1966; Thomas and Connell, 1985). Within the Broadstone Lodge diamictite no unambiguous dropstones have been discovered, although, outsized clasts are prevalent (compare to Schwab, 1981; Rankin and others, 1989).

The extreme angularity of some clasts in the Broadstone Lodge diamictite (for example, Fig. 3-3f) is *permissive evidence* for glacial derivation (basal zone to supraglacial transport entirely) allowing for no fluvial abrasion. Sub-glacial planing can also create extremely angular, striated clasts (for example, Anderson, 1989), however, striations on clasts have never been documented in the GMF. Extremely angular clasts can also be produced as blocks from rockfalls into lake or marine mud which are then transported by debris flows into the basin. The lack of unambiguous dropstones in the Broadstone Lodge diamictite argues against direct glacial influence. Unambiguous dropstones and other glacial features have been documented, however, in the uppermost member of the nearby Mount Rogers Formation (Upper Proterozoic) of southwestern Virginia (Blondeau and Lowe, 1972; Schwab, 1976; Miller, 1986).

From the above discussion, the upper siltstone unit is interpreted as having been deposited in a relatively deep lake or marine basin by suspension settling processes, with fluidal flows and debris flows periodically moving downslope and onto the basin floor. The water body may have formed due to rifting and extrusion of the underlying Montezuma basalt The basalt flows may have dammed rift-axial drainage, thereby creating a lake (for example, Waresback and Turbeville, 1990). Additional water may have been added to the lake from springs emanating from uplifted rift shoulders (for example, Blair, 1987; Blair and Bilodeau, 1988), from thermal bottom springs (for example, Shanks and Callender, 1992), one source of which is volcanic vents, or from glacial meltwater.

The fining from northeast *and* southwest pattern of the Broadstone Lodge diamictite (Neton, Part 2) is interpreted as representing two non-coalescent fan-deltas. Finer-grained laminite and thin grain flows dominate the sequence between the fan-delta loci, which were centered approximately at Localities 6a and 6e.

The lack of channels, however, and the sheet-like, flat-based to massive nature of Facies Sln, D and Gms in the Broadstone Lodge diamictite, as well as the strike continuous nature of the upper siltstone, suggest that the two fan-deltas were deposited on a steep delta-front slope upon which lobe-building channels were not well developed. Wehr (1983) and Porebski (1984) documented similar environments in the Devonian of Poland and the Late Proterozoic (Lynchburg Group) of Virginia, respectively. Due to their unchannelized nature, the mass flows, therefore, spread out to cover large areas of the slope and basin floor. The inferred steep slope which was backed by a high-relief coastal mountain range (rift flank) resulted in deposition of gravel into far deeper water and limited wave and tidal reworking areas to very narrow nearshore zones not often preserved and difficult to define (for example, Stanley, 1980; Wehr, 1983; Porebski, 1984). Evidence for the narrow shorezone as well as upgradient steep alluvial fans was not observed in the upper siltstone unit. The lower contact with the underlying upper arkose and Banner Elk conglomerate is loosely interpreted as an onlapping, retrogradational contact. It is speculated that as the basin continued to subside and a high rift flank/hanging wall developed to the northwest, lake or marine sediment (laminite and conglomerate) covered the lower alluvial fan/braidplain environments which had prograded southwestward from an accomodation zone area between the Grandfather Mountain and Mount Rogers basins (Fig. 3-11).

SMALL-SCALE COARSENING- AND FINING-UPWARD SEQUENCES

Three of the five conglomerate bodies contain small-scale coarsening-upward sequences and one contains a fining-upward sequence (m to 10's m thick; usage of Heward, 1978). These sequences are internal to megasequences and basin-fill sequences (100's to 1000's m thick) and are non-tectonic in origin, or are due to very localized faulting events which cause small-scale facies migration (Steel and others, 1977; Wilson, 1980). The small-scale coarsening-upward sequences within the Snakeden Ridge conglomerate (8 to 13.5 m thick; Fig. 3-8) probably represent progradation of coarse debris on the active portion of an alluvial fan possibly due to a localized faulting event on the basin margin (Steel and others, 1977; Bøe and Sturt, 1991). Alternatively, they may represent rapid abandonment/avulsion of the active channel due to trench filling and plugging by a debris flow or thick sieve deposit (for example, Hooke, 1967). The coarsening-upward sequences within the subaqueously-deposited Poplar Grove conglomerate (5 to 20 m thick; Figs. 3-4 and 3-6) and the subaqueously-deposited Broadstone Lodge diamictite (6 to 23 m thick; Figs. 3-4 and 3-10) may represent similar processes to the above, that of progradation of fan-delta lobes (Mutti, 1977) possibly (for the Poplar Grove conglomerate) within large-scale subaqueous channels.

The one small-scale fining-upward sequence at Locality 2a (27 m thick; Fig. 3-6) may represent gradual lobe or channel abandonment (Mutti, 1977) on a subaqueous fan/fan-delta or

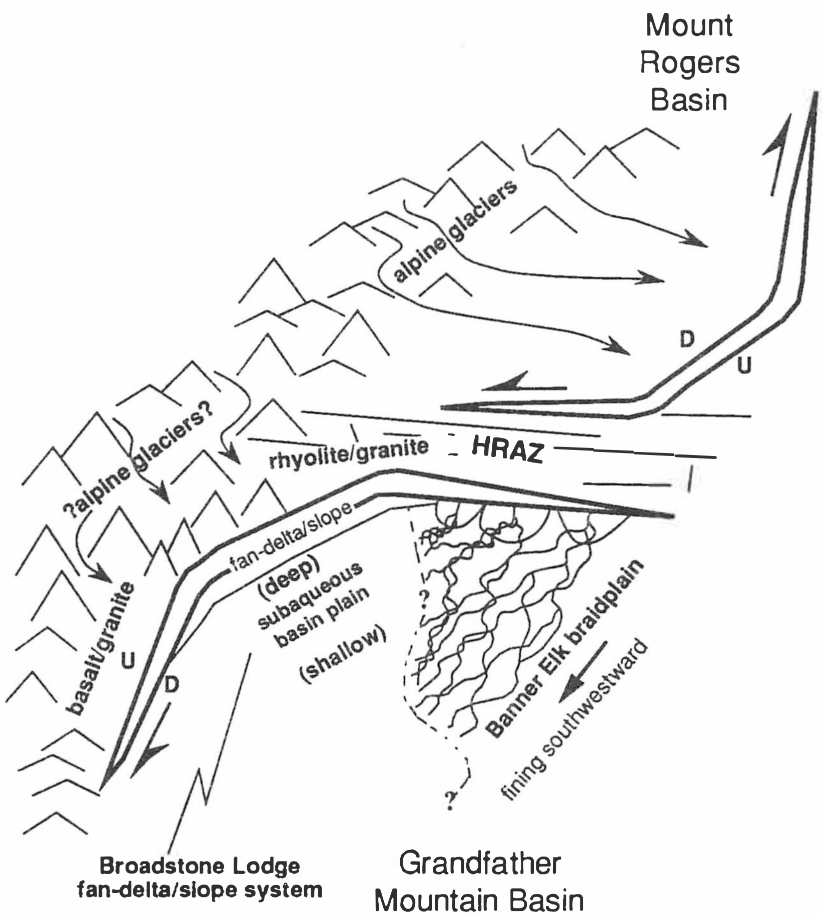

Figure 3-11. Speculative paleogeography of Grandfather Mountain and Mount Rogers basin(s) during Banner Elk - Broadstone Lodge depositional time. HRAZ = high relief accomodation zone. May also be a low relief accomodation zone. U = up, D = down; relative fault motion.

proximal to distal trends of turbidity currents in a large subaqueous channel just down gradient from a slope apron, along a basin margin fault scarp.

DISCUSSION

Table 3-3 summarizes relationships previously discussed.

The lack of any definite glacial features in the Banner Elk conglomerate or in either of the two siltstone units and their included conglomerate/diamictite suggests that glaciation either did not occur in or near the Grandfather Mountain basin, or that during upper siltstone (Broadstone Lodge diamictite) time alpine glaciers could have been present in the highlands to the northwest *but never advanced into or near* the basin proper (Fig. 3-9). The sediment preserved in the two fan-deltas then would represent immature debris derived from meltwater of these high mountain glaciers. In contrast, alpine glaciers did advance into the Mount Rogers basin. Well-preserved glacial features are present (including unambiguous dropstones) within the uppermost member of the MRF (Blondeau and Lowe, 1972; Schwab, 1976; Miller, 1986). Still further northeast (Wehr, 1986) documented unambiguous dropstones and other glacial deposits in the broadly correlative Rockfish Conglomerate. To the southwest of the GMF, Lowe (1980) suggested that much of the sandstone of the Great Smoky Group of the Ocoee Supergroup may be of proglacial origin.

The GMF basin definitely contained extensive deep, subaqueous environments as documented above. It is not clear, however, whether the basin was dominated by deep freshwater lakes such as those in the east African rift system and Lake Baikal, Russia or by marine waters possibly in a large embayment or inland sea. Perhaps detailed facies analysis and geochemical studies of GMF siltstone units will address this problem.

TABLE 3-3. CLAST SIZE, LATERAL FACIES ASSOCIATIONS AND INTERPRETED DEPOSITIONAL ENVIRONMENTS FROM FACIES ANALYSIS OF SIX DISTINCT CONGLOMERATE/SANDSTONE UNITS OF THE GMF.

Conglomerate Body	Lateral Clast Size Chars.	SW Facies Associations NE	Depositional Environment
Broadstone Lodge diamictite	**fining toward center of outcrop pattern**	**A**	debris flows on subaqueous slope (fan-deltas) of deep water body (?lake?) ?proglacial ice rafting?
Banner Elk conglomerate	**fining to SW**	**(minor B) C**	mid to lower alluvial fan or ?glacial outwash plain?
Norwood Hollow sandstone	**?**	**B C**	low gradient braidplain
Snakeden Ridge conglomerate	**fining to SW**	**C D (C,B) D B - - - - A**	mid/upper alluvial fan/fan-delta/deep laketo braidplain/playa lake
Poplar Grove conglomerate	**fining to SW?**	**A**	fan-delta/subaqueous channel
Fall Hollow conglomerate	**fining to SW**	**C B D**	water flow dominated mid/upper to lower alluvial fan and between-fan pond

CONCLUSIONS

1) The Grandfather Mountain Formation was deposited in a wide range of fluvial and lacustrine or marine environments whose interplay created discontinuous and heterogeneous facies relationships.

2) Alluvial fan, fan-delta and braidplain environments alternated with deeper water and playa environments in occupying the basin margins, largely in response to basin-margin faulting events, but probably also in response to volcanic events as well as changes in climate and ground- and surface-water flow paths.

3) Source regions were dominantly underlain by purple felsic volcanic rocks, granitic crystalline basement, and metaquartzite/sandstone as well as lesser amounts of basalt and siltstone.

4) Alluvial fans and subaerial portions of fan-deltas were dominated by gravelly fluidal flows (density-modified grain flows, sieve lobes and sheetfloods), as well as braided river processes, primarily due to the lack of mud-producing lithologies in source regions. The alluvial fan/fan-delta to braidplain transition is best preserved in the Snakeden Ridge conglomerate.

5) Alluvial fans and fan-deltas were generally very broad with relatively low gradients, due primarily to the lack of cohesive, mud-rich debris flows.

6) Subaqueous portions of fan-deltas, slopes, and large-scale subaqueous channels were dominated by sandy-matrix, density-modified grain flows, and high-and low-density turbidity currents (Poplar Grove conglomerate), as well as by muddy debris flows (Broadstone Lodge diamictite).

7) It is unclear whether deep water environments were lacustrine or marine. Possibly both were present at different times in the Grandfather Mountain basin.

8) Direct glacial deposition in the Grandfather Mountain basin did not occur. Proglacial environments (outwash plains, glacio-lacustrine/marine) may have existed, but evidence is ambiguous at best. The deposits in question are explained more simply as lower alluvial fan-

braidplain (Banner Elk conglomerate) and broad, subaqueous slope (Broadstone Lodge diamictite), respectively.

ACKNOWLEDGMENTS

Grants supporting field work for this research were from the University of Tennessee-Knoxville Department of Geological Sciences Professors Honor Fund, North Carolina Geological Survey, Geological Society of America - Southeastern Section, and the American Society of Petroleum Geologists. Informal discussions, in the field and otherwise, with Dan Walker (Kentucky Geological Survey), J. M. G. Miller (Vanderbilt University), L. Raymond (Appalachian State University), S. E. Boyer (University of Washington - Seattle), Ed Simpson (Kutztown State University) and UT colleague Joachim Dorsch were instrumental in the formulation of many of the above stated ideas. Colleagues from the UT - Tennessee Valley Authority Groundwater and Fluvial Deposits Research Group (Steven C. Young, Joachim Dorsch, and Chris Olson) are thanked for their varied insights concerning fluvial facies relationships. R. D. Hatcher, Jr. (University of Tennessee) is acknowledged for use of his Macintosh™ computer facilities. J. Berry (University of Tennessee) is thanked for his assistance and rapelling gear during investigation of the Fall Hollow and Snakeden Ridge conglomerates.

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4. Overall Conclusions and Suggestions for Further Research

CONCLUSIONS

1) The Grandfather Mountain Fonnation was deposited in a wide range of fluvial and lacustrine or marine environments whose interplay created discontinuous and heterogeneous facies relationships.

2) Alluvial fan, fan-delta and braidplain environments alternated with deeper water and playa environments in occupying the basin margins, largely in response to basin-margin faulting events, but probably also in response to volcanic events as well as changes in climate and ground- and surface-water flow paths.

3) GMF conglomerate units were deposited in alluvial fan, fan-delta/subaqueous slope, and braidplain environments which prograded basinward over braidplain, playa lake and deep lake/marine environments.

4) Five conglomerate/diamictite units and one pebbly sandstone unit cap five coarsening-upward basin-fill sequences averaging 1300 m thick.

5) Three of the five conglomerate units unambiguously fine toward the southwest. Southwest-fining along strike suggests derivation from a sourceland to the NE (?low-relief or high-relief accomodation zone?) or a higher sediment supply in the northern half of the basin, that ultimately produced more extensive, coarse-grained, northwest-to-southeast progradation than in the southern half of the basin.

6) GMF conglomerate is strikingly polymictic, but is dominated by greenish purple to black felsite and greyish black basalt clasts, NOT by crystalline basement clasts.

7) The rift shoulders in the northern half of the Grandfather Mountain basin were dominated by rhyolitic volcanic lithologies as well as by crystalline and sedimentary rocks, whereas the rift shoulders in the southern half of the basin were dominated by crystalline basement rocks, until Broadstone Lodge diamictite time when a basaltic terrane was exposed.

8) Basin history/unroofing sequence. Five major rifting events or clusters of rifting events created relief which eventually produced five coarsening-upward sequences.

1) Rifting - extrusion of outlier rhyolite and basalt (Zgfo)

Unroofing of rhyolite/felsite terrane (quartz and perthite porphyritic)

2) Rifting - extrusion of basalt (Zgvm)

Unroofing of sedimentary terrane (sandstone, siltstone, and metaquartzite)

3) Rifting - extrusion of lower basalt (Zgvm) and rhyolite (Zgf)

Unroofing of crystalline basement (Blowing Rock Gneiss and Wilson Creek Gneiss?, Brown Mountain Granite?, and other unknown units).

4) Rifting - deposition of siltstone and Norwood Hollow sandstone

5) Rifting - extrusion of upper rhyolite (Zgf) and Montezuma basalt (Zgm)

Unroofing of another felsite terrane (quartz porphyritic)

Unroofing of basalt terrane (also quartz and perthite porphyritic felsite)

The first three sequences exhibit the characteristics of a progressive unroofing through rhyolitic volcanic units, sedimentary units and finally down into crystalline basement. None of these conglomerate units are monomictic, indicating that all three source units (volcanic, sedimentary, and crystalline basement) were exposed at the same time. Crystalline basement (Globe massif and unknown basement lithologies) exposure, erosion and deposition, however, increased into Poplar Grove and Snakeden Ridge conglomerate time. Crystalline basement of the overlying Blue Ridge thrust sheet most probably did not provide sediment to the Grandfather Mountain basin.

9) Felsite was derived from MRF and/or GMF rhyolite bodies. MRF and GMF basins may have developed as an asymmetric, alternating half graben pair and probably were at various times joined or separated by an accomodation zone. Felsite and crystalline basement may have been shed from the accomodation zone (low relief or high relief) or from rift shoulders to the northwest.

10) The two most reliably matched sources for debris deposited in the Grandfather Mountain basin are the Grenvillian Blowing Rock Gneiss and the intraformational Montezuma basalt. These and other possible clast-source matches must be confirmed by further petrographic study and geochemical and chronologic methods.

11) Alluvial fans and subaerial portions of fan-deltas were dominated by gravelly fluidal flows (density-modified grain flows, sieve lobes and sheetfloods), as well as braided river processes, primarily due to the lack of mud-producing lithologies in source regions. The alluvial fan/fan-delta to braidplain transition is best preserved in the Snakeden Ridge conglomerate.

12) Alluvial fans and fan-deltas were generally very broad with relatively low gradients, due primarily to the lack of cohesive, mud-rich debris flows.

13) Subaqueous portions of fan-deltas, slopes, and large-scale subaqueous channels were dominated by sandy-matrix, density-modified grain flows, and high-and low-density turbidity currents (Poplar Grove conglomerate), as well as by muddy debris flows (Broadstone Lodge diamictite).

14) It is unclear whether deep water environments were lacustrine or marine. Possibly both were present at different times in the Grandfather Mountain basin.

15) Direct glacial deposition in the Grandfather Mountain basin did not occur. Proglacial environments (outwash plains, glacio-lacustrine/marine) may have existed, but evidence is ambiguous at best. The deposits in question are explained more simply as a lower alluvial fan-braidplain (Banner Elk conglomerate) and a broad, subaqueous slope downgradient from two non-coalescent fan-deltas (Broadstone Lodge diamictite), respectively.

16) Further studies of this nature, when synthesized with structural and petrologic studies of presently exposed Grenville and Crossnore massifs, would yield a relatively detailed picture of the paleolithologic distribution within the Grenville orogen and would lend considerable insight into the rather enigmatic Grenville orogeny in the southern Appalachians.

17) Stratigraphic patterns present in the Grandfather Mountain Formation, and other of the exposed Late Proterozoic successions, can be used as stratigraphic models for research and exploration in deeply buried, Mesozoic to Holocene rift to passive margin sequences such as those present along the east and west Atlantic coastlines.

SUGGESTIONS FOR FURTHER RESEARCH

Clast - Source Matching

- Detailed mapping/petrologic description and geochemical analysis (major and minor elements and REE, as well as further age dating) of Grenville and Crossnore crystalline basement rock within the GMW.

- The same methods should be used regarding volcanic units and the Linville Metadiabase within the GMF.

- Further sampling and description of GMF conglomerate clasts as well as geochemical analysis and age dating to match clasts with the above possible sources.

Structural Geology

- Renewed geologic mapping in the GMF to establish geometries and structure/structural style more precisely.

- GMF pebbles, cobbles, and boulders can be used as basis for strain analysis, shear sense, and ductility contrast studies. Studies such as these would lead to a better understanding of style and activity of the Linville Falls Fault and to large overthrusts in general. The GMF is a veritable ductility contrast laboratory.

Sedimentary Geology - Depositional Environments

- To delineate whether the Grandfather Mountain basin deep water environments were lacustrine or marine, or both at different times during basin development the following ideas are proposed.

a) Detailed facies analysis, mapping, and geochemical studies of GMF siltstone and limestone bodies and their relationship to conglomerate and sandstone units.

- Any relict evaporites present ? Even traces.

- Fossils present ? (microfossils, acritarchs, algae, soft-bodied metazoans, body fossils ?).

b) Detailed facies analysis, mapping and geochemical study of volcanic units, particularly the Montezuma basalt, and their relationship with surrounding lithologies.

- Arkose units of GMF: *Systematic* facies, paleocurrent, and petrographic analysis, particularly in the lower arkose, has not yet been performed.

- Further study, such as this, of conglomerate units in others of the Late Proterozoic successions will allow assessment of interconnectedness of the now disparate basin fills.

APPENDICES

APPENDIX 1:

OUTCROP LOCATION AND ACTION

APPENDIX 1. OUTCROP LOCATION AND ACTION. Compendium of major outcrops used in this study. Outcrops arranged in approximate stratigraphic order. May be used as a generalized field guide to conglomerate/diamictite bodies and related lithologies of the GMF. Other excellent field guides to the GMW and GMF are Raymond and others (1992) and in Boyer (1978).

Location abbrev./ name/ conglomerate unit	Locale	Basic description	Action/Data	Samples (date/otc./no.)	Comments
1b (FH) Fall Hollow Fall Hollow congl.	At 4200' elev. in Fall Hollow on Grandfather Mt., N45E from GK Grandfather Mt. (215-SE)	cobble-boulder clast-supported conglomerate (Gcsu), minor St, Smh	102 m meas. sxn AMCS clast type thin-sections	89/FH/1-3 11-8/FH/1,2,4-7,9-18 #'s 3 & 8 not collected	natural otc. massive poor lighting poor accessibility - off trail
1c (GK) Grandfather Knob Fall Hollow congl.	~4700' elev. on Grandfather Mt. Knob 0.6 mi NNW of Calloway Pk. NE of Wautauga-Avery Co. line Grandfather Mt. (215-SE)	pebble-large cobble clast-supported conglomerate (Gcsu)	AMCS clast type thin-sections	55/GK/1-6	natural otc. massive off trail otc. rapelled
1d Grandfather Mt. Visitors Ctr. Fall Hollow congl.	On Grandfather Mt. Entrance from US 221 Grandfather Mt. (215-SE)	pebbly sandstone (St common) to pebble clast-supported conglomerate	general descr.	none	good exposure
1e Linville Overlook Fall Hollow congl.	~0.5 mi N of Jct. NC 1510/1538 on 1510 NE of Linville, NC Grandfather Mt. (215-SE)	pebble clast-supp. congl. some cobbles	general descr.	none	natural otc. moss/lichen covered
2a (F) Foscoe Poplar Grove congl.	~0.35 mi SE of Jct 105/1559 (Foscoe) on 1559 Valle Crucis (215-NE)	pebble-cobble matrix-supp. congl., diamictite, and siltstone	43 m measured sxn AMCS clast type slabs thin-sections	718/F/1 24/F/1 927/F/1 1117/F/1-4	roadcut good exposure **dangerous curve**
2b (PG) Poplar Grove Poplar Grove congl.	0.7 mi SW of Jct 1551/1552 (Poplar Grove church) on 1552 Boone (221-NW)	inrterbedded pebble-boulder matrix to clast-supp. congl, sandstone, siltstone, basalt	18.2 m measured sxn AMCS clast type slabs thin-sections	726/1552/1 1116/PG/1-5	roadcut fair exposure

APPENDIX 1. OUTCROP LOCATION AND ACTION CONTINUED

Location abbrev./ name/ conglomerate unit	Locale	Basic Description	Action/Data	Samples (date/otc./no.)	Comments
2c (PB) PayneBranch Poplar Grove congl.	SE of Boone, NC At Jct. US 221/NC 1541 (Payne Branch Rd.) on 221 Boone (221-NW)	pebble-boulder matrix to clast-supp. congl. (Gmsi prevalent), diamictite, normally graded sandstone/siltstone, ?basalt?	113 m measured sxn AMCS clast type slabs thin-sections	1011/PB/1-3 1017/PB/4-9 1018/PB/10-21 1019/PB-L/a-f (7-17 m) 1019/PB-U (39.3-42.5 m)	spectacular roadcut So parallel shear zones quartz veins prominent dangerous road
3a (SM) Shull's Mills Snakeden Ridge congl.	roadcuts along NC Hwy. 105 between intersxns w/ 1557 &1568 W of Shulls Mills where NC 105 crosses Pine Ridge. Boone (221-NW)	pebble-cobble matrix to clast supp. congl. w/ sandy matrix (Gmsi)	13.5 m measured sxn AMCS clast type slabs thin-sections	720/SM/1 312/SM/1-13	roadcut s now being modified/leveled? by NC Hwy Dept. (4/92) see geologic map (Fig. 1-4)
3b (PR) Pine Ridge Snakeden Ridge congl.	scattered otcs. forming spine of Pine Ridge NW of NC Hwy. 105 Valle Crucis (215-NE)	pebble-boulder matrix to clast-supp. congl. (Gcsu, Gmsi) sandstone (Smh)	general descr. AMCS thin-section	12-1/PR/1	natural otcs. see geologic map (Fig. 1-4) gneiss boulder (45 cm)
3c (TG & SR) Townsend Gap Snakeden Ridge Snakeden Ridge congl.	TG: 0.12 mi SW of saddle where NC 1136 crosses Snakeden Ridge SR: otcs. SW of TG forming spine of Snakeden Ridge Valle Crucis (215-NE)	pebble-cobble matrix to clast-supp. congl. (Gcsu, Gmsi) sand and mud matrix sandstone (Smh, Sp, St, Sr)	22 m measured sxn AMCS	none	natural otcs. see geologic map (Fig. 1-4)
3d (I) Inversheid Snakeden Ridge congl.	0.55 mi NW of Jct. NC 105/184 on 184 Grandfather Mt. (215-SE)	sandstone, pebbly sandstone (Smh, Sp, St, Sr, Flm) Laminated silty limestone at base (facies L)	80.5 m measured sxn AMCS thin-section	top 1027/I/1 11-2/I/1 11-2/I/2 11-7/I/1-3 11-1/I/1 base	roadcut good exposure of sed. structures

APPENDIX 1. OUTCROP LOCATION AND ACTION CONTINUED

Location abbrev./ name/ conglomerate unit	Locale	Basic Description	Action/Data	Samples (date/otc./no.)	Comments
3e (L, LRC) Linville Linville Racquet Club Snakeden Ridge congl	0.25 mi W of Jct. NC 181/221 (Linville, NC) on 181 Newland (215-SW)	sandstone, pebbly sandstone/congl. (Smh, St, Sp, Gcsu)	15.7 m measured sxn AMCS thin-sections	511/LRC/1 56/LRC/1 (top)-4, 6-8 (base)	roadcut good exposure of sed. struct. So relatively flat otc. rapelled
4 (NH) Norwood Hollow Norwood Hollow sandstone	0.75 mi NW of Jct. NC 105/184 on 184 S of "Norwood Hollow" Valle Crucis (215-NE)	sandstone, pebbly sandstone, minor siltstone 0.5-1 m FU sequences (St -> Smh/Sp -> Flm)	6.2 m partial measured sxn	none	roadcut good exposure of sed. struct. **dangerous curve**
5a (BEQ) Banner Elk quarry Banner Elk congl.	0.5 mi SE of Jct. NC 194/1131, Just S of Jct. 1131/1355 and N of Wautauga-Avery Co. line Entrance from 1131 Valle Crucis (215 NE)	pebble-cobble clast-supp. congl. (Gcsmh) sandstone (Smh)	no measured sxn AMCS clast type slabs	320/BEQ/1-2	Quarry owner: Charles Townsend of Newland, NC Permission to enter denied for this study. See geologic map (Fig. 2-13)
(HB) Horse Bottom Ridge Banner Elk congl.	Horse Bottom Ridge Ridge NE of Banner Elk, NC, Just SE of NC 194 Valle Crucis (215-NE)	pebble-cobble clast-supp. congl. (Gcsmh) sandstone (Smh)	AMCS clast type thin-sections	1-27/HB/1-7 25/HB/1-5 211/HB/1	natural otcs. along ridgetop. data merged with BEQ. See geologic map (Fig. 2-13)
5b (BE) Banner Elk Banner Elk congl.	0.26 mi S of Jct. NC 184/194 on 184 in Banner Elk, NC Valle Crucis (215-NE)	pebble-cobble clast-supp. congl. (Gcsmh) and sandstone (Smh, St) lenses	64 m measured sxn AMCS clast type slabs thin-sections	510/BE/1-2 312/BE/1(top) -6(base)	roadcut data merged with BED. See geologic map (Fig. 2-13)

APPENDIX 1. OUTCROP LOCATION AND ACTION CONTINUED

Location abbrev./ name/ conglomerate unit	Locale	Basic description	Action/Data	Samples (date/otc./no.)	Comments
5c (BED) Banner Elk Dam Banner Elk congl.	0.12 mi W of NC 184 on one-way road Must enter from from NC 194 through town of Banner Elk otc. N of and topographically above dam and millpond "around corner" from BE Valle Crucis (215-NE)	pebble-cobble clast-supp. congl. (Gcsmh) and sandstone (Smh, Sp, Sr) lenses	44.5 m measured sxn AMCS clast type slabs thin-sections	311/BED/1-3 319/BED/l 1027/BED/1-3	fair exposure in roadcut Data merged with BE. See geologic map (Fig. 2-13)
5d (N) Newland Banner Elk congl.,	0.5 mi SE of Jct. NC 181/194 (Newland, NC) on181 Newland (215-SW)	pebble clast-supp. congl. (Gcsmh), sandstone, pebbly sandstone (Smh, Sp, St, Sr) and red siltstone (Flm) lenses overturned, NW vergent syncline, congl. exposed on overturned limb	119.7 m measured sxn AMCS clast type slabs thin sections	511/N/1-2 11-3/N/1-3 11-7/N/1	large roadcut, fair exposure
6a (BL or VC) Broadstone Lodge Valle Crucis Broadstone Lodge diamictite	0.95 mi W of Jct. NC 105/1112 on 1112 ~1.9 mi S of Valle Crucis on NC 1112 in Wautauga River valley Valle Crucis (215-NE)	basalt (Montezuma Mr.) pebble-boulder matrix-supported conglomerate (Gmsu), diamictite (D), laminated siltstone (Flm), soft sed. defm. structures overturned NW vergent syncline	4.5 m partial measured sxn AMCS clast type slabs thin sections	VC 510/VC/1-5 11-1/VC/1-9	roadcut, good exposure **Dangerous curve**
6b (BG) Bowers Gap Broadstone Lodge diamictite	0.2 mi SE of Jct. NC 194/1131 (Avery-Wautauga Co. line) Valle Crucis (215-NE)	laminated-thin-bedded sandstone/siltstone (Sln/Flm), soft-sediment deformation structures, ripple x-lams no clasts	general description	927/BG/1-4	roadcut pervasive S1 cleavage plates show excellent sedimentary structures

APPENDIX 1. OUTCROP LOCATION AND ACTION CONTINUED

Location abbrev./ name/ conglomerate unit	Locale	Basic Description	Action/Data	Samples (date/otc./no.)	Comments
(BC) (BCS) Blevins Cr. Church area BroadstoneLodge diamictite	From BC church east for ~0.2 mi along NC 1361 Old NC 194 far NW corner of GMW Elk Park (215-NW)	pebble-boulder diamictite (D), clast to matrix-supp. congl., sandstone (Sln), laminite (Sln, Flm) soft-sed. defm. structures	described	926/BCS/1-4	roadcuts generally very poor exposure some good cleavageplates of laminite behind mobile home ~0.2 mi E of BC church.
6c (SG) Smoky Gap Broadstone Lodge diamictite	0.13 mi NW of Jct. NC 194/1361 (Old NC 194) NW corner of GMW Elk Park (215-NW)	pebbly diamictite (D) pebbly lithic wacke siltstone	6 m measured sxn AMCS clast type slabs thin-sections	726/SG/1 1115/SG/2-10	roadcut, fair exposure, pervasive S1
6d (WP & T) White Pine Taylor Broadstone Lodge diamictite	WP: At Jct NC 194/1151 (Old 194) on NC 194 0.25 mi NE of Jct. NC 1151/White Pine Rd. T: Jct. Nc 194/1152 on 194 Newland (215-SW)	diamictite, matrix supported congl., sandstone, siltstone	43.5 m measured sxn AMCS clast type slabs thin-sections	320/WP/1-3 1026/WP/1(base) -7(top) 1024-T-1	roadcut fair to poor, weathered exposure
6e (MT) Mill Timber Creek Broadstone Lodge diamictite	At southern Jct NC 194/1151 on 194 ~0.5 mi S of WP locality Newland (215-SW)	diamictite, matrix supported congl., sandstone, siltstone	16 m measured sxn AMCS clast type slabs thin-sections	719/MT/1 320/MT/1 1026/MT/1(base)- 10(top)	roadcut fair to poor, weathered exposure

APPENDIX 2.
DETAILED FACIES DESCRIPTIONS

This appendix contains detailed descriptions of facies summarized in Table 2-2, Table 3-1, in descriptions of the five conglomerate/diamictite units in Part 2, and in discussions of facies associations in Part 3. Localities referred to are denoted in Figure 2-2 and Figure 3-1. Photos of many of the particular facies are in Parts 2 and 3. Detailed geographic locality, logistics, general outcrop description, and methods performed at each locality are shown in Appendix 1 which may be used as a generalized field guide to Grandfather Mountain Formation conglomerate and diamictite. Measured sections for each locality are presented in Parts 2 and 3. Sixteen stratigraphic sections were measured and described at Localities 1b (Fall Hollow conglomerate), 2a-2b-2c (Poplar Grove conglomerate), 3a-3bc-3d-3e (Snakeden Ridge conglomerate), 4 (Norwood Hollow sandstone), 5b-5c-5d (Banner Elk conglomerate), and 6a-6c-6d-6e (Broadstone Lodge diamictite). Stratigraphic sections at Localities 1a-1c-1d-1e, 5a. 6b and near Blevins Creek church along NC State Highway 1361 were not measured, but are more generally described.

Gcsu - Conglomerate, clast-supported, non-stratified.

Facies Gcsu conglomerate is commonly pebble to small-boulder sized, with medium cobble being the dominant clast size. It exhibits poor to moderate sorting. Clasts are mostly disc and roller-shaped and show no preferred orientation. Forming what may represent a crudely developed imbrication, however, some disc-shaped clasts are oriented with their long axis parallel to strike, but they show no preferred dip direction. Interstices are filled with a poorly sorted mixture of medium to coarse-grained sand and granules. Highly diffuse zones and lenses of very coarse-grained sand and pebble conglomerate are rare. Crude grading may be present, but commonly the deposits are massive and bedding is very subtle and difficult to discern. In Fall Hollow (Locality 1b) on Grandfather Mountain this facies is best exposed in an approximately 100 m section containing one interbed of Facies St in a 1 m deep scour. Facies Gcsu is also exposed at Locality lc on Grandfather Mountain. Localities 1b and lc are the only two localities in the GMF in which, with some effort, whole clasts may be plucked from the exposure. The largest clast measured is a boulder of dimension 40 x 22 x 22 cm. Thin-section microscopy reveals fairly well-developed pressure solution seams at some clast contact points. Presence of between-clast pressure solution suggests internal clast deformation is insignificant.

A variety of the above occurs at Linville (Locality 3e) and Pine Ridge/Townsend Gap/Snakeden Ridge (Locality 3bc) in the Snakeden Ridge conglomerate as well as one bed within the Poplar Grove conglomerate at Locality 2c. At Locality 3bc, grain size and sorting are similar to that at Locality 1b, but, clasts are generally much more angular in shape. An angular gneiss boulder exposed on Pine Ridge approximately 1.5 km northeast of Locality 3bc (between Localities 3bc and 3a) measures 45 x 30 cm. At Locality 3e, Facies Gcsu is finer-grained (granule to small pebble), and better sorted (moderate to moderately well). At both these localities Facies Gcsu occurs in internally unorganized thin-to medium-thick beds which are laterally extensive across the outcrop face and are interbedded with similarly structured beds of Smh. At Locality 3bc, single beds are in some areas clast-supported and in other areas almost matrix-supported with a higher proportion of sand around the cobbles. At Locality 3e, one bed of Gcsu overlies an undulose surface with 1 to 2 cm relief which forms the top of the underlying bed of Smh. At locality 2c, a thin Gcsu bed occurs interbedded with Facies Gms containing a sandy matrix. The clasts are pebbles and cobbles and are moderately rounded and sorted

Thin, clast-supported pebble to cobble conglomerate beds (1 to 2 clasts thick) occur intercalated with Facies Gmsi (silty sandstone matrix) near the base of Locality 2c.

Gcsmh - Conglomerate, clast-supported, massive to horizontally stratified.

This conglomerate facies is typically granule to medium-cobble sized, with medium pebble being the median grain size. It is moderately well sorted. Interstices are filled with fine to coarse-grained sand of the same general composition as Facies Smh, St , and Sp. Beds are lenticular, commonly with slightly undulose bases in abrupt contact with Facies Smh, St or Sp. Tops of lenses are gradational to abrupt with overlying sandstone facies. This facies rather commonly contains diffuse to distinct, planar bedded, pebbly sandstone, sandstone and siltstone horizons, lenses, and wisps best seen at Banner Elk (BE) and Banner Elk Dam (BED). Conglomerate beds and lenses range from approximately 0.2 m to 7 m thick with the average being 1 to 2 m thick. Internally, bedding is massive to crudely horizontal, but, locally beds fine or coarsen-upward slightly with fining-upward being more common. Lateral boundaries of conglomerate lenses, if seen, are either abrupt throughout their thickness (up to a few meters; Locality 5c) or pinch out in a gradational manner into surrounding sandstone. It is likely that thin conglomerate lenses/stringers represent the fringes of a thicker conglomerate lens projected into or out of the outcrop plane. As alluded to above, Facies Gcsmh interfingers and is interbedded with Facies Smh, St, and Sp. It is interbedded to a much lesser extent with Sr and only rarely with Gcsu or Gms-type facies. In many exposures displaying Gcsmh, if imbrication was present, it is now totally obscured, as clasts (especially ductile felsite and siltstone clasts) are flattened into the plane of pervasive cleavage. Facies Gcsmh is best exposed within the middle to upper part of the upper arkose unit in a conglomerate unit exposed discontinuously along strike for at least 14 km from Banner Elk quarry (Locality 5a) to south of Newland (Locality 5d). This conglomerate (Banner Elk conglomerate) also possesses a distinctive clast population that is very consistent along strike, and is more fully discussed in Parts 2 and 3. Facies Gcsmh is weakly developed within the Snakeden Ridge conglomerate and is also developed lower in the GMF in the southwestern localities (1d-1e) of the Fall Hollow conglomerate.

Gms - Conglomerate, matrix-supported.

Three matrix-supported conglomerate facies (mud to sand matrix containing > 35% gravel; Fig. 1-5) are present within the GMF. Facies Gmsi and Gmsu are most common followed by subordinate amounts of Gmsn. Field identification of especially Gmsi and Gmsn was, at times, hampered due to difficulty in identifying the nature of obscure bedding contacts in the deformed, metamorphosed and largely massive character of these deposits. At most localities, however, relations could be discerned.

Facies Gms ranges from pebble to boulder in clast size with the average clast size being small to medium cobble. The two largest clasts of Facies Gms occur at Locality 2c and measure 100 x 45 cm and 65 x 15 cm, being within facies variant Gmsi with a slightly muddy sandstone matrix. Sorting is poor to moderate and preferred clast orientation within beds is absent. Clasts range from angular to rounded with clasts of highly varying degrees of roundness occurring in the same bed, especially at Localities 2a, 3bc, and 6a. Beds generally range from 0.3 to approximately 3 m thick, but some may reach 10 m thick (for example, Locality 6d). Locally they contain very thin diffuse sand or silt lenses and/or clast-poor areas. Tops and bases of Gms beds are generally planar, where exposed and not obscured by later deformation, metamorphism and weathering. Locally, clasts project from the top of one Gms bed, impinging upon the base of the overlying bed, as occurs at Locality 6a.

Matrices are composed of silty sand, muddy sand, sandy mud, and mud. Silty sand and muddy sand are more common than the latter two, with only three outcrops (within Broadstone Lodge diamictite unit) containing appreciable amounts of Gms with a predominantly mud matrix. Facies Gms may be subdivided into three facies variants which generally differ in their grading, matrix type, and clast size.

Gmsi - Conglomerate, matrix-supported, non-stratified, inversely graded. Facies variant Gmsi is inversely graded and upper parts of beds may be locally or almost entirely clast-supported. Matrix is composed of silty- to muddy-sandstone (fine- to medium-grained sandstone). Clast size ranges between pebble and boulder.

Facies variant Gmsi occurs at Localities 2a, 2b, 2c, 3a, and 3bc. At 2c the inversely-graded nature is most spectacularly exposed. Here, as at Localities 2b, 3a, and 3bc, the matrix consists predominantly of a slightly muddy fine- to medium-grained sandstone. The exposure at Townsend Gap (Locality 3bc), however, contains one Gmsi bed with a muddier matrix composed of sandy mudstone. Problems of facies identification exist at Locality 2a, where the rock is particularly massive and bed contacts are cryptic. Matrix at Locality 2a is also composed of sandy mudstone. The repetitious sequence at Locality 2a of Facies D to Gmsu may instead be a sequence of stacked Gmsi beds. Whether these sequences are 1 or 2 beds, they nonetheless are small, coarsening-upward packages.

Gmsu - Conglomerate, matrix-supported, ungraded. Facies variant Gmsu is ungraded and massive. The matrix is composed of muddy sandstone (fine- to medium-grained sandstone) to sandy mudstone. Gmsu is generally finer grained than Gmsi with clast size consisting predominantly of pebbles and cobbles with only rare boulders.

Facies variant Gmsu occurs at Localities 2a, 2b, 2c, 3bc, 6a, 6d, and 6e. At 2c it appears as beds up to approximately 0.5 m thick containing unorganized/indistinct clast-poor and clast-rich zones up to 0.3 m thick. It is interbedded with similar beds of Gmsi as well as with Facies Smh/Sln.

Gmsn - Conglomerate, matrix-supported, normally graded. Facies variant Gmsn is normally graded and is not well exposed in the field. It appears, however, to be composed of the muddiest matrix of the three and is finer-grained, being granule and pebble-bearing with rare cobbles.

Facies variant Gmsn occurs only at Localities 2a and 6c.

D - Diamictite

Diamictite in the GMF is quite heterogeneous. This facies is very poorly sorted, generally being bimodal to polymodal and ranging from clay to boulder. Clasts larger than 2 mm comprise a trace to 35% of the rock (Fig. 1-5) with the average clast size being in the pebble range. Cobbles are common, whereas, boulders are common to rare. Clasts range from angular to rounded with clasts of highly varying degrees of roundness occurring in the same bed, especially at Localities 2a and 6a. The largest clast measured in this facies is 100 cm x 55 cm at Locality 6a. Facies D is commonly massive, however, locally it is laminated to thick-bedded; a collage of lithologies. Bedding is distinct to very cryptic and diffuse. Laminations are composed of green and black clay and yellow, very fine-grained sand and silt, as well as thin, poorly-sorted granule and pebble horizons. Commonly these granule and pebble horizons fine and coarsen subtley into overlying horizons. Laminations are distinct to diffuse, diffuse being most common. Wavy and slightly disrupted laminae are also present. Laminae thicknesses range from being barely measurable to approximately 3 cm. Distinctive couplets or other rhythmic alternations are not readily evident. Instead, the laminae and sets of laminae, up to approximately 5 to 10 cm thick, are randomly interbedded with thin to thick beds of gravelly, sandy mudstone, lithic wacke and other similar diamictite lithologies, as well as with Facies Gmsu, Gmsn, Sln, and Flm. Internally, diamictite beds are massive and unorganized, although normally-graded beds are present. Locally clast long axes are perpendicular to bed contacts, as at Locality 6a, where the tip of a siltstone cobble impinges upon the diamictite bed above. Bed contacts are planar to slightly undulose, however, commonly are very cryptic. Soft sediment deformation structures include loads, slightly disrupted laminae, and outsized clasts. It is not clear if outsized clasts deform underlying laminae depositionally. Some of these clasts may occur in "clusters" or areas of higher clast density as at a highly weathered exposure north of Locality 6c near Blevins Creek church..

Facies D occurs as pebbly mudstone, gravelly laminite, laminated to thin-bedded granule-bearing mudstone, pebbly silty sandstone and similar diamictite lithologies (Fig. 1-5) within the upper siltstone unit (Broadstone Lodge diamictite), where it is most well-developed. Within this unit it was observed at Localities 6a, 6c, 6d, and 6e and a very diffusely bedded variety at Blevins Creek church in the northwest corner of the window along State Highway 1361. It is also present to a lesser degree and is less commonly laminated at three other localities. At 2c, it is interbedded with Facies Gmsi, Sln/Smh and St. It is interbedded with Gmsu and Gcsu at Locality 2a. At 2b it is massive and interbedded with Gmsi and vesicular basalt.

Sln - Sandstone, laminated, locally normal graded.

Facies Sln consists of fine to coarse-grained sandstone which is moderately to well-sorted yet, does contain appreciable silt. Granules and pebbles occur sparsely and are generally quite well-rounded. It occurs as horizontal laminae and also as thin to thick planar beds (3 cm to 70 cm) which, particularly at Locality 2c, are continuous across the outcrop face and have subtley undulose to planar boundaries. Commonly Facies Sln is loaded into the underlying horizon. Normal grading is present at microscopic as well as macroscopic scale, as are parallel laminae (0.5 to 3 mm thick) and ripple cross-laminae sets (5 to 9 mm thick) which occur within normally graded beds. Recognition of these fine-scale parallel laminae and ripple cross-laminae at outcrop scale is difficult due to the quartzitic nature of the sandstone, however, these features were noted in thin-section (1018 PB 20; approximately at 51 m mark at Locality 2c: Payne Branch outcrop). Partial Bouma sequences are evident at Locality 2c. Normally-graded laminae and beds range from approximately 15 mm to 70 cm and commonly grade from coarse-grained, silty sandstone, commonly containing granules and small pebbles, to coarse-grained siltstone.

Facies Sln is best exposed at Locality 2c where it is planar-stratified and the laterally continuous nature is most evident. Here it is loaded into Facies Flm as well as the finer grained top of underlying normally graded beds of Sln. At Localities 6d and 6e it is less well exposed and may be loaded into Flm and D or Gmsu horizons. Loading at these localities, however is not as easy to document as they are very near the Linville Falls Fault where the siltstone was probably more ductile during fault movement than the sandstone beds.

In a sequence at the top of the GMF (east of Blevins Creek church, north of Locality 6c), stratigraphically above Localities 6d and 6e, Facies Sln is intimately interbedded and laminated with Facies Flm. Some parts of the succession may be termed "laminite". The bases of many fine-grained sandstone beds are loaded into the underlying mudstone laminae, locally forming flames and small ball and pillow structures. Outsized clasts are absent in well-developed laminite of the GMF.

On Flattop Mountain southwest of Locality 2c, within the lower siltstone unit, in generally poor exposure, feldspathic and lithic arenite beds of Sln, measuring between 5 to 10 cm, are interbedded with amygdaloidal basalt (lower basalt), rhyolite (lower rhyolite) and massive black and grey siltstone.

Smh - Sandstone, massive to horizontally stratified.

This facies ranges in grain size from fine-to-very coarse-grained sandstone and is poorly-to moderately well-sorted. Sand grains are subangular to rounded. Granules and pebbles are sparse to common, are subangular to well-rounded, and generally consist of quartz, feldspar, rhyolite, and rare quartzite, granite, siltstone and basalt. Typically, the most angular grains are feldspar sand and gravel. Bedding thickness ranges from several centimeters to several meters, to massive successions in which bedding planes are unrecognizable and description and measurement were based on gross grain size changes. Bedding is planar, but locally gently undulose bases are evident as are large-scale, diffusely lensoid geometries. Horizontal stratification is most easily observed where it is defined by pebble stringers. Pebble stringers are discontinuous horizons most commonly composed of granules and pebbles and are rarely more than two clasts thick. The clasts within the stringer are not generally in contact with each other except for isolated clast pairs and triplets. Isolated cobbles along stringer horizons are rare, but do occur. Contacts between other Smh bodies are generally gradational. Contacts with other facies, such as Gcsmh, are locally sharp and are best observed at Localities 5b and 5d.

Facies Smh is quite widespread in the GMF and occurs at least sparingly at almost every locality. It is typically in sharp or gradational contact with Facies St, Sp, and Sr, as well as Flm, Gcsmh, and Gcsu. Common facies transitions are St --> Smh/Gcsmh, Smh <---> Gcsmh, and St --> Sp --> Smh/Flm. Facies Smh forms the thickest successions of any single facies and is best exposed within the Banner Elk conglomerate at Localities 5a, 5bc, and 5d where it occurs both in monotonous succession as well as in interfingering relationship as described above.

St - Sandstone, small and large-scale trough cross-stratified.

This facies possesses much the same grain size and texture as Facies Smh except is trough cross-stratified. Facies St is defined by grain size changes, commonly in the trough base as well as by heavy mineral concentrations, particularly on foresets.

Small-scale trough cross-strata are defined as having a set thickness between 3 and 10 cm. Average thickness is approximately 5 cm. Large-scale trough cross-strata are defined as being greater than 10 cm thick.

Small-scale St. Sets of small-scale St normally occur singularly, but also in beds up to approximately 1 meter thick which alternate with Facies Smh forming successions up to 10 m thick. Gravel is less common at the base of small-scale troughs than it is in large-scale St. Purple and less commonly green, fine-grained sand (heavy minerals) and silt commonly define upwardly concave as well as upwardly convex undulose, diffuse to distinct wisps. Whereas the geometry of these structures may locally be indeterminant and complex, they are no doubt some type of cross-strata which may or may not be slightly deformed due to soft-sediment deformation processes as well as structural deformation. These purple wisps are herein defined as small-scale trough cross-strata. They are most commonly associated with Facies Smh forming thick successions. Small-scale St are best exposed at Localities 3d and 4, and are intimately interbedded with Facies Smh, Sp as well as large-scale St. Purple wisp small-scale St are best exposed at Localities 5bc and 5d, to **the exclusion of large-scale** St, and are intimately interbedded with Facies Smh, large-scale Sp, and Gcsmh.

Large-scale St. The thickest sets of large-scale St are 1 m, whereas, the average thickness ranges between 15 and 40 cm. Average set width is approximately 1 to 4 m and adjacent troughs commonly intersect one another. Beds of large-scale trough cross-strata are present in successions up to 5 m thick, but also as singly occurring sets amidst, most commonly, Facies Smh or as the base of a fining-upward sequence. Locally, granules and pebbles as well as rare isolated cobbles line trough bases or are suspended in sand matrix above the base. Clast long axes are most commonly aligned subparallel to the trough base, however, there are isolated cases of clast long axes oriented distinctly perpendicular to the trough base. Large-scale St is best exposed at Localities 3d, 3e, and 4, and is intimately interbedded with Facies Smh and Sp, as well as with small-scale St. It is also exposed at Locality 1b in a 1 m deep scour, which is enclosed within Facies Gcsu. Large-scale St are curiously absent within the Banner Elk conglomerate (Localities 5a-5d) where instead small-scale St are in facies association with Smh, large-scale Sp, and Gcsmh, as well as Sr, and Flm.

Sp - Sandstone, small and large-scale planar-tabular cross-stratified.

Facies Sp possesses much the same grain size and texture as Smh and St, except is planar-tabular cross-stratified. Facies Sp does not, however, contain cobbles along or at foreset bases as does St. Nowhere is grain size greater than small pebble. Small and large-scale Sp set dimensions are the same as that defined for St. Foresets are defined by grain size changes, as well as by heavy mineral concentrations.

Small-scale Sp. Small-scale Sp is most commonly defined by heavy-mineral foresets, but also by grain size changes in the fine-to-very coarse-grained sand range. Pebbles are absent. Sets of small-scale Sp commonly range between 4 and 7 cm thick, occurring singly and in beds ranging from approximately 10 to 100 cm thick. Sets and beds alternate with Facies Smh, Sr, and Flm within successions also containing small-and large-scale St and Gcsu. Small-scale Sp is best exposed at Localities 3d and 3e. Very low-angle small-scale Sp are sporadically present at Locality 4 in the following fining-upward succession: large-scale St --> small-scale Sp/Smh --> Sr --> Flm.

Large-scale Sp. Contrary to foreset definition of small-scale Sp, large-scale Sp foresets are more commonly defined by grain size alternations. Foreset definition by heavy mineral concentrations is less common. Sets of large-scale Sp range between 15 and 70 cm thick with the average being approximately 20 to 40 cm thick. They occur singly and in beds ranging from 0.5 to 5 m thick. Large-scale Sp sets and beds are intercalated with Facies Smh, small and large-scale St, Sr, and Flm within successions also containing Gcsu, Gcsmh, and Gmsu.

Large-scale Sp is best exposed at Localities 3bc, 3d, 3e, and 5c. At Locality 3bc, along Snakeden Ridge, a single set measuring 70 cm thick is interbedded with Smh overlying a meter-thick bed of Gmsu with a muddy sandstone matrix. This set is the thickest set of Sp observed in any succession containing conglomerate in the GMF. Foresets at Locality 3bc are defined largely by heavy mineral concentrations. Large-scale Sp foresets defined by grain size changes are best exemplified at Locality 3d and also in the uppermost part of the Banner Elk Dam section (Locality 5c). At 5c, large-scale Sp foresets have the following character: moderately-sorted, medium-grained sandstone alternates with poorly-sorted, pebbly sandstone in foresets measuring 0.5 cm to 3 cm thick. Grain size of pebbly sandstone foresets ranges from coarse sand to small pebble. Commonly, these foresets are only one to two granules/pebbles thick. Individual set thickness at Locality 5c is approximately 30 to 55 cm.

Sr - Sandstone, rippled and ripple cross-laminated

Facies Sr consists of coarse silt to fine-grained sand. Ripples and ripple cross-laminae are defined as being less than 3 cm thick. Ripple structures observed within the GMF include symmetric ripples, ripple and climbing ripple cross-lamination as well as small-scale trough cross-lamination which was the term used if both limbs of the trough were observed. Cross-lamination foresets are most commonly defined by slight grain size alternations.

Symmetrical ripples. Symmetrical ripples were observed in only one locality within the GMF, on Grandfather Mountain, at approximately 4300 feet elevation on Fall Hollow Ridge (approximately 0.25 km west of Locality 1b). These symmetrical ripples, composed of fine-grained sandstone have an amplitude of approximately 3 mm and a wavelength of 2 to 2.5 cm. They were observed on an out-of-place boulder derived from the adjacent outcrop containing large-scale Sp and St (10 to 25 cm thick) as well as thin-bedded/laminated fine to medium-grained sandstone (3 to 5 cm thick) intercalated with 1 mm shale partings (Facies Smh and Flm).

Ripple cross-laminae. Ripple cross-laminae were observed at Localities 3bc, 3d and 4. At Localities 3d and 4 ripple cross-laminae are very similar in geometry, having thicknesses of approximately 1 cm. They occur as parts of similar successions, Locality 4 containing more classic fining-upward successions as follows: undulose base --> large and/or small-scale St --> Smh/?Sp --> Sr --> Flm. This fining-upward succession at Locality 4 occurs repeatedly and each is between 60 and 100 cm thick. Ripple cross-laminae occur only once at Locality 3d in the following 6 m succession: large-scale St --> Smh --> Sp --> Smh --> Sr --> Flm --> Smh. At Locality 3bc, ripple cross-laminae (approximately 3 cm thick) are composed of fine-grained sandstone and are quite cryptic, occurring within the following succession: Gmsu --> Flm --> Gmsu --> Flm --> Sr --> Smh --> Gmsi --> Flm.

Climbing ripple cross-laminae. Climbing ripple cross-laminae were observed only at Locality 5d within a 15 cm thick lens of purple, laminated siltstone (Facies Flm) which thins laterally over approximately 20 m to a feather edge before pinching out. They are composed of silt and very fine-grained sand and have an amplitude of approximately 1 cm. The purple siltstone lens also contains very-thin laminae of sand and granules interlaminated with silt and clay and cannot be observed at road level. Fine to medium-grained Smh, pebbly Smh and lenses of Gcsmh surround the purple siltstone lens. The climbing ripple cross-laminae are more evident in slab sections of the siltstone than on the outcrop due to slickensided quartz veins which transect the siltstone lens.

Small-scale trough cross-laminae. Small-scale trough cross-laminae occur only at Locality 5c, are composed of purple silt and very fine-grained sandstone and have an amplitude of 3 to 5 cm This variant of Facies Sr occurs with Flm and Smh in very-thin beds which directly overlie sets of pebbly, large-scale Sp in the uppermost 5 m of the Banner Elk Dam section.

Facies Sr is not common in conglomerate-bearing successions of the GMF, as per the above discussion. Within siltstone and sandstone bodies as mapped by Bryant and Reed (1970b) it does not appear to be altogether common either. The rarity of these fine scale, delicate structures within the GMF may be real, but they may also be obscured, at least partially, due to the degree of deformation and metamorphism experienced by the rocks.

Flm - Fines, thinly laminated to massive

Facies Flm is composed of claystone to very fine-grained sandstone, containing less than a trace of clasts larger than 2 mm. It is predominantly horizontally laminated to very finely bedded, although locally it is massive. Where Facies Flm is massive mudstone, it may be confused with Facies D containing no visible clasts. Where Facies Flm is laminated and contains between a trace and 35% clasts larger than 2 mm diameter, it is more properly described as Facies D in the form of laminated diamictite or gravelly laminite with gravel either deforming laminae or forming gravelly laminae.

Planar to wavy laminae range in color from black and green or green and yellow to maroon and grey. Claystone and siltstone laminae are generally black, green and maroon, whereas, siltstone and very fine-grained sandstone laminae are generally green, yellow, and grey. Laminae range from 0.1 mm to 3 cm thick and distinct couplets or other rhythmic alternations are not readily evident.

In general, clay laminae are thicker than intervening siltstone and very fine-grained sandstone laminae. Intercalated laminae and thin beds of fine- to coarse-grained Facies Sln are usually thicker than any horizon of Facies Flm. "Compound laminae" or laminasets are common. One typical example of a laminaset occurs at Locality 6b where a green claystone lamina (15 mm thick) contains three yellow siltstone laminae ranging from 0.1 to 0.5 mm thick.

Loads, flames, and sparse, small ball and pillow structures occur where siltstone/very fine-grained sandstone lies directly upon claystone and siltstone of Facies Flm. Loads range from 1 mm to 1 cm in height and up to 3 cm in width parallel to bedding. Flames range from 0.1 to 6 mm height into the overlying siltstone or sandstone bed and locally thin tips of flames extend through the immediately overlying siltstone/sandstone layer joining with the overlying claystone. Other soft sediment deformation structures include mesoscale folds and thrusts with an amplitude of up to a few cm and displacement of approximately 1 mm, respectively.

Ripple cross-laminae sets are present and composed of very fine-grained sandstone and mudstone. Foresets commonly are defined by green clay laminae. The cross-laminae range from 3 to 7 mm thick and commonly truncate underlying laminae forming small scours and troughs up to 7 mm deep. Foresets range from 20o to 25o inclination from horizontal.

Isolated sand grains and granules are locally embedded (that is, "floating")***within*** claystone laminae and do not truncate lamination. Outsized clasts are absent within laminite of Facies Flm. East of Blevins Creek church, however, loosely aggregated concentrations of muddy sandstone up to 5 mm long are present which appear to truncate laminae.

Thin lens-like bodies and horizons of Facies Flm occur at Localities 2c, 3bc, 3e, 4, 5bc, and 5d and are interbedded with sandstone and conglomerate Facies Smh, St, Sp, Sr, and Gcsmh. Thicker, more massive Flm units occur at Localities 2a, 2c, 6c, 6d, and 6e. The thinly-laminated variety containing more prevalent soft sediment deformation structures is best observed at Localities 6a, 6b, and along North Carolina State Highway 1361, east of Blevins Creek church, within the upper siltstone unit.

APPENDIX 3

ORIENTATION DATA: HORSE BOTTOM AND SNAKEDEN RIDGES

APPENDIX 3. ORIENTATION DATA: HORSE BOTTOM RIDGE AND SNAKEDEN RIDGE.

HORSE BOTTOM RIDGE. SEE FIG. 2-12a and b.

S_0	S_1	L_1
N 30 W 61 NE	N 3 E 68 SE	41 N 81 E
N 35 W 59 NE	N 3 E 40 SE	41 S 80 E
N 35 W 59 NE	N 3 E 61 SE	
N 20 W 29 NE	N 9 E 63 SE	
N 27 E 66 NW	N 15 E 82 SE	
N 31 W 49 NE	N 29 E 69 SE	
N 55 E 30 NW	N 10 E 74 SE	
N 70 W 45 NE	N 10 E 64 SE	
N 80 E 46 NW	N 10 E 73 SE	
N 43 E 75 SE	N 0 E 80 E	
N 90 E 39 NE	N 19 E 65 SE	
N 75 E 40 NW	N 15 E 64 SE	
N 40 E 69 SE	N 0 E 60 E	
N 20 W 57 NE	N 3 E 74 SE	
N 15 W 49 NE	N 0 E 57 E	
N 35 E 60 SE	N 8 W 36 NE	
N 55 W 42 NE	N 0 E 50 E	
N 15 W 27 SW	N 25 E 46 SE	
N 62 W 60 NE	N 15 E 88 SE	
N 60 E 80 NW	N 9 E 66 SE	
N 75 E 80 NW	N 3 E 60 SE	
N 65 E 51 NW	N 15 E 74 SE	
N 14 E 89 SE	N 3 W 45 NE	
N 35 E 85 SE	N 10 W 62 NE	
	N 5 W 55 NE	
	N 25 E 70 SE	
	N 10 W 66 NE	

PINE - SNAKEDEN RIDGE. SEE FIG. 1-4a and b.

S_0	S_1
N 0 E 54 E	N 30 E 71 SE
N 2 E 45 SE	N 25 E 65 SE
N 25W 31 NE	N 10 E 70 SE
N 5W 29 NE	N 0 E 54 E
N 29W 55 NE	N 5 W 70 NE
N 40W 59 NE	N 5 W 55 NE
N 75W 47 NE	N 7 E 62 SE
N 70E 70 NW	N 7 W 40 NE
N 80W 60 NE	N 5 W 70 NE
N 45E 63 NW	N 17 E 70 SE
N 50E 24 NW	N 15 W 46 NW
N 0E 35 E	N 38 W 52 NE

APPENDIX 4.

CLAST SIZE DATA

OUTCROP	CLAST LITH	A1(//S1&LA2)	A2(LS1&LA3)	A3(//S1&LA1)	SEE NOTES IN CELLS A1, B1, C1
FH-GK					Top lower arkose (PEga) [all measurements in cm]
FH (1B)	Gran	10.0	4.0		little to no S1 evident (relatively undeformed)
FH	Gran	30.0	10.0		3 mutually L axes; oblique to So (So = N56W 33NE)
FH	Gran	15.0	12.0	7.0	max axis // strike (commonly)
FH	Gran	24.0	20.0	7.0	mostly discs
FH	Gran	12.0	10.0	6.0	some rollers/footballs
FH					
FH	Grn lg Qtzl	18.0	10.0	11.0	
FH					
FH	PurpPorphVolc	20.0	15.0	10.0	
FH	PurpPorphVolc	32.0	12.0	20.0	
FH	PurpPorphVolc	40.0	22.0	22.0	roller
FH	PurpPorphVolc	17.0	15.0	8.0	
FH	PurpPorphVolc	20.0	12.0	7.0	
FH	NON DUCT (6)	18.2	11.0	7.8	
FH	DUCTILE (5)	25.8	15.2	13.4	altogether larger depositionally
FH-GK					
GK (1C)	VQ	5.5		3.0	A1//So//S1 ? So or ?S1? = N15E 54SE
GK	VQ	7.0		5.5	
GK	VQ	6.0	4.5		
GK					
GK	Gran	3.0		2.5	
GK	Gran	11.0		10.0	
GK	Gran	25.0		17.0	
GK	Gran	21.0		20.0	
GK	Gran	4.0	2.0		
GK	Gran	10.0	8.0		
GK					
GK	WhFGQtzl	5.0		2.0	
GK					
GK	PurpPorphVolc	20.0		12.0	
GK	PurpPorphVolc	9.0		5.0	
GK	PurpPorphVolc	26.0		15.0	
GK	PurpPorphVolc	9.0		8.0	
GK	PurpPorphVolc	18.0		13.5	
GK	PurpPorphVolc	12.0		5.0	
GK	PurpPorphVolc	12.0		6.0	
GK	PurpPorphVolc	11.0	6.0		
GK	PurpPorphVolc	27.0	12.0		
GK	PurpPorphVolc	7.0	4.0		
GK	NON DUCT (10)	9.8	4.8	8.6	
GK	DUCTILE (10)	15.1	7.3	9.2	altogether larger depositionally
PB (2C)					
PBL	Gran	7.0	15.0		A1//S1 oblique So (So = N64W 57 NE)
PBL	Gran	7.0	10.0		A2 L S1
PBL	Gran	7.0	7.0		
PBL					
PBL	Tan Qtzl	4.0	15.0		A2 L S1
PBL					
PBL	PRSist/Vol	100.0	45.0		
PBL	PRSist/Vol	25.0	10.0		
PBL	PRSist/Vol	60.0	15.0		
PBL	PRSist/Vol	40.0	9.0		
PBL	PRSist/Vol	80.0	25.0		
PBL					
PBL	Volc Breccia	60.0	15.0		
PBL	Volc Breccia	65.0	15.0		
PBL	NON DUCT (4)	6.3	11.8		
PBL	DUCTILE (7)	61.4	19.1		altogether larger depositionally
PB					
PBUL	MGGran	9.0	3.5		
PBUL					
PBUL	black rk	45.0	11.0		siltstone/?basalt?
PBUL	black rk	30.0	7.0		
PBUL	black rk	30.0	5.0		
PBUL	black rk	15.0	3.0		
PBUL	black rk	20.0	5.0		
PBUL	black rk	50.0	20.0		
PBUL	black rk	40.0	7.0		
PBUL	black rk	30.0	10.0		
PBUL					
PBUL	GrYellLamSlst	9.0	3.5		
PBUL	NON DUCT (1)	9.0	3.5		
PBUL	DUCTILE(9)	29.9	7.9		
PB					
PBUM	VQ	5.0	6.0		
PBUM	VQ	4.0	2.0		
PBUM	VQ	3.6	5.0		
PBUM	VQ	4.0	6.5		
PBUM					
PBUM	F-MG Gran	4.5	6.0		
PBUM	F-MG Gran	5.5	3.0		
PBUM	F-MG Gran	3.5	5.5		
PBUM	F-MG Gran	4.5	5.5		
PBUM	F-MG Gran	4.5	7.0		
PBUM					
PBUM	WhTanQtzl	3.0	5.5		
PBUM	WhTanQtzl	1.5	6.0		
PBUM	WhTanQtzl	3.5	9.0		
PBUM	NONDUCT (10)	4.2	5.9		
PBUM	DUCTILE (none)				
PB					
PBUU	FGGran	6.0	7.0		
PBUU					
PBUU	WhTanQtzl	6.0	6.0		
PBUU	WhTanQtzl	5.0	7.0		
PBUU	WhTanQtzl	12.5	2.0		
PBUU					
PBUU	black rk	15.0	4.0		

PB U U	black rk	23.0	6.0		
PB U U	black rk	15.0	5.0		
PB U U	black rk	9.5	3.5		
PB U U					
PB U U	Volc Breccia	22.0	6.0		
PB U U					
PB U U	GrYellLamSist	13.0	4.0		
PB U U	NON DUCT (4)	7.4	5.5		
PB U U	DUCTILE (6)	16.3	4.8		
PB overall	NON DUCT (10)	6.9	7.9		
PB overall	DUCT (10)	57.0	17.2		
F (2A)	VQ/Gran	16.0	8.0		some VQ, Gran very angular So = N80W 40NE
F	VQ/Gran	5.5	4.0		
F	VQ/Gran	8.0	5.0		Q veins within clast
F	VQ/Gran	8.6	6.0		
F	VQ/Gran	7.0	4.0		
F	VQ/Gran	4.9	2.5		
F	VQ/Gran	4.7	5.0		
F	VQ/Gran	11.5	5.3		coarsely porph (.7cm diam.)
F	VQ/Gran	10.0	7.0		
F					
F	grey/tan/Grn	16.0	7.0		
F	Qtzt	10.5	4.5		
F		13.0	4.0		
F		14.0	6.0		
F		8.0	5.0		
F					
F	PurpVolc	7.0	2.5		
F	PurpVolc	7.0	2.5		
F	PurpVolc	3.2	0.9		
F	PurpVolc	8.0	1.5		
F	PurpVolc	6.0	2.5		
F	PurpVolc	16.0	5.0		
F	PurpVolc	11.2	2.5		
F	PurpVolc	6.5	3.5		
F	PurpVolc	5.9	3.5		
F	PurpVolc	8.5	4.0		
F	PurpVolc	12.0	3.0		
F	NON DUCT (10)	11.6	5.8		
F	DUCTILE (10)	9.2	2.8		
PG (2B)	Granitoid	15.0	5.0		Little to no S1 evident (relatively undeformed)
PG	Granitoid	25.0	15.0		A1 * A2 = max axis * L axis (So = ~N50E 46SE)
PG	Granitoid	25.0	17.0		large clasts subrounded
PG	Granitoid	17.0	12.0		pebbles angular
PG	PorphGranitoid	16.0	11.0		coarsely porph (BR Gneiss?)
PG	PorphGranitoid	16.0	8.0		largest Kspar pheno = 3*2
PG					
PG	GreenFgQtzt	19.0	10.0		
PG	GreenFgQtzt	30.0	10.0		
PG	GreenFgQtzt	20.0	14.0		
PG	GreenFgQtzt	13.0	10.0		
PG	GreenFgQtzt	24.0	10.0		
PG	GreenFgQtzt	21.0	11.0	4.0	11-16-PG-4
PG					
PG	basalt	11.0	9.0		
PG	basalt	15.0	7.0		
PG					
PG	PurpRock	13.0	8.0		volc
PG	NON DUCT(10)	21.3	11.8	4.0	A3 (1)
PG	DUCT(3)	13.0	8.0		
SM-PR-TG					
SM (3A)	WhGmQPerthV		3.0	11.0	A1 ~//S1~//So (So = N1E 50SE)
SM	WhGmQPerthV		6.0	19.0	
SM	WhGmQPerthV		5.5	8.0	
SM	WhGmQPerthV		5.5	14.0	
SM	WhGmQPerthV		5.5	9.0	
SM	WhGmQPerthV		2.5	8.0	
SM	WhGmQPerthV		8.0	11.0	
SM	WhGmQPerthV		3.0	8.0	
SM	WhGmQPerthV		1.0	2.0	
SM	WhGmQPerthV		8.0	30.0	
SM	WhGmQPerthV		2.0	10.0	
SM	WhGmQPerthV		2.0	8.0	
SM					
SM	Qtzt	11.0	6.0	20.0	312-SM-11
SM	Gran	20.0	8.0		
SM	Gran	35.0	10.0		
SM	CG Gran	9.1	5.0	7.0	312-SM-6
SM	NON DUCT (4)	18.8	7.3	13.5	
SM	DUCTILE (10)	-	4.9	12.8	
SM-PR-TG					
PR (3B)	Same as TG +	20.0		15.0	Same as TG: A1 L A3 (see strip map for So/S1)
PR	GmYelLamSist	19.0		11.0	A1 * A3 = max axis * L axis
PR	Gns <10%FMg	32.0		19.0	unless max axis is L So
PR	Purp Qtzt	18.0		12.0	A1 sub // So subL S1
PR	WhTanGmPorV	19.0		13.0	A1&A3 in plane of S1
PR		18.5		11.5	clasts rnd,triangle,box,rhombus
PR		21.0		20.0	Q veins w/in some clasts
PR		22.0		15.0	
PR		45.0		17.0	
PR		35.0		22.0	
PR		32.0		18.0	
PR	Gneiss	45.0		30.0	Q vein riddled
PR	MIXED (10)	29.0		18.0	
SM-PR-TG					
TG (3C)	Mixed	12.0		8.0	Same as PR (So = N65E 59NW)

TG	Decr. abund.	14.0		25.0	A1 L A3
TG	Pink/wh Gran	7.0		5.0	A1 // A3
TG	wh/green qtzl	20.0		15.0	A1 sub // to So in plane of S1
TG	PurpPorphVolc	7.0		5.0	
TG	BlacPorphVolc	7.0		5.0	
TG	PurpSiSt	6.0		3.0	
TG		20.0		10.0	
TG		7.0		7.0	
TG		13.0		8.0	
TG	MIXED (10)	11.3		6.9	
I-L					
I (3D)	VO/Feld	1.6	0.9		A1 oblique So So overturned at N75E 60SE
I	VO/Feld	1.0	1.0		little to no S1 evident (relat. undeformed)
I	VO/Feld	2.0	1.0		A1 ' A2 = max axis ' L axis
I	VO/Feld	1.5	1.0		A1 oblique So
I	VO/Feld	2.5	1.5		A1 sub // So in troughs
I	VO/Feld	1.2	1.2		
I	VO/Feld	1.7	1.4		A1 oblique So
I	VO/Feld	2.5	1.4		
I	VO/Feld	4.8	1.9		
I	VO/Feld	6.0	3.5		
I	VO/Feld	10.0	9.0		
I	VO/Feld	9.0	6.0		
I	VO/Feld	1.9	1.9		
I					
I	Bl. Lith SS	4.0	2.0		mica rich
I	Bl. Lith SS	5.0	4.0		mica rich
I					
I	PurpRedVolc	3.0	1.0		
I	PurpRedVolc	1.0	0.9		
I	PurpRedVolc	4.0	3.0		
I	PurpRedVolc	4.8	2.1		
I	PurpRedVolc	6.0	3.5		
I	PurpRedVolc	4.0	1.5		
I	PurpPorphVolc	2.0	1.4		A1 oblique So
I	NON DUCT (10)	4.8	3.2		
I	DUCTILE (7)	3.5	1.9		
I-L					
L (3E)	VO/Gran	3.5	3.0		little to no S1 evident (~undeformed)So = N35E 10N
L	VO/Gran	8.0	4.5		A1 ' A2 = max axis ' L axis
L	VO/Gran	3.5	1.6		A1 sub //So in troughs
L	VO/Gran	3.0	2.0		
L	VO/Gran	6.8	4.5		Many small pebbs & granules in
L	VO/Gran	1.5	1.0		.2 - .7 cm diam. range
L	VO/Gran	5.5	4.0		
L	VO/Gran	21.0	6.7		
L	VO/Gran	5.0	5.0		
L	VO/Gran	6.0	4.0		
L					
L	M-CG SS	2.3	2.0		
L	M-CG SS	4.0	3.0		
L	VFG SS	6.0	4.0		
L					
L	Bas	5.0	2.9		
L	Bas	9.0	5.0		
L	porph Bas	6.0	3.0		
L	NON DUCT (10)	6.0	4.5		
L	DUCTILE (none)	-	-		
NH (4)	VO	2.2	2.2		little to no S1 evident (~undeformed)
NH	VO	2.0	1.0		A1 or A2 = max axis, A1 L A2 (So = N60W 50NE)
NH	VO	4.5	2.3		A1 usually sub //So in troughs
NH	VO	2.0	3.0		
NH	VO	3.0	2.0		
NH	VO	3.0	2.3		
NH	VO	3.0	1.0		
NH	VO	1.1	1.6		long axis L So
NH	VO	4.0	2.5	3.0	
NH	VO	5.5	5.0		
NH	VO	2.3	1.3		
NH	VO	4.0	2.6		
NH	VO	2.9	2.9		
NH					
NH	Felds/Pegm.	2.8	2.0		
NH	Felds/Pegm.	9.0	5.0		
NH	Felds/Pegm.	10.0	4.5		
NH					
NH	F-MG Gran	5.0	5.5	6.0	
NH	F-MG Gran	4.0	1.0		
NH					
NH	basalt	6.6	2.9		
NH	basalt	3.0	3.2		long axis L So
NH					
NH	Tan/Purp Volc	2.4	1.3		
NH	Tan/Purp Volc	3.0	1.2		
NH	Tan/Purp Volc	4.0	2.1		
NH	Tan/Purp Volc	2.8	1.3		
NH	tuff?	10.0	2.0		
NH					
NH	SiSt	2.0	3.0		long axis L So
NH	NON DUCT (10)	5.5	3.4	4.5	
NH	DUCT (6)	4.0	1.8		
BEO-HB,BE-BED,N					near Linville Falls Flt.
BED-HB					see strip map for So/S1 data
BEO (5A)	VO	7.0	4.0		
BED	VO	7.0	4.0		
BED	VO	9.0	4.0		
BED	VO	11.0	6.0		
BED	VO	12.0	8.0		

BED	VO		6.0	14.5	
BED	VO		4.0	6.0	
BED	VO		3.0	9.0	
BED					
BED ·	XbddPurpQtzl	19.5	14.0	8.5	320-BEQ-1
BED	PurpQtzl	14.0	7.0	7.0	320-BEQ-2
BED					
BED	PurpRedVol		4.0	17.0	
BED	PurpRedVol	12.5	1.0		
BED					
BED	WhGrnFelsite	20.0	4.0		
BED	WhGrnFelsite	6.0	3.0		
BED	WhGrnFelsite	16.0	4.0		
BED	WhGrnFelsite	10.0	4.0		
BED-HB					
HB	VO/Gran	10.0	6.3	10.0	1-27 HB 7
HB	PRedVolc	12.0	2.5	10.0	25 HB 3
BED-HB	NON DUCT (10)	11.8	6.2	9.2	
BED-HB	DUCTILE (7)	12.8	3.2	13.5	
BED-HB,BE-BED,N					
BE-BED					see strip map for So/S1 data
BE (5B)	VO/Gran	9.0		8.0	A1//S1 oblique So
BE	VO/Gran	3.5		7.5	
BE	VO/Gran	2.9		3.3	
BE	VO/Gran	3.5		8.0	
BE	VO/Gran	4.5		6.0	
BE	VO/Gran	8.6		10.0	
BE	VO/Gran	4.0		13.0	
BE	VO/Gran	5.3		10.0	
BE	VO/Gran	12.0		14.0	
BE	VO/Gran	4.0		8.0	
BE					
BE	PurpRedVol	4.0		6.0	
BE	PurpRedVol	7.0		11.0	
BE	PurpRedVol	6.0		14.0	
BE	PurpRedVol	5.0		10.5	
BE	PurpRedVol	5.0		18.0	
BE-BED					
BED (5D)	VO/Gran	6.0	4.0		A1//S1 oblique So
BED	VO/Gran	10.0	5.5		
BED	VO/Gran	7.0	2.4		
BED	VO/Gran	6.1	4.0		
BED	VO/Gran	9.0	4.0		
BED	VO/Gran	7.3	4.6		
BED	VO/Gran	5.0	3.0		
BED	VO/Gran	4.0	4.0		
BED	VO/Gran	4.9	4.9		
BED	VO/Gran	5.5	6.0		
BED	VO/Gran	8.5	4.2		
BED	VO/Gran	3.5	2.2		
BED	VO/Gran	10.5	4.0	7.0	
BED	VO/Gran	6.0	5.0	6.0	
BED					
BED	PurpRedVol	20.0	6.0		
BED	PurpRedVol	10.0	2.0		
BED	PurpRedVol	9.0	1.5		
BED	PurpRedVol	10.0	1.0		
BED	PurpRedVol	9.0	1.5		
BED	PurpRedVol	7.0	0.6		
BED	PurpRedVol	5.0	1.0		
BE-BED	NON DUCT (10)	6.4	4.6	9.5	
BE-BED	DUCTILE (10)	6.6	2.2	13.4	
BED-HB,BE-BED,N					
N (5D)	VO	0.6	0.6		A1//S1//So limbs overt sync.
N	VO	0.7	0.6		see strip map lor So/S1 data
N	VO	1.7	0.5		
N	VO	1.1	0.6		
N	VO	0.8	0.7		
N	VO	1.2	1.2		
N	VO	2.0	1.0		
N	VO	1.9	0.8		
N	VO	2.0	1.0		
N	VO	1.7	1.6		
N	VO	1.7	1.5		
N	VO	2.0	1.3		
N	VO	2.2	0.6		
N	VO	1.5	1.0		
N	VO	3.5	1.0		
N	VO	2.0	2.1		max axis L S1 & So
N	VO	2.0	1.5		
N	VO	3.0	1.7		
N	VO	2.5	2.0		
N					
N	whChert	1.0	1.3		max axis L S1 & So
N	PurpRedVol	2.6	0.6		
N	PurpRedVol	1.5	0.4		
N	PurpRedVol	1.1	0.5		
N	PurpRedVol	3.0	0.4		
N	PurpRedVol	2.5	0.4		
N	PurpRedVol	4.0		2.7	
N	PurpRedVol	1.0		2.2	
N	PurpRedVol	1.3		1.8	
N	PurpRedVol	1.0		2.0	
N	PurpRedVol	0.9		1.8	
N					
N	WhGrnFelsite	2.6	0.5		
N	WhGrnFelsite	2.5	0.5		
N	NON DUCT (10)	2.3	1.3		
N	DUCTILE (10)	2.2	0.5	2.1	

VC,SG,WP-T,MT					TOP OF GMF SECTION
VC (6A)	Gran	7.0	5.0		A1=max axis; A2=L max (So = N5W 20NE)
VC	Gran	7.5	4.0		axes at all angles to So
VC	Gran	15.0	10.0		most defm. taken up by matrix
VC	Gran	22.0	15.0		high mud matrix
VC	Gran	17.5	14.0		overturned syncline
VC	Gran	22.0	18.0		many square and triang. clasts
VC	Gran	14.5	6.0		very angular clasts
VC					
VC	Purp Volc.	22.0	21.5		
VC	Purp Volc.	25.0	15.0		triangle-shaped
VC	Purp Volc.	45.0	13.0		GMF rhyolite?
VC	Purp Volc.	30.0	23.0		GMF rhyolite?
VC					
VC	Black lg Bas.	100.0	55.0		?93x50cm?
VC	Black lg Bas.	23.0	14.0		VC bas.?
VC	Black lg Bas.	10.5	9.0		
VC	Black lg Bas.	10.0	9.5		
VC	Black lg Bas.	28.0	21.0		
VC	Black lg Bas.	15.0	11.0		
VC	Black lg Bas.	14.0	13.0		
VC					
VC	GrYelLamSist	20.0	12.0		
VC	GrYelLamSist	16.0	13.0		
VC	GrYelLamSist	30.0	6.5		A1 L So
VC	NON DUCT (10)	27.1	17.7		
VC	DUCTILE (7)	26.9	14.9		
VC,SG,WP-T,MT					
SG (6C)	Mixed	2.5	1.0		A1 // S1 // So (So = ~N17E 40SE)
SG	Decr. Abund.	1.1	1.0		high mud matrix
SG	Basalt,	2.0	1.5		
SG	PB/Grn Felsite,	3.5	2.0		
SG	VO, Gran, SiSt	2.5	1.5		
SG	purpFg SS/Qtz	9.0	4.0		
SG		6.0	1.5		
SG		5.5	2.5		
SG		2.0	1.0		
SG		4.0	2.0		
SG		2.0	1.0		
SG		3.5	2.0		
SG		2.5	1.0		
SG	MIXED (10)	4.1	1.9		
VC,SG,WP-T,MT					
WP-T					A1 // S1 // So (So = N20E 60SE)
WP (6D)	MIXED	4.2	.7		high mud matrix
WP	Mostly basalt,	6.2	2.7		
WP	granite, PPV,	7.5	2.6		
WP	and VO	1.9	1.7		
WP	Gen.same as SG	4.0	1.4		
WP		3.1	1.2		
WP		2.0	1.6		
WP		4.0	1.5		
WP		3.6	10.0		max axis L to S1 & So
WP		4.2	1.7		
WP		5.0	2.0		
WP		5.0	1.6		
WP-T					
T	MG- Gran		4.0	5.0	1024-T-1
T	basalt	8.0	5.0	9.0	1024-T-1
WP-T	MIXED(10)	5.3	3.2	7.0	A3 (2)
WP-T	(Non-Ductile)				
VC,SG,WP-T,MT					
MT (6E)	MIXED	4.0	1.5		A1 // S1 // So So = ?N10E 35SE?
MT	Mostly basalt,	15.0	2.0		high mud matrix
MT	granite, PPV,	12.2	4.3		
MT	and VO	1.5	1.0		
MT	Gen.same as SG	11.6	1.5		
MT		4.0	1.5		
MT		4.0	4.0		triangle - shaped
MT		9.0	2.3		
MT		1.7	1.0		
MT		2.3	1.0		
MT		7.3	2.2		
MT		6.0	2.1		
MT		9.9	4.0		
MT		6.5	2.0		
MT		5.0	3.0		
MT		4.0	2.9		
MT	MIXED(10)	6.7	2.7		

APPENDIX 5.

CLAST COMPOSITION DATA

Clast Types\Outcrop	GK - FH %	GK - FH freq	F %	F freq	PG%	PG freq	Clast Types\Outcrop	PBlow%	PBlow freq	PBup% 35-36.6	PBup 35-36.6 freq	PBup% 38.3-41.5
P/BqpV	41	112	29	123	35	35	P/BqpV	7	28	3	3	0
P/BqF	4	10	0	0	0	0	P/BqF	0	0	0	0	0
BPTnV	0	0	9	38	0	0	BPTnV	18	71	8	9	1
Volc Brecc	0	0	0	0	0	0	Volc Brecc	1	4	0	0	0
Purp/Black Felsite	45	122	38	161	35	35	Purp/Black Felsite	26	103	11	12	1
WGqpV	11	31	0	0	0	0	WGqpV	0		0	0	0
WGqF	0	0	0	0	0	0	WGqF	0		0	0	0
WhGreenFels	11	31	0	0	0	0	WhGreenFels	6	24	0	0	3
Purp/BlackGrnFels	57	153	38	161	35	35	Purp/BlackGrnFels	33	127	11	12	3
Andesite	0		2	8	0	0	Andesite	5	21	4	5	5
Basalt	0		0	0	12	12	Basalt	17	65	9	10	11
And/Bas	5	14	2	8	12	12	And/Bas	22	86	13	15	17
•							•					
VQ/Quartz	5	13	7	30	2	2	VQ/Quartz	7	27	8	9	16
Granite	17	45	34	142	38	38	Granite	16	62	18	20	29
Feldspar	0	0	7	29	0	0	Feldspar	5	20	5	6	20
Gneiss	2	5	1	6	0	0	Gneiss	3	10	0	0	4
Gran/Gneiss	19	50	42	177	38	38	Gran/Gneiss	24	92	23	26	53
•							•					
Tan/green fg SS/Qtzt	14	38	11	45	14	14	Tan/green fg SS/Qtzt	3	11	12	13	3
Purp X-bedded Qtzt	0	0	0	0	0	0	Purp X-bedded Qtzt	0	0	0	0	0
Rust/red,Milky chert	0	0	0	0	0	0	Rust/red,Milky chert	0	0	0	0	0
Grn/yell/purpLamSiSt	0	0	0	0	0	0	Grn/yell/purpLamSiSt	12	47	25	28	0
BlackGreySiltstone	1	2	0	0	0	0	BlackGreySiltstone	0	0	8	9	8
Total %/n	100	270	100	421	100	101	Total n	100	390	100	112	100
VOLCANIC	**62**	**167**	**40**	**169**	**47**	**47**	**VOLCANIC**	**55**	**213**	**24**	**27**	**20**
PLUT/MET	**23**	**63**	**49**	**207**	**40**	**40**	**PLUT/MET**	**31**	**119**	**31**	**35**	**68**
SEDIMENTARY	**15**	**40**	**11**	**45**	**14**	**14**	**SEDIMENTARY**	**15**	**58**	**45**	**50**	**11**
Graph Categories							***Graph Categories***					
PTG Felsite	57	153	38	161	35	35	PTG Felsite	33	127	11	12	3
And/Basalt	5	14	2	8	12	12	And/Basalt	22	86	13	15	17
												0
VQ/Quartz	5	13	7	30	2	2	VQ/Quartz	7	27	8	9	16
Gran/Gneiss	19	50	42	177	38	38	Gran/Gneiss	24	92	23	26	53
												0
SS/Qtzt/Ch	14	38	11	45	14	14	SS/Qtzt/Ch	3	11	12	13	3
Siltstone	1	2	0	0	0	0	Siltstone	12	47	33	37	8
Total	100	270	100	421	100	101	Total	100	390	100	112	100
STDEV	21		19		16			11		10		19
NOTES							NOTES					
Matrix (vol %)	26 % sandy		63.5% muddy	sand	27% sand		Matrix (vol%)	42.2% sandy		50% muddy	sand	31% muddy
VOLC TERN DATA							VOLC TERN DATA					
Tot QP+Q+And/Bas	100	167	100	131	100	47	Tot QP+Q+And/Bas	100	114	100	18	100
Total QPerth Volc	86	143	94	123	74	35	Total QPerth Volc	25	28	17	3	0
Total Q Volc	6	10	0	0	0	0	Total Q Volc	0	0	0	0	0
Total And/Basalt	8	14	6	8	26	12	Total And/Basalt	75	86	33	15	100

PBup38.3-41.5freq	Clast Types\Outcrop	PBup%43.1-45	PBup43.1-45freq	PBupTOT%	PBupTOT freq	PB Tot %	PB Tot freq.	SM %	SM freq	BEQ-HB%	BEQ-HB freq	BE %	BE freq
0	P/BqpV	1	1	1	4	4	32	0	0	0	0	0	0
0	P/BqF	0	0	0	0	0	0	0	0	37	89	26	80
1	BPTnF	1	1	3	11	11	82	1	2	16	38	11	34
0	Volc Brecc	1	1	0	1	1	5	0	0	0	0	0	0
1	Purp/Black Felsite	3	3	5	16	16	119	1	2	53	127	37	114
	WGqpV	0	0	0	0	0	0	41	55	0	0	0	0
	WGqF	0	0	0	0	0	0	0	0	17	40	23	70
3	WhGreenFels	0	0	1	3	4	27	41	55	17	40	23	70
4	Purp/BlackGrnFels	3	3	6	19	20	146	43	57	70	167	60	184
6	Andesite	7	8	6	19	5	40	1	1	0	0	0	0
13	Basalt	9	10	10	33	13	98	0	0	0	0	0	0
19	And/Bas	16	18	15	52	19	138	1	1	0	0	0	0
18	VQ/Quartz	16	18	13	45	10	72	4	6	23	55	35	108
33	Granite	18	20	22	73	19	135	16	21	0	1	2	6
23	Feldspar	4	4	10	33	7	53	0	0	0	0	0	0
5	Gneiss	6	7	4	12	3	22	9	12	0	0	0	0
61	Gran/Gneiss	28	31	35	118	29	210	25	33	0	1	2	6
4	Tan/Grn/pink fg SS/Qtz	24	27	13	44	8	55	28	37	0	0	0	0
0	Purp X-bedded Qtzt	0	0	0	0	0	0	0	0	4	9	1	2
0	Rust/red,Milky chert	0	0	0	0	0	0	0	0	3	7	2	7
0	Grn/yell/purpLamSiSt	9	10	11	38	12	85	0	0	0	0	0	0
9	BlackGreySiltstone	4	5	7	23	3	23	0	0	0	0	0	0
115	Total n	100	112	100	339	100	729	100	134	100	239	100	307
23	**VOLCANIC**	**19**	**21**	**21**	**71**	**39**	**284**	**43**	**58**	**70**	**167**	**60**	**184**
79	**PLUT/MET**	**44**	**49**	**48**	**163**	**39**	**282**	**29**	**39**	**23**	**56**	**37**	**114**
13	**SEDIMENTARY**	**38**	**42**	**31**	**105**	**22**	**163**	**28**	**37**	**7**	**16**	**3**	**9**
	Graph Categories									BEQ-HB%		BE%	
4	PTG Felsite	3	3	6	19	20	146	43	57	70	167	60	184
19	And/Basalt	16	18	15	52	19	138	1	1	0	0	0	0
18	VQ/Quartz	16	18	13	45	10	72	4	6	23	55	35	108
61	Gran/Gneiss	28	31	35	118	29	210	25	33	0	1	2	6
4	SS/Qtzt/Ch	24	27	13	44	8	55	28	37	7	16	3	9
9	Siltstone	13	15	18	61	15	138	0	0	0	0	0	0
115	Total	100	112	100	339	100	729	100	134	100	239	100	307
		9		10		8		18		28		25	
	NOTES												
sand	Matrix (vol%)	47% sandy	mud					15% ?		7% sand			
	VOLC TERN DATA												
19	Tot QP+Q+And/Bas	100	19	100	56	100	175	100	56	100	129	100	150
0	Total QPerth Volc	5	1	7	4	5	9	98	55	0	0	0	0
0	Total Q Volc	0	0	0	0	0	0	0	0	100	129	100	150
19	Total And/Basalt	95	18	93	52	95	166	2	1	0	0	0	0

Clast Types\Outcrop	BED %	BED freq	N %	N freq	VC %	VC freq	SG %	SG freq	Clast Types\Outcrop	WP %	WP freq	MT %	MT freq
P/BqpV	0	0	0	0	5	12	5	11	P/BqpV	3	9	10	29
P/BqF	28	44	42	195	12	32	7	14	P/BqF	3	8	2	6
BPTnF	19	29	10	45	14	36	0	0	BPTnF	0	0	0	0
Volc Brecc	0	0	0	0	0	0	0	0	Volc Brecc	0	0	0	0
Purp/Black Felsite	47	73	52	240	31	80	12	25	Purp/Black Felsite	6	17	12	35
WGqpV	0	0	0	0	0	0	0	0	WGqpV	0	0	0	0
WGqF	16	25	12	55	0	0	0	0	WGqF	0	0	0	0
WhGreenFels	16	25	12	55	0	0	0	0	WhGreenFels	0	0	0	0
Purp/BlackGrnFels	63	98	64	295	31	80	12	25	Purp/BlackGrnFels	6	17	12	35
Andesite	0	0	0	0	5	13	0	0	Andesite	0	0	0	0
Basalt	0	0	0	0	16	40	57	116	Basalt	79	212	77	229
And/Bas	0	0	0	0	21	53	57	116	And/Bas	79	212	77	229
•									•				
VQ/Quartz	30	46	28	130	10	26	11	22	VQ/Quartz	4	11	4	13
Granite	2	3	1	3	28	71	9	18	Granite	5	13	2	7
Feldspar	0	0	2	10	0	0	0	0	Feldspar	0	0	0	0
Gneiss	0	0	0	0	1	3	0	0	Gneiss	0	0	0	0
Gran/Gneiss	2	3	3	13	29	74	9	18	Gran/Gneiss	5	13	2	7
•									•				
an/Grn/purp fg SS/Qtz	0	0	0	0	9	22	3	7	an/Grn/purp fg SS/Qtz	2	5	1	3
Purp X-bedded Qtzt	3	4	3	16	0	0	0	0	Purp X-bedded Qtzt	0	0	0	0
Rust/red,Milky chert	3	4	1	6	0	0	0	0	Rust/red,Milky chert	0	0	0	0
Grn/yell/purpLamSiSt	0	0	0	0	0	0	0	0	Grn/yell/purpLamSiSt	0	0	0	0
BlackGreyGrnSiltstone	0	0	0	0	1	3	8	17	BlackGreyGrnSiltstone	4	11	4	11
Total n	100	155	100	460	100	258	100	205	Total n	100	269	100	298
VOLCANIC	**63**	**88**	**64**	**295**	**52**	**133**	**69**	**141**	**VOLCANIC**	**85**	**229**	**88**	**264**
PLUT/MET	**32**	**49**	**31**	**143**	**38**	**100**	**20**	**40**	**PLUT/MET**	**9**	**24**	**7**	**20**
SEDIMENTARY	**5**	**8**	**5**	**22**	**10**	**25**	**12**	**24**	**SEDIMENTARY**	**6**	**16**	**5**	**14**
Graph Categories	BED %		N %						***Graph Categories***				
PTG Felsite	63	98	64	295	31	80	12	25	PTG Felsite	6	17	12	35
And/Basalt	0	0	0	0	21	53	57	116	And/Basalt	79	212	77	229
VQ/Quartz	30	46	28	130	10	26	11	22	VQ/Quartz	4	11	4	13
Granite	2	3	3	13	29	74	9	18	Granite	5	13	2	7
SS/Qtzt/Ch	5	8	5	22	9	22	3	7	SS/Qtzt/Ch	2	5	1	3
Siltstone	0	0	0	0	1	3	8	17	Siltstone	4	11	4	11
Total	100	155	100	460	100	258	100	205	Total	100	269	100	298
	25		26		12		20			30		30	
NOTES									NOTES				
Matrix (vol%)	6%sand		22%sand		52% sandy	mud	69%sand	mud-	Matrix (vol%)	46%muddy	sand	77%muddy	sand-
							muddy	sand				sandy	mud
VOLC TERN DATA									VOLC TERN DATA				
Tot QP+Q+And/Bas	100	69	100	250	100	97	100	141	Tot QP+Q+And/Bas	100	229	100	264
Total QPerth Volc	0	0	0	0	12	12	8	11	Total QPerth Volc	4	9	11	29
Total Q Volc	100	69	100	250	33	32	10	14	Total Q Volc	3	8	2	6
Total And/Basalt	0	0	0	0	55	53	82	116	Total And/Basalt	93	212	87	229

VITA

Michael Joseph Neton was born in Milwaukee, Wisconsin on September 2, 1964. His family moved when he was two and he grew up in Appleton, WI where he attended Highlands Elementary School, and Einstein Junior Highschool. Many brisk days were spent at hockey practice and games. He graduated from Appleton West Highschool in May, 1983 where he played football, and soccer. Throughout his school years and into college he played the violin and viola in symphonies and in highschool jazz band.

After some deliberation, his path led him 100 miles south to the "Badger Den". Not long after he arrived he knew he was supposed to attend UW-Madison all along – why was there ever a question? While at Madison, Michael worked hard and played hard. Play included intramural hockey and football and some occasional ice-fishing, among other things. Work included engineering at first, then geography, then both geology and geography. In May, 1988 he received the Bachelor of Science degree with a double major in Geology and Geography from the University of Wisconsin at Madison.

Michael then worked the intervening summer as a geologist for Donohue Engineers, Architects, and Scientists before entering the University of Tennessee at Knoxville in August, 1988 – mobile belt geology! After many fine experiences at UT, including: field camp teaching assistant, a summer position with Exxon in Texas and Alaska, many memorable field experiences on Grandfather Mountain and in the southern Appalachians in general, and a continuing position with TVA, he received a Master of Science degree in Geology in 1992.

Tiger → Eagle → Terror → **Badger** → **VOL**