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THE ORIGIN OF REFLECTIONS BENEATH THE BLUE RIDGE-PIEDMONT ALLOCHTHON: A VIEW THROUGH THE GRANDFATHER MOUNTAIN WINDOW

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Abstract. A perplexing variety of crustal models have been proposed for the region beneath the southern Appalachian overthrust. Determining the true nature of crustal composition and structure in this region carries important scientific and economic implications. To evaluate the numerous models, compressional wave velocities and densities were measured on 30 rock samples collected within the Grandfather Mountain window in the Blue Ridge of North Carolina. The window breaches high-grade crystalline rocks, exposing Grenville gneisses, Late Proterozoic metasedimentary and metavolcanic rock, and Cambrian quartzite, phyllite, and dolostone that are likely to underlie the regional Blue Ridge-Piedmont thrust. Measured velocities range widely from 4.21 km s^{-1} for Cambrian phyllite to 7.47 km s^{-1} for tectonized Cambrian Shady Dolomite at 200 MPa. Velocity anisotropy is as great as 47% in the phyllite. The samples exhibit a broad range in densities as well: from 2500 kg m^{-3} in fractured quartzite to 3000 kg m^{-3} in metabasalts. Synthetic reflection seismograms were generated using these physical properties to consider the origin of subthrust reflection events. In addition to the much-publicized interpretation of Paleozoic sedimentary rocks residing beneath the crystalline sheet, modeling reveals that the reflections could also be explained by metamorphosed Paleozoic strata, by the regional Late Proterozoic metavolcanic and metaclastic rift sequence, and by pervasive shear zones (i.e., mylonites) within compositionally homogeneous gneisses. We interpret field data to strongly favor mylonitic gneisses as the subthrust reflectors. Still, surface data remain sufficiently ambiguous that the question will not be definitively settled without continental drilling.

INTRODUCTION

On the basis of geologic studies in the southern Appalachians (Figure 1), it has long been speculated that many, if not all, of the surface rocks have been thrust northwest from their original position along numerous faults [e.g., Jonas, 1932; Hatcher, 1971]. Bryant and Reed [1970*a*] and Hatcher [1971, 1972] suggested, based solely on geologic data, that the entire crystalline southern Appalachians are allochthonous, having been transported northwestward for some 200 km over autochtonous rocks. However, geologists have historically lacked subsurface information to constrain the behavior and geometry of the faults at depth. Subsequently, seismic reflection surveys have confirmed the magnitude of transport and provided important insight into fault geometry at depth. Allochthony of such an expansive area carries important implications for the mechanics of overthrusting, the involvement and subsequent migration of fluids, the potential for hydrocarbon generation and entrapment, and the timing of tectonic events in the region.

Seismic reflection interpretation in frontier regions tends to be speculative. Seismic interpreters rely on projecting known surface geology into the sections, often with only a guess as to the expected seismic expression of that geology. Laboratory physical property measurements, when compared with field data and used to generate synthetic reflection models, offer a tie between the surface exposures and subsurface geophysical information. This technique may be especially useful in regions where well information is sparse or absent. This paper uses laboratory-derived physical properties information to evaluate the origin of reflections beneath the southern Appalachian Blue Ridge-Piedmont overthrust.

REFLECTIVITY BENEATH THE BLUE RIDGE-PIEDMONT ALLOCHTHON

During the past decade, several seismic reflection surveys have been conducted in the crystalline Blue Ridge and Piedmont provinces of the southern Appalachians. These surveys imaged relatively continuous, high-amplitude reflections at depths between 6 and 12 km (Figure 2). The origin of these reflectors has been the subject of much speculation and controversy. As with most deep crustal seismic reflection studies, interpretation and data have become so strongly intertwined that it is often difficult for the casual reader to separate the two.

The first seismic reflection survey well within the crystalline southern Appalachians was conducted by Clark et al. [1978] just southeast of the Brevard fault zone, which forms the boundary between the Blue Ridge and Piedmont crystalline terranes (Figure 1). High-amplitude reflections observed at depths between 7 and 10 km were interpreted by Clark et al. to originate from Cambrian strata underlying crystalline Blue Ridge and Piedmont rocks. They also considered the possibility that these reflections could be produced by a layered volcanic or plutonic complex or by layered metamorphic rocks, such as the layered gneiss and amphibolite exposed in the Piedmont. However, they favored the interpretation of lower Paleozoic sedimentary rocks for two reasons: the discovery by Hatcher [1971, 1978] of exotic, presumed Paleozoic, carbonate slices within the Brevard fault zone; and their findings of high-amplitude reflections from the lower Paleozoic sedimentary section of the Valley and Ridge.

The Consortium for Continental Reflection Profiling (COCORP) conducted a coordinated seismic reflection program in the southern Appalachians [Cook et al., 1979, 1981]. The lines extended 480 km, from the extreme eastern Valley and Ridge and westernmost Blue Ridge of eastern Tennessee across the Piedmont to the interior coastal plain just northwest of Savannah, Georgia. There is, however, a gap of approximately 60 km in the line across the rugged Blue Ridge. This survey was the first extensive seismic reflection investigation in the southern Appalachians to suggest that sedimentary rocks similar to those in the Valley and Ridge underlie the Blue Ridge and Piedmont crystalline terranes. By their interpretation, a 6- to 15-km thick crystalline sheet was thrust a minimum of 260 km northwestward over sedimentary rocks

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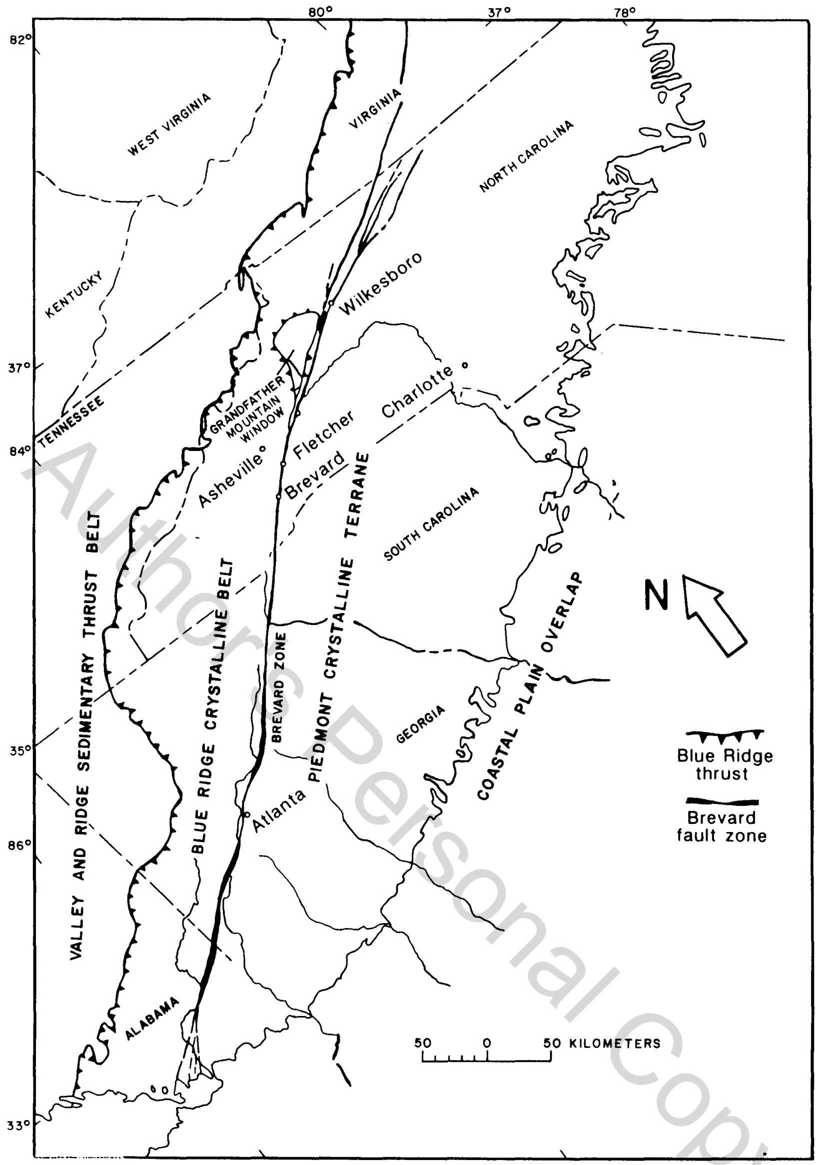

Fig. 1. Geologic provinces of the southern Appalachians showing location of Grandfather Mountain window.

that crop out in the Valley and Ridge. On the COCORP records, the Blue Ridge thrust dips steeply near the surface but flattens rapidly into a zone of near-horizontal layered reflectors at 5 to 6.5 km depth. The layered reflectors were assumed to originate from a relatively unmetamorphosed Cambro-Ordovician sequence underlying the crystalline thrust sheet, as suggested by Clark et al. [1978]. Cook et al. [1979] interpreted the decollement (Blue Ridge thrust) to reside at the top of these horizontal reflectors. The reflector package continues eastward at a depth of 9 to 12 km as far southeast as the surface exposure of the Kings Mountain belt of northwest South Carolina (Figure 1). Cook et al. [1979] interpreted these reflectors as a continuation of the sedimentary sequence, thickened and tilted beneath the Kings Mountain belt by southeast-dipping imbricated thrusts. However, Hatcher and Zietz [1980] suggested that the dipping reflectors indicate that the decollement roots beneath the Kings Mountain belt. To the southeast, beneath the Charlotte and Carolina slate belts, the reflectors again flatten. If these reflectors are continuous with those at the northwest edge of the Blue Ridge, then the Blue Ridge-Piedmont crystalline sheet may be allochthonous for the entire 260 km length of the profiles. Hatcher [1989] and Hatcher et al. [1989*a*,*b*] have shown, using balanced cross sections, that the minimum displacement is 350-400 km.

As supplemental evidence for the existence of unmetamorphosed Cambro-Ordovician platform sedimentary strata beneath the crystalline overthrust, Cook et al. cited two pieces of geologic evidence: the presence of relatively unmetamorphosed platform sedimentary rocks in the Grandfather Mountain window in the Blue Ridge of North Carolina and the occurrence of possible Paleozoic carbonate slices within the Brevard fault zone. Hatcher et al. [1973] concluded via statis-

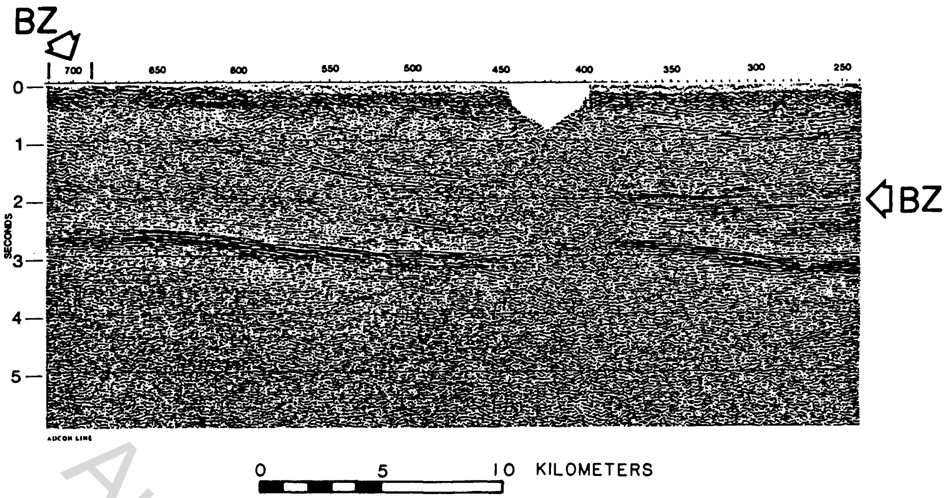

Fig. 2. ADCOH Line 1. BZ location of Brevard fault zone. Data from Hatcher et al. [1986]. Processed by J.K. Costain and C. Coruh, Virginia Tech.

tical comparison of geochemical data that the carbonate slices belong to the Cambro-Ordovician Knox Group. Reed and Bryant [1980], based on their detailed mapping in the Grandfather Mountain window [Bryant and Reed, 1970*b*], objected to Cook et al.'s interpretation. They noted that the rocks exposed within the window are the miogeoclinal (not platform) Cambrian (not Ordovician) Chilhowee Group and Shady Dolomite. These rocks compose the 1-km-thick Tablerock thrust sheet. This sheet is sandwiched between the overlying Linville Falls thrust sheet (which eroded, creating the window) and the underlying Middle Proterozoic plutonic gneisses and Late Proterozoic metasedimentary and metavolcanic rocks. The Cambrian rocks of the Tablerock thrust sheet are uniformly metamorphosed to greenschist facies assemblages. As an alternative, Bryant and Reed proposed that "some or all of the subhorizontal reflectors beneath the Blue Ridge may be in cataclastic rocks near the sole of the Blue Ridge thrust sheet, rather than in undeformed and little-metamorphosed Paleozoic strata." They conceded that if the tectonic slices in the Brevard fault zone are Cambrian or Ordovician, some lower Paleozoic rocks must be present in the subsurface to the southeast, but they have little hope that these will be of lower metamorphic grade.

Moench [1980] proposed that the subhorizontal reflectors beneath the southern Appalachians represent an extensive flat-lying granitic sheet complex like those in Maine. Such a complex would consist of sheets of granite alternating with schist and slate layers. He added that subhorizontal faults within such a body might enhance the overall reflectivity. In response to Moench, Cook et al. [1980] cited seismic reflection surveys by Harris and Bayer [1979] in northeast Tennessee and by the Societe Quebecoise d'Initiative Petrolier in southern Quebec. These surveys imaged continuous reflections from surface outcrops of sedimentary strata extending beneath crystalline terranes, but Cook et al. conceded that the reflections on the COCORP profiles could also be attributed to layered intrusives, intrabasement reflections of multiples, or layered mylonitic rocks.

Harris et al. [1981] reported the results of seismic reflection work in 1979 in the Valley and Ridge, Blue Ridge and Piedmont of northeast Tennessee and northwest North Carolina. Previous lines discussed by Milici et al. [1979] extended only 5 km into the Blue Ridge and indicated a 6-km-thick sedimentary section continuing beneath the Blue Ridge. The COCORP line had a 60-km gap across the Blue Ridge. The survey described by Harris et al. was intended to determine the continuity of reflectors, and hence the geologic continuity of sedimentary strata, beneath the Blue Ridge and Piedmont Provinces. The lines extend 110 km, from the Valley and Ridge of northeast Tennessee across the Mountain City and Grandfather Mountain windows of the Blue Ridge, then across the Brevard fault zone into the inner Piedmont of North Carolina. On the profiles, Harris et al. interpreted a lower crystalline basement uninvolved in thrusting and an overlying, completely detached sequence of sedimentary, metamorphic, and igneous rock. Beneath the Piedmont, the basement appears to be broken by a series of tilted fault blocks containing horizontal reflectors. They proposed that these reflectors are not sedimentary rock, but rather Precambrian metasedimentary and metavolcanic rocks such as those exposed in the Grandfather Mountain window.

Iverson and Smithson [1982] considered the dipping layered reflectors beneath the Kings Mountain belt to represent a wide zone of ultramylonite or cataclasite, as suggested by Reed and Bryant [1980]. The horizontal layers southeast of the dipping reflectors were interpreted as either granite sheets, as Moench [1980] suggested, or perhaps layered intrusives related to island-arc magmatism.

Behrendt [1985, 1986] reported on three Vibroseis lines in the Blue Ridge and Piedmont of the southern Appalachians. Behrendt [1986] interpreted the large number of diffraction events beneath the Carolina slate belt as the product of complexly faulted metasedimentary rocks.

In 1985, the Appalachian Ultradeep Core Hole Project (ADCOH) undertook a site selection study to locate a proposed ultradeep (10 km) drillhole in the southern Appalachians. The site study included the collection of 182 km of high-fold, high-quality vibroseis reflection data in the Blue Ridge and inner Piedmont of the Carolinas and Georgia (Figure 2). Interpretation of the data [Coruh et al., 1987; Hatcher et al., 1987; Costain et al., 1989*a,b*] was in general agreement with the finding of Cook et al. [1979, 1981] and Harris et al. [1981] that the Blue Ridge and Piedmont are allochthonous. However, the high resolution achieved by this survey also led to some major departures from previous interpretations. First, the thickness of the Blue Ridge thrust sheet is now believed to be 3 km, rather than the 6 to 8 km cited by earlier studies. This sheet is therefore underlain by 5 km of rock, interpreted by Hatcher et al. [1987] to be parautochthonous Paleozoic sedimentary strata overthickened by duplex faulting. As these stacked duplexes tend to underlie windows within the Blue Ridge, Hatcher et al. [1986] proposed that the crystalline Blue Ridge sheet was passively warped as fault stacking progressed in the underlying Paleozoic sedimentary rocks. Coruh et al. [1987] suggested that the wedge-shaped geometry of tectonically imbricated sedimentary slices of appropriate thickness produces high-amplitude reflections by tuning effects.

At least four major crystalline thrust faults are interpreted from the ADCOH sections [Costain et al., 1989*a,b*]. In contrast to the COCORP interpretation, the Brevard fault zone may not root in the master decollement (Blue Ridge-Piedmont thrust), but instead may carry the Piedmont allochthon over a thick sequence of parautochthonous sedimentary rocks. Harris et al. [1981] reached a similar interpretation for the Brevard fault zone near the Grandfather Mountain window. The interpreted master decollement underlies the platform sedimentary sequence and overlies basement of probable Grenville age, plus rift basins containing up to 2 km of Eocambrian and Cambrian metasedimentary strata.

The 3-km-thick interpreted Blue Ridge plate is largely acoustically transparent, with the exception of a few internal (thrust?) reflectors. The transparency is presumably due to the structural complexity of the Blue Ridge rocks [Costain et al. 1989*a,b*]. The underlying interpreted Paleozoic platform strata also have thick transparent zones, which led Hatcher et al. [1987] to consider these to be massive Cambro-Ordovician Knox Group carbonates, overthickened by faulting.

In summary, seismic reflection work in the southern Appalachians has raised more questions to date than it has answered. At issue is not only the geologic continuity of the reflectors beneath the Blue Ridge and Piedmont terranes, but also their lithologic composition. A wide variety of interpretations have been put forward: (1) unmetamorphosed and little-deformed Cambrian and Ordovician platform sedimentary rocks, (2) tectonically overthickened Ordovician carbonates with lesser shales, (3) metamorphosed Paleozoics, (4) metavolcanic and metaclastic Precambrian rift facies, (5) layered intrusives, (6) compositionally layered, high-grade metamorphic rocks (gneiss-amphibolite), (7) granitic sheet complexes with alternating slate and schist layers, (8) intrabasement reflectors, and (9) mylonites or cataclasites associated with pervasive shear zones. Of these interpretations, the relatively undeformed, Paleozoic platform sedimentary sequence has enjoyed the most publicity. Seismic reflection and laboratory studies within the Valley and Ridge to the northwest [e.g., Harris, 1976; Tegland, 1978; Christensen and Szymanski, 1991] clearly demonstrate that the lower Paleozoic sedimentary rocks of the region are quite capable of producing significant reflections. Seismic modeling by Christensen and Szymanski [1988] of the Brevard fault zone separating the Blue Ridge and Piedmont terranes demonstrated the reflectivity of mylonites within the zone. Other proposed origins are difficult to evaluate since many of these southern Appalachian sequences have not been seismically modeled. In the following sections, we examine the seismic properties and reflectivity of the rocks exposed in the Grandfather Mountain window.

GRANDFATHER MOUNTAIN WINDOW LITHOLOGIES AND THEIR SEISMIC PROPERTIES

Erosion has breached the gently domed Linville Falls fault plane in the eastern Blue Ridge of northwest North Carolina, creating the Grandfather Mountain window (Figure 3). The window is roughly 72 km long in a north-south direction and 32 km across at its north end, tapering southwestward to a point [Bryant and Reed, 1970*b*]. Exposed within the window are approximately 1200 km^2 of Grenville basement gneisses, Eocambrian metasedimentary and metavolcanic units, and a limited area of Lower Cambrian sedimentary rocks, metamorphosed to upper greenschist facies, which are clearly in sequence and thus correlative with the Chilhowee Group and Shady Dolomite exposed in the western Blue Ridge.

The area was first recognized as a window in a major overthrust by Jonas [1932] and was named [Stose and Stose, 1944] for the highest point within the area. Bryant and Reed [1970*b*] identified the Linville Falls fault as the major overthrust which transported high-grade metamorphic rocks over lower-grade, metamorphosed, Precambrian clastic and volcanic rocks, Cambrian and Eocambrian sedimentary rocks and Grenville-age gneisses. Bryant and Reed [1970*b*] speculated on the possibility of a master decollement underlying the Blue Ridge, indicating that basement rocks within the window are also allochthonous and that the Blue Ridge consisted of stacked thrust sheets. Harris et al. [1981] interpreted the rocks within the Grandfather Mountain window as part of a thrust sheet which was originally positioned several tens of kilometers east of the present day Brevard fault zone.

The oldest unit, exposed in the eastern area of the window, is the Wilson Creek Gneiss. The gneiss is typically foliated but not strongly compositionally layered, except for limited outcrops of layered gneiss along the eastern margin of the window. It is compositionally homogeneous, typically quartz monzonite, although outcrops of diorite also occur here. Deformation in the gneiss varies widely: some outcrops show little recrystallization, whereas other areas have been strongly sheared and mylonitized. Rankin et al. [1973] considered the Wilson Creek Gneiss to be part of a 1050 to 1190 Ma old plutonic group. On the basis of seismic interpretation, Harris et al. [1981] estimated a thickness of 2 km for the Wilson Creek Gneiss within the window down to the top of the underlying Pulaski thrust sheet, although the unit could be substantially thicker.

The Blowing Rock Gneiss, which occupies a belt 5 to 8 km wide and 24 km long within the Wilson Creek Gneiss, is a coarse, black and white, feldspar augen gneiss. Compositionally, it is a quartz monzonite with some occurrences of granodiorite to granite. It is unclear if the Blowing Rock Gneiss may be intrusive to the Wilson Creek Gneiss. Zircon dating yields concordant dates of 990-1055 Ma.

The Brown Mountain Granite is a 27 km^2 body exposed within the Wilson Creek Gneiss in the eastern part of the window. It is a medium- to coarse-grained, light red to pink homogeneous biotite granite. The Brown Mountain Granite probably intruded the Blowing Rock and Wilson Creek gneisses after the Grenville metamorphic-plutonic episode. Rankin

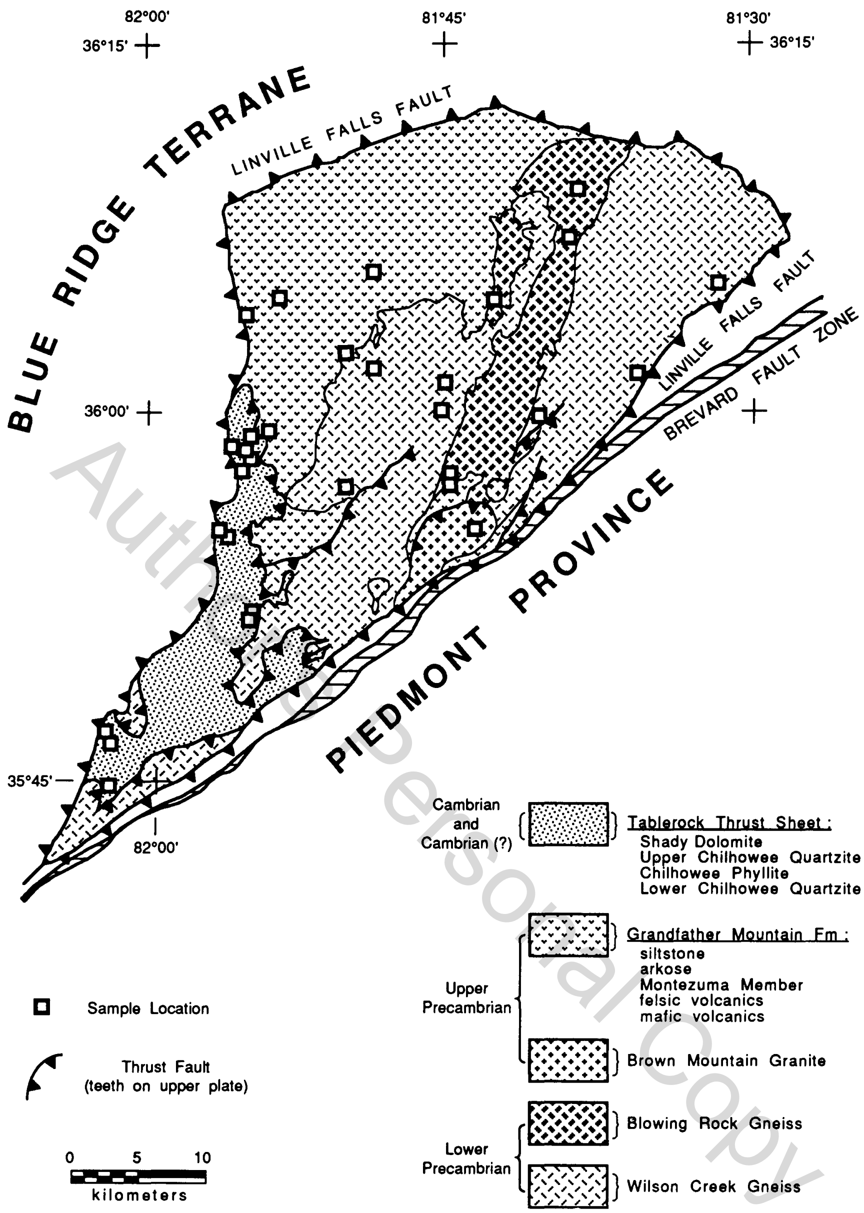

Fig. 3. Generalized geologic map of the Grandfather Mountain window [after Bryant and Reed, 1970*b*]. Dots locate 30 samples collected for velocity and density measurements.

et al. [1973] placed the Brown Mountain Granite in the Crossnore plutonic-volcanic group dated at 820 Ma and coeval with volcanism in the Grandfather Mountain Formation.

The Grandfather Mountain Formation occupies the northwestern third of the window. Bryant and Reed [1970*b*] recognized five interbedded and intertongued members within the Grandfather Mountain Formation: arkose, siltstone, felsic volcanic rocks, mafic volcanic rocks, and the mafic volcanic rocks of the Montezuma Member. The clastic rocks form the bulk of the unit. The arkose member ranges from metagraywacke, through quartzite, to a finer-grained metasiltstone. It also includes beds of pebble to boulder conglomerate. Siltstones are now typically grayish-green phyllites displaying good slaty cleavage parallel to bedding. Felsic volcanic rocks occur both in the basal Grandfather Mountain Formation, where they are interbedded with siltstone and, higher up in the formation, interbedded with arkose and Montezuma Member mafic volcanic rocks. The felsic flows, tuffs, and tuffaceous sedimentary rocks occupy an area of about 13 km^2 within the window. The mafic flows, flow breccias, and tuff breccias, are interfingered and interlayered with arkose and siltstone. Total exposure of the mafic volcanics is about 8 km^2. All rocks have been equally metamorphosed to greenschist facies assemblages. The Montezuma Member consists of mafic volcanics (now greenstone or greenschist), interbedded with arkoses and siltstones in the upper part of the Grandfather Mountain Formation. The rocks are exposed in a continuous belt about 24 km long in the northwestern part of the window (Figure 3). The Montezuma Member rocks differ from the mafic volcanic rocks in the lower part of the Grandfather Mountain Formation mainly in their nonporphyritic character, lack of tuffs, presence of amphibole, and lesser albite content [Bryant and Reed, 1970*b*].

The Linville Metadiabase occurs as scattered intrusions in the Grandfather Mountain Formation and Wilson Creek and Blowing Rock Gneisses. Bryant and Reed [1970*b*] did not include this unit in the Grandfather Mountain Formation but entertained the idea that it might be younger. However, their observation that no volcanics occur higher than the Montezuma Member, plus the cross-cutting character of the Linville Metadiabase, suggests that the metadiabase served as feeders for the mafic volcanic rocks [Rankin et al., 1973].

Bryant and Reed noted that abrupt changes in thickness and lithology within the Grandfather Mountain Formation suggest deposition in a rapidly subsiding basin. Rankin [1972] suggested that the bimodal volcanism and clastic influx were related to rifting and attenuation of the crust during the opening of the proto-Atlantic Ocean. Zircon dating of the felsic volcanics yields an age of 850 Ma, suggesting a late Precambrian age for the Grandfather Mountain Formation. Bryant and Reed [1970*b*] estimated that the thickness of the formation varies from 2100 to 9000 m, but measurement of stratigraphic sections is confounded by incomplete exposures, lack of distinctive, continuous markers, and complex structure.

The Chilhowee Group of Cambrian and Eocambrian age is confined to the Tablerock thrust sheet in the southwestern part of the window and to small tectonic slices along the Linville Falls fault surrounding the window. Areally, it constitutes most of the ~180 km^2 of the Tablerock thrust sheet within the window. Bryant and Reed [1970*b*] divided the Chilhowee Group into upper and lower quartzites separated by a relatively continuous phyllite unit. Both the upper and lower quartzites contain thin, interbedded, green phyllite. Stratigraphic thicknesses range from 240 to 415 m for the lower quartzite and from 400 to 760 m for the upper quartzite. The phyllite unit is finely laminated and strongly foliated and is generally less than 45 m thick. This thin unit is the extent of the "Cambrian shales" [Cook et al., 1980] exposed in the window.

The Shady Dolomite conformably overlies the upper Chilhowee quartzite. Outcrops of the Shady Dolomite occur along the west edge of the Tablerock thrust sheet near the Linville Falls fault. Areally, these outcrops amount to only ~2.5 km^2. Bryant and Reed [1970*b*] estimated a minimum stratigraphic thickness of 240 m of dolostone. Thin section fabrics clearly indicate that the dolostone is tectonized.

For this study, 30 samples were collected within the window from quarries and fresh road cuts for physical property measurements. Locations are shown in Figure 3. Acoustic velocities of the samples were measured at room temperature and hydrostatic confining pressures to 500 MPa using the pulse transmission technique described by Christensen [1985]. Bulk densities were obtained from the weights and dimensions of the cores used for the velocity measurements. Sample numbers, formation names, densities, and velocities are summarized in Table 1.

Figure 4 summarizes the measurements at 200 MPa in a

TABLE 1. Compressional Wave Velocity as a Function of Pressure

Sample	Orientation	Density kg m^{-3}	P = 20 MPa	P = 60 Mpa	P = 100 MPa	P = 200 MPa	P = 400 MPa	P = 600 MPa
GMW-1	A	2618	4.51	5.44	5.79	6.04	6.17	6.24
Wilson Creek	B	2587	5.37	5.94	6.11	6.24	6.32	6.36
Gneiss	C	2615	5.74	5.82	5.89	5.99	6.12	6.19
	MEAN	2607	5.21	5.73	5.93	6.09	6.20	6.26
GMW-2	A	2655	5.15	5.62	5.81	6.00	6.14	6.22
Wilson Creek	B	2658	5.67	6.00	6.12	6.24	6.34	6.40
Gneiss	C	2645	5.56	5.91	6.02	6.13	6.22	6.28
	MEAN	2653	5.46	5.84	5.98	6.12	6.23	6.30
GMW-3	A	2771	4.76	5.26	5.36	5.47	5.58	5.64
Wilson Creek	B	2768	6.80	6.94	7.01	7.11	7.20	7.24
Gneiss	C	2767	5.84	6.02	6.09	6.19	6.27	6.32
	MEAN	2769	5.87	6.07	6.16	6.26	6.35	6.40
GMW-4	A	2624	5.13	5.67	5.90	6.12	6.26	6.34
Wilson Creek	B	2636	5.39	5.85	6.08	6.29	6.40	6.46
Gneiss	C	2633	5.36	5.83	6.04	6.25	6.38	6.45
	MEAN	2631	5.29	5.78	6.01	6.22	6.35	6.42
GMW-5	A	2698	4.58	5.50	5.70	5.86	6.00	6.09
Wilson Creek	B	2687	5.60	6.00	6.24	6.37	6.46	6.51
Gneiss	C	2687	5.15	5.82	6.02	6.17	6.27	6.32
	MEAN	2691	5.11	5.77	5.99	6.13	6.24	6.31

TABLE 1. (continued)

Sample	Orien-tation	Density kg m^{-3}	P = 20 MPa	P = 60 Mpa	P = 100 MPa	P = 200 MPa	P = 400 MPa	P = 600 MPa
GMW-6	A	2693	4.18	5.02	5.41	5.80	6.03	6.15
Wilson Creek	B	2697	6.03	6.22	6.32	6.43	6.52	6.57
Gneiss	C	2694	5.46	5.82	5.93	6.06	6.18	6.25
	MEAN	2695	5.22	5.69	5.89	6.10	6.24	6.32
GMW-7	A	2701	5.04	5.34	5.46	5.60	5.72	5.80
Wilson Creek	B	2688	5.94	6.11	6.19	6.29	6.38	6.44
Gneiss	C	2701	4.90	5.41	5.67	5.94	6.13	6.22
	MEAN	2697	5.29	5.62	5.77	5.94	6.08	6.15
GMW-8	A	2600	3.43	3.95	4.24	4.66	5.04	5.24
Wilson Creek	B	2602	5.09	5.40	5.58	5.82	6.03	6.14
Gneiss	C	2636	4.11	4.56	4.81	5.17	5.48	5.62
	MEAN	2613	4.21	4.64	4.88	5.22	5.52	5.67
GMW-9	A	2604	4.46	5.22	5.56	5.89	6.08	6.19
Blowing Rock	B	2603	5.32	5.79	5.99	6.18	6.30	6.36
Gneiss	C	2625	4.88	5.54	5.84	6.13	6.28	6.36
	MEAN	2611	4.89	5.52	5.80	6.06	6.22	6.30
GMW-10	A	2554	3.98	6.73	5.11	5.54	5.86	6.03
Blowing Rock	B	2579	4.75	5.34	5.62	5.95	6.19	6.33
Gneiss	C	2545	4.10	4.85	5.23	5.64	5.91	6.05
	MEAN	2559	4.28	4.97	5.32	5.71	5.99	6.14
GMW-11	A	2741	5.06	5.54	5.71	5.85	5.97	6.04
Blowing Rock	B	2740	5.42	5.89	6.09	6.25	6.35	6.40
Gneiss	C	2739	5.35	5.88	6.08	6.24	6.35	6.41
	MEAN	2740	5.28	5.77	5.96	6.11	6.22	6.28
GMW-12	B	2600	5.73	6.06	6.16	6.26	6.35	6.40
Brown Mountain								
Granite								
GMW-13	A	2874	5.25	5.72	5.99	6.32	6.55	6.64
GMF Mafic	B	2877	5.76	6.15	6.37	6.61	6.76	6.82
Volcanic Member	C	2880	5.32	5.78	6.04	6.36	6.57	6.65
	MEAN	2877	5.44	5.88	6.13	6.43	6.62	6.70
GMW-14	A	2663	5.53	5.70	5.79	5.90	6.00	6.06
GMF Felsic	B	2657	6.07	6.19	6.25	6.33	6.40	6.44
Volcanic Member	C	2669	5.75	5.90	5.97	6.07	6.16	6.22
	MEAN	2663	5.78	5.93	6.00	6.10	6.19	6.24
GMW-15	A	2990	5.18	5.58	5.80	6.10	6.33	6.44
GMF Montezuma	B	3003	6.00	6.27	6.42	6.64	6.84	6.93
Member	C	3007	6.17	6.43	6.58	6.78	6.96	7.03
	MEAN	3000	5.79	6.09	6.27	6.51	6.71	6.80
GMW-16	A	2676	5.08	5.59	5.72	5.83	5.92	5.97
GMF Arkose	B	2679	5.70	6.18	6.30	6.38	6.45	6.48
Member	C	2678	5.21	5.81	5.97	6.08	6.17	6.22
	MEAN	2678	5.33	5.86	6.00	6.10	6.18	6.22

TABLE 1. (continued)

Sample	Orien-tation	Density kg m^{-3}	P = 20 MPa	P = 60 Mpa	P = 100 MPa	P = 200 MPa	P = 400 MPa	P = 600 MPa
GMW-17	A	2711	3.85	4.27	4.50	4.85	5.22	5.41
GMF Siltstone	B	2762	6.35	6.47	6.52	6.61	6.72	6.79
Member	C	2723	5.94	6.13	6.22	6.34	6.47	6.55
	MEAN	2732	5.38	5.62	5.75	5.94	6.14	6.25
GMW-18	A	2930	5.52	5.80	5.96	6.19	6.38	6.47
Linville	B	2930	6.35	6.48	6.56	6.68	6.81	6.87
Metadiabase	C	2938	5.82	6.10	6.26	6.48	6.67	6.75
	MEAN	2935	5.90	6.13	6.26	6.45	6.62	6.70
GMW-19	A	2554	3.53	4.24	4.63	5.11	5.45	5.62
Lower Chilhowee	B	2550	4.76	5.26	5.45	5.64	5.79	5.88
Quartzite	C	2556	3.88	4.86	5.30	5.70	5.91	6.02
	MEAN	2553	4.05	4.79	5.13	5.48	5.72	5.84
GMW-20	A	2692	3.14	3.59	3.84	4.21	4.61	4.84
Chilhowee	B	2678	5.73	6.05	6.22	6.46	6.62	6.70
Phyllite	C	2760	6.61	6.79	6.88	7.00	7.11	7.17
	MEAN	2710	5.16	5.48	5.65	5.89	6.12	6.24
GMW-21	A	2705	4.15	4.61	4.83	5.10	5.32	5.46
Chilhowee	B	2746	6.26	6.33	6.37	6.44	6.55	6.62
Phyllite	C	2672	5.70	5.98	6.12	6.27	6.39	6.46
	MEAN	2708	5.37	5.64	5.77	5.94	6.09	6.18
GMW-22	A	2583	4.10	4.57	4.80	5.08	5.32	5.46
Chilhowee	B	2588	5.96	6.10	6.18	6.31	6.44	6.50
Phyllite	C	2610	5.41	5.63	5.75	5.92	6.08	6.15
	MEAN	2594	5.16	5.43	5.58	5.77	5.95	6.04
GMW-23	A	2522	3.82	4.44	4.78	5.20	5.52	5.69
Chilhowee	B	2595	4.78	5.23	5.47	5.74	5.92	6.01
Phyllite	C	2557	5.26	5.44	5.52	5.65	5.80	5.90
	MEAN	2558	4.62	5.04	5.26	5.53	5.75	5.87
GMW-24	A	2637	5.56	5.75	5.84	5.95	6.06	6.12
Upper Chilhowee	B	2616	5.71	5.88	5.95	6.03	6.10	6.14
Quartzite	C	2646	5.80	5.90	5.96	6.03	6.10	6.13
	MEAN	2633	5.69	5.85	5.92	6.00	6.08	6.13
GMW-25	A	2488	3.57	4.04	4.33	4.77	5.21	5.42
Upper Chilhowee	B	2522	3.59	4.10	4.39	4.81	5.22	5.44
Quartzite	C	2498	3.54	4.02	4.31	4.74	5.15	5.34
	MEAN	2503	3.56	4.06	4.34	4.78	5.19	5.40
GMW-26	A	2600	5.09	5.54	5.72	5.89	6.00	6.06
Upper Chilhowee	B	2592	5.36	5.66	5.81	5.98	6.09	6.14
Quartzite	C	2595	5.48	5.77	5.90	6.03	6.11	6.16
	MEAN	2596	5.31	5.66	5.81	5.97	6.07	6.12
GMW-27	A	2648	4.96	5.55	5.74	5.89	6.02	6.09
Upper Chilhowee	B	2657	5.03	5.52	5.71	5.88	6.02	6.09
Quartzite	C	2643	5.46	5.85	5.98	6.09	6.20	6.26
	MEAN	2649	5.15	5.64	5.81	5.95	6.08	6.15

TABLE 1. (continued)

Sample	Orien-tation	Density kg m^{-3}	P = 20 MPa	P = 60 Mpa	P = 100 MPa	P = 200 MPa	P = 400 MPa	P = 600 MPa
GMW-28	A	2855	6.20	6.80	7.00	7.14	7.23	7.28
Shady	B	2857	6.35	6.98	7.17	7.30	7.37	7.41
Dolomite	C	2855	6.45	7.09	7.23	7.32	7.38	7.42
	MEAN	2856	6.33	6.95	7.14	7.25	7.33	7.37
GMW-29	A	2851	5.68	6.70	7.01	7.18	7.26	7.31
Shady	B	2857	6.06	6.98	7.23	7.36	7.45	7.50
Dolomite	C	2855	6.50	7.16	7.35	7.47	7.54	7.59
	MEAN	2854	6.08	6.94	7.20	7.34	7.42	7.46
GMW-30	A	2842	6.68	6.91	7.02	7.14	7.23	7.28
Shady	B	2851	6.86	7.07	7.16	7.25	7.33	7.37
Dolomite	C	2851	6.17	6.78	7.02	7.22	7.32	7.38
	MEAN	2848	6.57	6.92	7.07	7.20	7.29	7.34

Compressional wave velocity is given in kilometers per second.

plot of velocity versus mean density. Velocities for the samples vary from a low of 4.21 km s^{-1} measured normal to foliation in Chilhowee phyllite sample GMW-20, to a high of 7.47 km s^{-1} for Shady Dolomite sample GMW-29, measured in the foliation. Mean densities vary from a low of 2503 kg m^{-3} for fractured upper Chilhowee quartzite (GMW-25), to 3000 kg m^{-3} for Montezuma Member greenstones (GMW-15). Superimposed on the plot in Figure 4 are curves of constant acoustic impedance (Z). The acoustic impedance is the product of velocity and density. The more widely disparate two samples are in their Z values, the greater would be the amplitude of a reflection at their interface. This plot can be used to quickly calculate the expected reflection coefficient between any two samples. For the samples in this study, Z ranges between 11 and 22. Due to anisotropy, it is possible for different core orientations from the same sample to have very different Z values. Note that it is possible for samples with very different velocities and densities to fall along the same Z curve due to nonlinear velocity-density relationships.

The mean velocity for the Wilson Creek Gneiss cores is 6.0 km s^{-1}, and the mean density is 2669 kg m^{-3}, although there is considerable variation about this mean. The samples with the greatest degree of ductile deformation display high anisotropy. Increasing deformation is expressed as an increased percentage and orientation of micas, reduction in the size of feldspars, most of which are cannibalized for quartz and muscovite, and stringers or ribbons of strongly recrystallized quartz in a fine matrix of recrystallized quartz and feldspar.

The mean velocity for the Blowing Rock Gneiss is 5.88 km s^{-1}, and the mean density is 2624 kg m^{-3}. In sample GMW-10, the foliation is irregular as it wraps around large feldspars. The anisotropy of this sample is related to a fast B velocity which parallels lineation. In the finer-grained GMW-9, foliation is better developed, explaining the slower velocity normal to foliation.

Velocity was measured for one core of Brown Mountain Granite (GMW-12). This core is oriented parallel to a lineation defined by elongate biotite. The velocity of 6.26 km s^{-1} at 200 MPa is very similar to velocities reported for other granites by Birch [1960]. Since the rock is unfoliated, it is expected that the A and C velocities should be equal.

The arkosic quartzite (or metagraywacke) of the Grandfather Mountain Formation (GMW-16) has a relatively high velocity anisotropy of 9% at 200 MPa. A fast B velocity suggests a good mineral lineation in the foliation. The mean density of 2678 kg m^{-3} and mean velocity of 6.1 km s^{-1} are close to the mean velocity of Wilson Creek Gneiss. The phyllitic character of the Grandfather Mountain Formation siltstone (GMW-17) is indicated by a foliation-normal velocity that is 30% slower than foliation-parallel velocities. The mean velocity of this sample is 5.94 km s^{-1}, and the mean density of 2732 kg m^{-3}. The felsic volcanic rocks of the Grandfather Mountain Formation (GMW-14), having a mean density of 2663 kg m^{-3} and a mean velocity of 6.01 km s^{-1}, would be difficult to distinguish seismically from the Wilson Creek Gneiss or the Grandfather Mountain Formation arkose.

The mafic volcanic rocks (GMW-13), Linville Metadiabase (GMW-18), and Montezuma Member (GMW-15) are all properly described as greenschists or greenstones. They are characterized by high mean densities (2877-3000 kg m^{-3}). Mean velocities, which are similar for the three samples (~6.5 km s^{-1}), increase slightly with increasing density. The velocities for the greenstones are generally higher than cores of similar orientation for all other rock types, except for the carbonates and the fast foliation-parallel velocities in the phyllites. The greenstones will be highly reflective when in contact with the other Grandfather Mountain Formation lithologies.

The Chilhowee quartzite is characterized by uniform velocities (5.78 km s^{-1}) and densities (2608 kg m^{-3}), and minimal anisotropy. Despite a strong bedding-parallel foliation, mica content is apparently too low to affect velocities. GMW-19 has an anomalously low density of 2553 kg m^{-3} and an anomalously high anisotropy of 11% that is attributed to the fractured character of the sample.

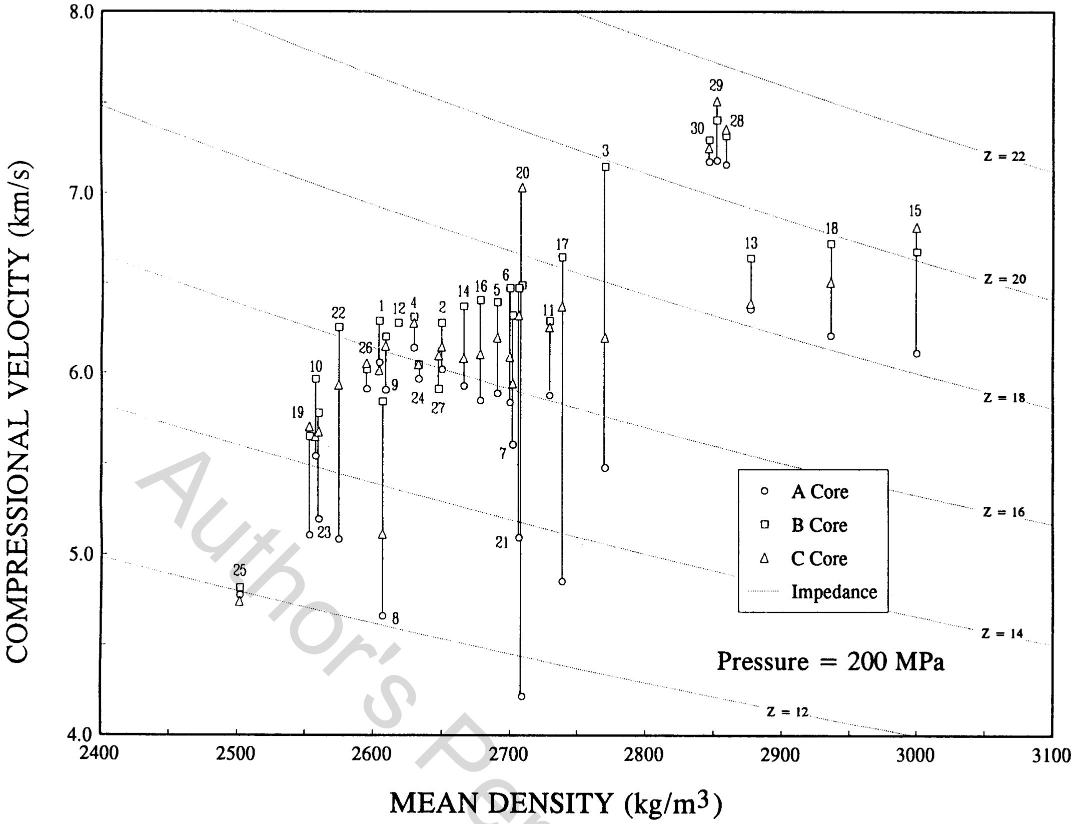

Fig. 4. Compressional wave velocity versus mean density at 200 MPa for all samples. Lines connect mutually perpendicular cores from a given sample. The length of the lines is proportional to the anisotropy of the samples. Circles represent cores oriented normal to foliation or bedding (A cores). Squares indicate cores lying in the foliation parallel to the trend of the lineation (B cores). Triangles indicate cores which are normal to the A and B cores. Stratigraphic units corresponding to the sample numbers are presented in Table 1.

The exceptional anisotropy of the Chilhowee phyllite results in markedly different velocity observations when viewed by the seismic reflection technique versus the seismic refraction technique. Sample GMW-20 has 47% anisotropy, with a 4.21 km s^{-1} velocity normal to foliation and 7.00 km s^{-1} in the foliation. Sample GMW-21 has an anisotropy of 22%, but the velocity normal to foliation is much higher (5.10 km s^{-1}) than in GMW-20, due to a well-developed crenulation. Phyllites in contact with the quartzite produce strong reflections because of the low velocities normal to foliation in the phyllites. Thus, anisotropy is important in generating strong reflections in this unit. The extremely high velocities in the foliation suggest that extensive phyllite layers could be detected by detailed refraction experiments, although the measured velocities could be close to those of carbonates. Samples GMW-22 and 23 are transitional between phyllite and quartzite.

The Shady Dolomite, with a mean velocity of 7.26 km s^{-1}, is extremely fast. The mean density of 2853 kg m^{-3} is also high. These velocities are characteristic of dolomitic marbles. Velocities normal to bedding are slower than those parallel to bedding. Thin section fabric indicates a tectonite origin. The high velocity and density of these dolostones give them the highest acoustic impedance of all the samples. The reflection coefficient at the Shady Dolomite-Chilhowee quartzite contact is about -0.14.

These physical property measurements suggest that the Grandfather Mountain window exposes three highly reflective sequences. The metamorphosed Paleozoic rocks (Chilhowee Group-Shady Dolomite) should produce several high-amplitude reflection events. The Grandfather Mountain Formation also appears to be a reflective unit, but reflectivity is complicated by the lenticular character of the members. The observed variations in velocity in the Wilson Creek Gneiss, originating from nonuniform shear, offers an additional source of reflections. In the following section, we explore the reflectivity of these units.

REFLECTION MODELING

In the remainder of the paper, synthetic seismograms are used to examine the origin of reflections within and beneath the Blue Ridge terrane. First, we consider the reflectivity of the Grandfather Mountain Formation, along with the overlying metamorphosed Paleozoic section exposed in the window. Then we use the velocity and density data measured for the suite of Wilson Creek Gneiss samples to demonstrate the inherent reflectivity of these Precambrian crystalline rocks. Finally, the reflectivity is presented for a Paleozoic sedimentary section metamorphosed to the greenschist facies. These

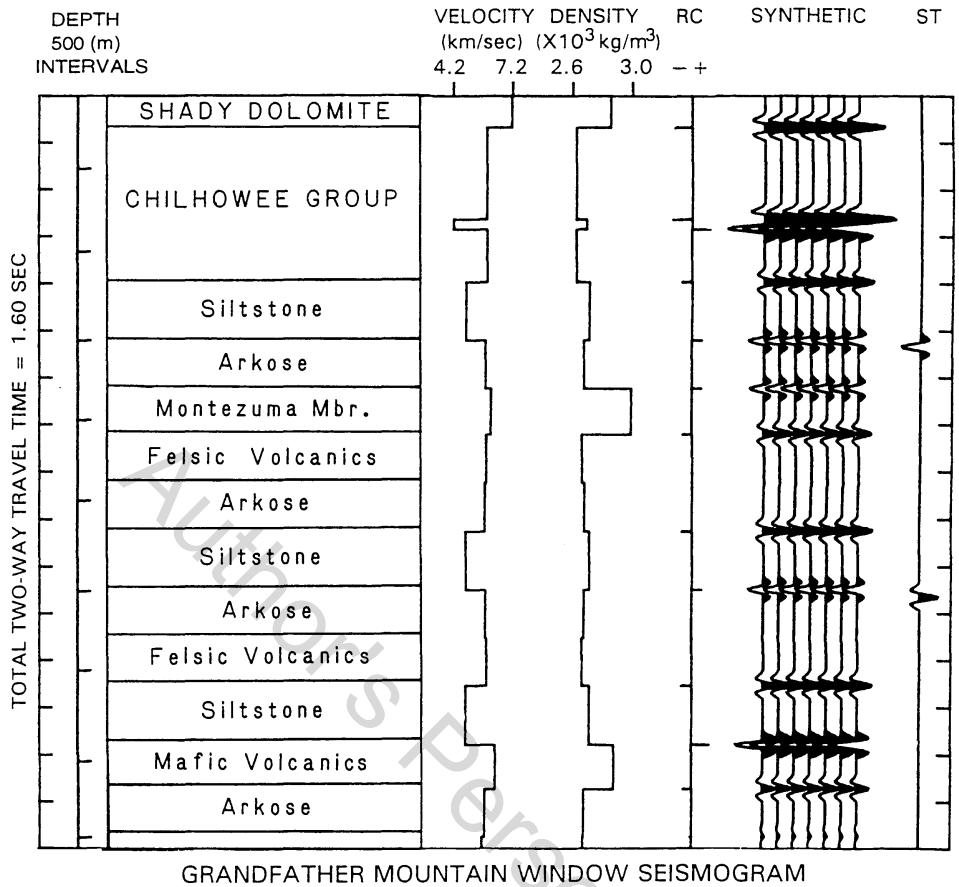

Fig. 5. Vertical incidence synthetic seismogram for the complete stratigraphic column exposed in the Grandfather Mountain window.

models reveal the ambiguity of interpreting lithologies from seismic reflection records in areas with no well control.

Synthetic reflection seismograms emulate the behavior of a seismic wave impinging with normal incidence upon a plane-layer model [Wuenschel, 1960; Robinson and Treitel, 1977]. This behavior is governed by the acoustic impedance (Z) of the rock, defined as the product of density (r) and velocity (V). The reflection coefficient is a measure of the portion of energy reflected from an interface. At vertical incidence, the simple reflection coefficient for an interface between layers with impedances Z_1 and Z_2 is $R = (Z_2 - Z_1)/(Z_2 + Z_1)$, where $-1 \leq R \leq 1$. This equation serves as a useful approximation for angles of incidence approaching 20°. A value of $R = \pm 1$ indicates total reflection of energy; $R = 0$ implies total transmission.

Using the laboratory density and velocity data and estimating thicknesses of lithologic units, a time series containing the reflection coefficient information is constructed. This series is convolved with a zero phase, Ricker wavelet to produce the seismograms. A 25-Hz wavelet is used, corresponding to a frequency typically exploited in crustal surveys [Coruh et al., 1987]. Random noise, which generally deteriorates the coherency and hence the interpretability of seismic reflection events, is neglected here. Multiple reflections are not shown. Transmission losses are accounted for, but no corrections are made for dispersion, geometrical spreading, or attenuation.

Figure 5 is a one-dimensional seismogram for the stratigraphic column consisting of the Grandfather Mountain Formation and overlying Chilhowee Group and Shady Dolomite metamorphosed Paleozoic rocks. The vertical scale is total two-way travel time in seconds, which is 1.6 s for this model. The leftmost trace is a depth scale in 500-m intervals. To the right of this is the stratigraphic column used in the model. A conservative choice of 3000 m is taken as the total thickness of the Grandfather Mountain Formation. The unit is divided into 10 members, each arbitrarily considered 300 m thick. In this model, the underlying Wilson Creek Gneiss is considered homogeneous and isotropic and therefore of uniform velocity and density. The velocity and density models are seen to vary between 4.2 and 7.2 km s^{-1}, and 2600 and 3000 kg m^{-3}, respectively. Velocities and densities used are for the cores normal to foliation. The reflection coefficient (RC) series depicts increases in acoustic impedance as excursions to the left. The synthetic seismogram consists of seven identical traces, simulating a segment of a zero-offset, two-dimensional seismic record. A standard trace (ST), corresponding to a three-layer model consisting of a +0.1 and a -0.1 reflection coefficient event, is provided so that the magnitude of the model events can be better appreciated and crudely quantified. A 0.1 reflection coefficient is about the magnitude of that associated with a sandstone-limestone contact in a sedimentary sequence.

A negative reflection event (RC = -0.14) occurs at the Shady Dolomite-Chilhowee Group contact. The phyllite in the Chilhowee Group is marked by an unusually high-amplitude event. Though the reflection coefficient (RC = $\pm$ 0.15) for the phyllite-quartzite contact is not much greater than for the Shady Dolomite-Chilhowee quartzite interface, constructive interference between reflections from the top and base of the phyllite enhances amplitudes.

The reflection events within and at the top of the Grandfather Mountain Formation are strong. For most of these contacts the reflection coefficients are $\pm$0.07, with the exception of the almost negligible acoustic impedance contrast between the felsic volcanic rocks and arkose and between the arkose and the underlying Wilson Creek Gneiss. The coefficient for the siltstone-mafic volcanic rocks contact is high (0.14). This model shows that the Grandfather Mountain Formation and its equivalents are characterized in the subsurface by high-amplitude reflection events, which support the opinion of Harris et al. [1981] that the horizontal events beneath the Piedmont allochthon may represent layered metasedimentary and volcanic rocks. Hence, the Piedmont and perhaps the Blue Ridge as well may overlie rift basins similar to, but probably narrower than, those exposed in the Grandfather Mountain window.

The velocity model used here is an oversimplification of the complexities of the Grandfather Mountain Formation. Bryant and Reed [1970*b*] described the siltstone and arkoses as interbedded and interfingered. Also, the mafic volcanic rocks reportedly contain interbeds of phyllite. This variability will probably enhance the reflectivity of the section, especially if the layers are the appropriate thickness for constructive interference of the source wavelet. Reflectors may be discontinuous, due to lateral variability.

As discussed earlier, the velocity of the Wilson Creek Gneiss underlying the Grandfather Mountain Formation varies according to the degree of ductile deformation. A seismogram (Figure 6), which models the measured velocity variability, demonstrates that the reflections within and/or beneath the Blue Ridge-Piedmont thrust sheet may be produced by phyllonite and mylonite along pervasive shear zones, as suggested by Reed and Bryant [1980].

Hatcher et al. [1987], using ADCOH reflection records, identified possible fault duplexes beneath another Blue Ridge window, the Shooting Creek window in Georgia. They proposed that the duplexes consist principally of Ordovician carbonates, for several reasons. First, a stack of shales would be too mechanically weak to support the overlying crystalline sheet. Second, carbonates compose most of the lower Paleozoic section exposed in the Valley and Ridge, although this stratigraphic section would have to be repeated about 3 times to equal the thickness of the imaged duplex. Third, the duplexes are largely acoustically transparent, with only a few internal reflectors. Most of the reflections are concentrated at the top and base of the structure.

The finding that phyllonites and mylonites along discrete shear zones can produce multicyclic reflections similar to a layered sedimentary sequence creates the possibility that the structures are crustal duplexes, involving thrust stacking of granitic gneisses or other high-grade crystalline rocks. Since many of the shear zones would have relatively low amplitude reflections, it would not be surprising that the duplex interior lacks reflections. Reflections would be strongest where the

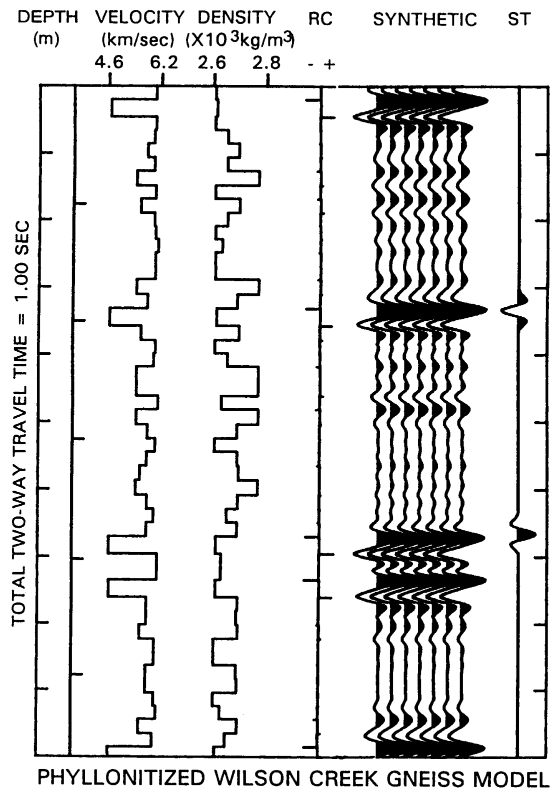

Fig. 6. Vertical incidence synthetic seismogram for a random distribution of the foliation-normal velocities and densities of the Wilson Creek Gneiss samples. Layers are 60 m thick.

shearing was greatest and the rock most deformed; namely, at the top and base of the structure.

Significantly, the velocities of some of the possible dulex materials are distinctive. At 200 MPa, measured parallel to bedding, the Shady Dolomite has a velocity of ~7.3 km s^{-1}, while the Wilson Creek Gneiss averages 6.4 km s^{-1} and the Chilhowee quartzite ~5.8 km s^{-1}. A detailed seismic refraction experiment could distinguish between a predominantly carbonate duplex and a quartzite or gneiss duplex.

Analysis of the velocity spectra of the ADCOH data by Coruh et al. [1987] yielded interval velocities from 4.2 to 6.5 km s^{-1} and average velocities from 5.2 to 5.6 km s^{-1}. This range of interval velocities encompasses all of the Grandfather Mountain window lithologies, except the Shady Dolomite, which at 200 MPa is 0.5 to 1.0 km s^{-1} faster than the highest reported interval velocity. The mean velocity of the normal-foliation-normal cores for the Wilson Creek Gneiss at 200 MPa is 6.0 km s^{-1}. Thus, based on velocity information, it is more likely that the duplexes consist of granitic gneiss than metamorphosed carbonates.

IMPLICATIONS

The interpretation of reflections beneath the Blue Ridge-Piedmont thrust sheet is still open to much debate. Existing interpretations favor a relatively continuous, unmetamorphosed Paleozoic sedimentary sequence as the source of the reflections beneath the allochthon, but the synthetic modeling il-

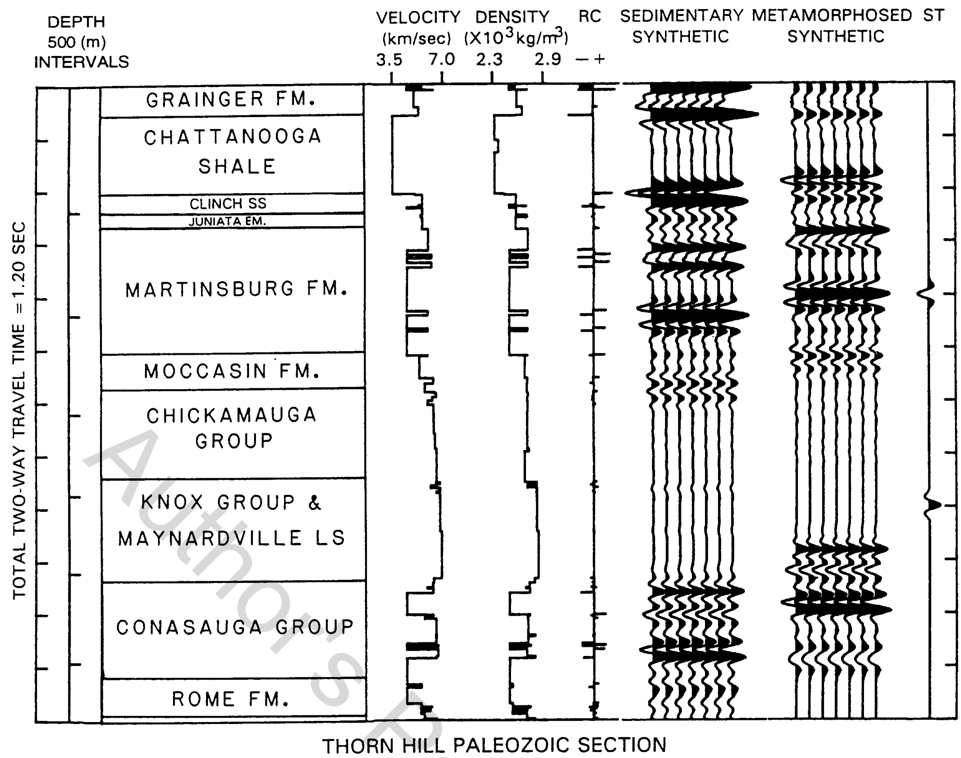

Fig. 7. Comparison of synthetic reflection models for an unmetamorphosed and metamorphosed Paleozoic sedimentary section.

lustrates that such multicyclic reflections can also be attributed to Precambrian metaclastic and metavolcanic rift facies such as the Grandfather Mountain Formation and to variable shearing in Precambrian gneisses. The mylonites may be responsible for some of the reflections in the Blue Ridge-Piedmont overthrust sheet as well. A fourth possible origin for the reflections is suggested in Figure 7 where a synthetic seismogram was generated using the velocities for the Thorn Hill Paleozoic sedimentary section [Christensen and Szymanski, 1991] with velocities and densities adjusted to greenschist facies conditions. The synthetic modeling shows that the unmetamorphosed section has a greater reflectivity within the upper section, although the metamorphosed section is clearly highly reflective.

The fastest rocks likely to occur beneath the Blue Ridge-Piedmont are dolostone (mean velocity = 7.26 km s^{-1} at 200 MPa). Limestones would have slightly lower velocities (~6.90 km s^{-1}). Because of this unique high velocity, extensive carbonate layers should be detectable by seismic refraction studies. The mean density of dolostone (2853 kg m^{-3}) is high relative to Blue Ridge thrust sheet lithologies surrounding the windows, such as biotite gneisses, garnetiferous schist and metagraywacke (2733 kg m^{-3}). The mean density for the Wilson Creek Gneiss is 2669 kg m^{-3}. Duplexes composed mainly of dolostone would be expected to register as gravity highs, as opposed to the lows observed over these structures [Haworth et al., 1980]. The slowest rocks likely to lie beneath the overthrust sheet are Cambrian phyllites (4.21 km s^{-1} measured normal to foliation), but because of the extreme anisotropy (up to 47%) of the phyllites, extensive phyllite layers would have refraction velocities as much as 1.5 times faster.

In summary, seismic modeling shows that prominent reflections within and beneath the crystalline Blue Ridge-Piedmont allochthon can be explained by metamorphosed Paleozoic rocks, by clastic-volcanic rift sequences such as the Grandfather Mountain Formation, and by shear zones within Precambrian granitic gneiss. Metamorphosed Paleozoic rocks, although present within Blue Ridge windows, are areally and stratigraphically minimal compared to granitic gneisses within the windows. Seismic velocity and gravity information for the Blue Ridge appears to be best explained by the presence of granitic gneiss complexes beneath the surface lithologies. Wide-angle seismic surveys, gravity modeling, and additional laboratory studies of velocities and densities may narrow the range of interpretations, although it is clear that the origin of these reflectors, and the timing of tectonic events, will not be unequivocally known until the Blue Ridge-Piedmont allochthon is drilled. Meanwhile, the reader may accept one or more of these interpretations, or may prefer "none of the above."

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