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Paleozoic and Grenvillian Structures

in the

Southern Appalachians:

Extended Interpretation from

Seismic Reflection Data

by

Susan Sharpless Hubbard

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Geophysics

in

Department of Geological Sciences

APPROVED:

Cahit Çoruh, Chairman

John K. Costain

Edwin S. Robinson

January 30, 1990

Blacksburg, Virginia

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(ABSTRACT)

Interpretive reprocessing of seismic reflection data and correlation of the seismic data with gravity data have elucidated Paleozoic and Grenvillian structures in the southern Appalachians. The seismic data include ADCOII, Seisdata, and COCORP reflection profiles which traverse the Blue Ridge and Inner Piedmont geologic provinces of South Carolina, North Carolina, and Georgia.

Based on the reprocessed data, all of the major faults within the allochthonous upper crust, including the Brevard fault zone and the Hayesville fault, are interpreted to root in the Blue Ridge master decollement. Reflectors extending beneath the surface location of the Hayesville fault may be a deformational zone that extends in the direction of structural strike and is associated with Alleghanian transpression. Alternatively, the reflectors may actually represent the subsurface location of the Hayesville fault, in which case convergent reflector geometry of the Hayesville fault and the Blue Ridge thrust suggest that the Blue Ridge thrust occupied a zone of weakness previously created by the Hayesville fault. Both the Blue Ridge thrust and Brevard fault zone ramps are interpreted to have a genetic relation to underlying basement topography. Relative amplitude data enabled the discrimination between Blue Ridge-Inner Piedmont crystalline rocks from underlying Lower Paleozoic shelf strata, thereby allowing the delineation of the Blue Ridge thrust. The revised geometry of the Blue Ridge thrust constrains the top of the shelf sequence beneath the Blue Ridge to depths less than 3 km. This relatively shallow depth of the shelf sequence, and the pres-

ence of duplex structures and bright spots within the sequence are auspicious factors for hydrocarbon exploration.

Reflectors within the upper-to-lower crust are interpreted to be preserved Grenvillian structures that were reactivated at the basement surface during Late Proterozoic-Early Cambrian extension. The reflectors are cross-cut by proposed post-Grenvillian, pre-Alleghanian low density intrusions that have acoustically transparent bases. Correlation of seismic and gravity data suggests that disturbances in the Bouguer gravity field can be attributed to these structures within the autochthonous crust.

Discontinuous reflection packages from depths of 36-42 km are interpreted to originate from the Mohorovicic Discontinuity. The reflectors trend about N15°E with a true dip of approximately 15°NW.

Acknowledgements

I would like to thank Cahit Çoruh for being a truly wonderful advisor. His original conception of the project, insightful and circumspect guidance, help obtaining financial support, and friendship have been invaluable. Working with Cahit has been a real pleasure. I would also like to thank John Costain for his unbridled enthusiasm about everything, including my project, and especially for careful editing of manuscripts and valuable discussions regarding different facets of Appalachian geology. I am obliged to Mildred Memitt, regional geophysics laboratory computer lead operator, for day-to-day system assistance and for patiently answering my weekend cries of help. Thanks is extended to Edwin Robinson for serving on my committee, and to Rick Williams (University of Tennessee, Knoxville), William Iverson (University of Wyoming), Bob Hatcher (University of Tennessee, Knoxville and Oak Ridge National Laboratory), and Bob Lillie (University of Oregon), who provided insightful conversation or data or both. Lastly, a special thanks to my husband, Alan Hubbard, for (among *many* other things) listening to me talk about seismic wavelets when he'd rather be reading or sleeping, and to my parents, Leslie and Barbara Sharpless, for always seeing me through the rosier of glasses.

Support for the VAX 11/780 and personal assistance was obtained from the Department of Geological Sciences, as well as from ARCO Oil and Gas, Chevron, and Amoco Oil Companies.

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Introduction

A myriad of geological and geophysical investigations has been conducted in the southern Appalachians, particularly in the past 10 years. Although a thin-skinned tectonic mechanism has been generally accepted as the method of emplacement of the Blue Ridge-Inner Piedmont overthrust sheet, the geometry and timing of some of the individual geologic structures within and beneath the allochthon remain ambiguous. Uncertainties are associated with the thickness and internal structure of the Blue Ridge-Inner Piedmont overthrust sheet, the timing and sense of faults within the overthrust sheet, the locations of the Taconic and Alleghanian sutures, the hydrocarbon potential within the shelf strata beneath the Blue Ridge-Inner Piedmont allochthon, the origin of potential field anomalies, and the structure of the Grenvillian basement. The ADCOH (Appalachian ultraDeep COre Hole) site study (Hatcher et al., 1988) was conducted to determine the optimal location for a 12 km scientific core hole designed, among other objectives, to test hypotheses pertaining to the southern Appalachian tectonic framework. ADCOH, Seisdata, and COCORP seismic reflection data were acquired within the ADCOH site, which is situated in the Blue Ridge and Inner Piedmont of North Carolina, South Carolina, and Georgia (Figure 1 and Figure 2). Reprocessing of the ADCOH and Seisdata seismic data sets using both relative amplitude and conventional methods, automatic line drawings of reprocessed COCORP data, and correlation of the interpreted seismic data with potential field data have helped to address some of the aforementioned questions.

The reprocessed data have delineated the internal and external geometry of the crystalline Blue Ridge-Inner Piedmont allochthon, including the locations of the Blue Ridge, Hayesville, and Brevard fault zones. The depth and thickness of the Lower Paleozoic shelf strata beneath the allochthon and the associated hydrocarbon potential within the sequence are discussed. Reflectors within the upper-to-lower autochthonous Grenvillian crust are interpreted to be structures that have originated during the Grenville orogeny and were reactivated at the basement surface during a later extensional event (Hubbard et al., 1989b). These structures are cross-cut by interpreted post-Grenvillian, pre-Alleghanian low density intrusions that acoustically transparent bases. Topography at the basement surface, which is partially controlled by the intrusions, is interpreted to have

controlled the formation of some of the structures within the overlying allochthon, including the Blue Ridge thrust and Brevard fault zone ramps. Correlation of seismic time-structure contour maps with available gravity data and two-dimensional gravity modeling suggest that disturbances in the gravity field can be attributed to structures within the autochthonous crust.

Figure 1. Geographic setting of the ADCOH Site.

Figure 2. Geographic and geologic setting of ADCOH site: ADCOH, Seisdata and COCORP seismic reflection profiles in the Blue Ridge and Inner Piedmont provinces of North Carolina, South Carolina, and Georgia.

Southern Appalachian Geological History

The Appalachian orogen extends northeast to southwest from Newfoundland to Alabama. The southern Appalachians extend from central Virginia to central Alabama and consist of westward-verging structures with a strike of approximately N45°E. The southern Appalachians are usually divided along strike into 3 major geological provinces (from west to east): the Valley and Ridge marginal fold and thrust belt, the Blue Ridge Province, and the Piedmont Province. The latter is represented by the Inner Piedmont, the Charlotte Belt, and the Carolina Slate Belt. The geologic history spans from the Proterozoic through the Mesozoic and includes rifting events, arc-continent, and continent-continent collisional events.

The metamorphic and deformational history of the southern Appalachians is complex. Deformation and metamorphism accompanied the Proterozoic Grenvillian and Paleozoic orogenies. As a result, many of the rocks have been polydeformed and polymetamorphosed, and several older faults have been reactivated under a later brittle stress regime. Metamorphism within the Blue Ridge-Inner Piedmont allochthon can be described as classic Barrovian, with an increasing grade from lower greenschist in the western Blue Ridge to upper amphibolite in the eastern Blue Ridge and central Piedmont (Hatcher, 1978). Geologic mapping, geochronology, potential field, and seismic data have helped to decipher the complex geologic history of the southern Appalachians. The following overview will emphasize the tectonic evolution of the Blue Ridge and Inner Piedmont of North Carolina, South Carolina, and Georgia.

Proterozoic

The Grenville is the oldest orogeny to have affected the rocks in the study area. The principal Grenvillian orogeny occurred approximately 1140-1000 Ma ago, although various parts of the Grenville crust were involved in a series of Archaean through mid-Proterozoic deformational and thermal events. The orogeny culminated around 1100 Ma, with pervasive thermal and north-to-northwest directed compression (Moore, 1986). The compression may have been the result of

intracratonic thrusting or a collision between the North American craton and a Euro-African craton (Woussen et al., 1986). The result of the deformation was the juxtaposition of North American Central (1200-1500 Ma), Penokean (1600-1900 Ma), and Superior (2300-3300 Ma) basement rocks with eastern North American Proterozoic Grenvillian rocks along what is now referred to as the Grenville front.

Late Proterozoic-Early Cambrian

Extension was initiated in eastern North America during the Late Proterozoic as a result of the separation of the Laurentia and Baltica continents. A debate ensues as to whether the rifting of a continental fragment from the southeastern continental margin during this extensional event resulted in the generation of oceanic crust within an intervening marginal sea (compare Hatcher, 1978 and Wehr and Glover, 1985). The Iapetus (Northern Proto-Atlantic) Ocean opened (Rankin, 1976; Thomas, 1977), and the alkalic Crossnore plutonic-volcanic suite was emplaced. During this extensional event, normal faulting and thermal subsidence of the Grenville crust resulted in rift basins. Rift basins on the continental side of the marginal basin, west of a "hinge zone" (Wehr and Glover, 1985) that separated attenuated and non-attenuated crust, were infilled with clastics such as the Ocoee turbidite Supergroup, the Mount Rogers and Grandfather Mountain Formations (Figure 3). The shedding of sediments from a southeastern, western, and northwestern clastic source probably indicates erosion of deformed and intruded 1100 Ma Grenvillian mountains (Hatcher, 1989). Rift basins east of the hinge zone were formed on attenuated crust (Wehr and Glover, 1985) and deep water sediments such as the Tallulah Falls Formation, and subsequently the Coweeta Formation were deposited. The Coweeta Group may be the time equivalent of the Chilhowie group, within which the Late Precambrian rift-to-passive margin transition may be recorded (Simpson and Eriksson, 1989). Progradation of a passive margin is represented in part by the deposition of the Shady Dolomite (Simpson and Eriksson, 1989). The Shady Dolomite and the Rome Shale are both constituents of the Lower Paleozoic shelf strata that were deposited upon the eastern edge of the North American craton. The Upper Cambrian and Lower Ordovician are represented by the Knox Dolomite. The Knox unconformity separates the karsted uppermost member of the Knox Group from the overlying Middle Ordovician shales and limestones (Harris, 1969).

		LITHOLOGY	FORMATION	H m	V km/sec	ρ gm/cm ³
ORDOVICIAN						
		MIDDLE ORDOVICIAN LIMESTONES		300	6.30	2.70
CAMBRIAN		DOLOMITE WITH QUARTZ ARENITE	KNOX	830	6.50	2.80
		DOLOMITIC SILTSTONE	NOLICHUCKY	17	5.63	2.71
		DOLOMITE	HONAKER	380	7.30	2.85
		RED MUDROCK	ROME	150	3.70	2.67
		DOLOMITIC REEFS	SHADY	100	6.70	2.84
		QUARTZ ARENITE	ERWIN	300	6.00	2.59
		SHALE SILTSTONE	HAMPTON	300	5.40	2.71
		ARKOSIC SANDSTONE SOME VOLCANICS	UNICOI	300	6.20	2.67
		PRECAMBRIAN BASEMENT AND SEDIMENTS			-	6.00

Figure 3. Stratigraphic Column: Modified from Gresko (1985). Compressional seismic velocities and densities are given along with approximate unit thicknesses. The parautochthonous rocks in the study area are interpreted to be of Late Proterozoic-Middle Ordovician in age, and the allochthonous crust is likely Late Proterozoic-Early Cambrian in age. Precambrian units include the Grenvillian basement rocks, Crossnore Suite, Great Smoky Group, Ocoee Supergroup, Mount Rogers and Grandfather Mountain Formations. The Ocoee passive-margin Supergroup may be the time equivalent of the Tallulah Falls outer continental margin Formation of the eastern Blue Ridge and Inner Piedmont. The Chilhowie group includes the Erwin, Hampton, and Unicoi Formations, and may be the time equivalent of the Coweeta Group of the eastern Blue Ridge (Hatcher, 1978). According to Simpson and Eriksson (1989), the Late Proterozoic rift-to-passive margin transition is recorded within the Unicoi Formation.

Taconic Orogeny

The Taconic event in the southern Appalachians is estimated to have occurred 450-480 Ma (Drake et al., 1989). The closing of the marginal sea began in Mid-Late Cambrian, possibly with the development of an east-dipping subduction zone along the western side of the rifted margin (Hatcher, 1978). Mafic and ultramafic rocks, presently located east of the Hayesville fault in the Blue Ridge, may represent oceanic material brought up along the east-dipping subduction zone (Hatcher, 1978); however, as noted above, there is considerable disagreement concerning the protoliths of these mafic rocks. All of the major granitic plutons of Late Precambrian to Early Paleozoic age in the Blue Ridge occur east of the Hayesville fault, suggesting that the intrusive bodies may have been emplaced above a subduction zone represented in remnant form by the Hayesville thrust sheet (Hatcher, 1978, 1987). The Iapetus Ocean separated the Carolina arc on the east from North American rocks on the west during the Early Paleozoic. A consuming subduction zone beneath the Carolina arc during the Ordovician may have resulted in the accretion of the arc to Laurentia and forced the closure of the Iapetus Ocean. Hatcher (1978) proposed that the rifted continental fragment was transported toward the present northwest and collided with North America. According to Wehr and Glover (1985), the Hayesville-Fries-Rockfish Valley fault was carried westward within crust that decapitated a Late Proterozoic hinge zone, thereby incorporating basement rocks and syn-rift volcanics into the thrust sheet. The clipped-off basement rocks, along with the eastern marginal basin sediments, were thrust westward, juxtaposing the mafic, ultramafic, and deep-water sediments from the east side of the rifted basin with the western facies predominantly non-volcanic, alluvial-shallow marine deposits. Other faults of the Blue Ridge, such as the Chunky Gal Mountain and Shope Fork fault, were probably initiated during the Taconic orogeny (Hatcher and Zeitz, 1980; Lacazette and Rast, 1989). The Brevard fault zone, an complex Appalachian feature, may have experienced ductile deformation during the Taconic orogeny (Hatcher and Odom, 1980). The Taconic orogeny marks the southern Appalachian thermal-metamorphic maximum (Butler, 1972; Hatcher, 1989), and is roughly coeval with the Caledonian orogeny of Europe.

Acadian Orogeny

In the southern Appalachians the Acadian orogeny, which occurred during the Devonian and Mississippian, does not appear to have been as extensive as in the northern Appalachians. Rodgers (1967) initially noted the lack of evidence for an Acadian orogenic event in the southern Appalachians. Bobyarchick (1981) also concluded that the history of metamorphism and deformation in the southern Appalachians does not indicate a major Acadian orogenic event. Other studies suggest that a major high-grade event occurred during the Acadian orogeny, possibly accompanied by faulting (Lacazette and Rast, 1989; Hatcher and Thomas, 1989). It may be that the metamorphism and deformation resulting from the Acadian orogeny have been grossly overprinted by the more recent and intense Alleghanian orogeny as to result in the obliteration of the evidence of a major Acadian orogenic event. Alternatively, the Acadian event, which was the principle thermal event in the northern Appalachians, may be correlative with the waning of the Taconic orogeny in the southern Appalachians (Glover et al., 1984).

Alleghanian Orogeny

The Alleghanian orogeny, which occurred in the southern Appalachians approximately between 220-270 Ma (Bobyarchick, 1981), was a result of the collision of the Laurentia and Gondwana continents. This orogeny is coeval with the Hercynian-Variscan orogeny in Europe and northwest Africa. Most sedimentological and stratigraphic correlations (Secor et al., 1986) and paleogeographic reconstructions indicate that North America collided with northwest Africa. This orogeny constitutes the largest known compressional event in the southern Appalachians and is predominantly responsible for the present-day tectonic architecture. The collision resulted in the northwest-directed thrusting of the Blue Ridge-Piedmont metamorphic allochthon over the Lower Paleozoic shelf strata a minimum distance of 325 km along the Blue Ridge master décollement (Hatcher et al., 1987a). Hatcher et al. (1989a) estimated that the crustal shortening resulting from this orogenic event near the ADCOH study area is as much as 54 percent. The location of the Alleghanian suture continues to engender controversy within the geologic community. Iverson (1983) and Iverson and Smithson (1982, 1983) placed the root zone beneath the Kings Mountain Belt on the basis of reflection terminations interpreted to originate from within the shelf strata and

the location of the Appalachian gravity gradient. Others (Harris and Bayer, 1979; Cook et al., 1979; Secor et al., 1986; Hatcher et al., 1989b) speculate that suture is located farther east beneath the Coastal Plain sediments.

The concept of thin-skinned tectonics as applied to the southern Appalachians has been a subject of many geological and geophysical investigations. Rich (1934) observed that the faults mapped on the surface did not bring up basement rocks and concluded that fault activity was confined to the rocks above the basement. The transport of massive, intact crystalline sheets over large distances with little deformation of the basement rocks was discussed by Byrant and Reed (1970) as the method of emplacement of the Blue Ridge allochthon. Subsequent investigations of the southern Appalachian tectonic model have continued to support the concept of thin-skinned tectonics. Hatcher (1978) speculated that the entire Blue Ridge-Inner Piedmont allochthon was underlain by Paleozoic shelf strata based on weakly metamorphosed carbonate slices exposed near the Brevard zone-Blue Ridge contact. These slices were interpreted to be chemically similar to the rocks of the Upper Cambrian-Lower Ordovician Knox Group of the Valley and Ridge, and to have been emplaced during northwest-vergent thrusting along the Brevard fault zone (Hatcher, 1971; Hatcher et al., 1973). The shelf strata are considered to be correlative with the sedimentary rocks of the Valley and Ridge province (Cook et al., 1979; Harris et al., 1981) 50 km to the northwest of the ADCOH site. Seismic investigations (Clark et al., 1978; Tegland, 1978; Cook et al., 1979; Harris and Bayer, 1979; Harris et al., 1981; Behrendt, 1986; and Çoruh et al., 1987) further supported the concept of large-scale overthrusting in the southern Appalachians by recognizing reflection packages at depths of 2-10 km that have been interpreted to be shelf strata beneath an allochthonous crystalline terrane.

Several hypotheses exist pertaining to the role of the Brevard fault zone during the Alleghanian orogeny. Cook et al. (1979) used seismic data to interpret the Brevard fault zone as a splay from the Alleghanian Blue Ridge master decollement. Hatcher and Odom (1980) suggested that ductile deformation occurred in the Brevard fault zone during the Taconic orogeny, and that the Rosman fault splayed off of the master decollement during the Alleghanian orogeny, ramping up to the surface along the stratigraphically weak zone. Edelman et al. (1987) and Bobyarchick et al. (1988) concluded that the present-day Brevard fault zone ramp was controlled by pre-Alleghanian structure and developed during a late phase of the Alleghanian orogeny. Correlative units of the Tallulah Falls Formation are present on both sides of the Brevard fault, indicating that the Brevard fault

does not represent a large-scale suture as previously suggested by Odom and Fullagar (1973) and Rankin (1975). As an example of the enigmatic nature of the Brevard fault zone, Bobyarchick et al. (1988) listed 31 different interpretations of the structure, dating from 1905.

Mesozoic Orogeny

During the Mesozoic era, the southern Appalachians experienced an extensional event as the continent of Africa retreated from North America, resulting in the formation of the present-day Atlantic Ocean. This extensional event was accompanied by normal faulting, formation of rift basins, sedimentation, and intrusion of diabase dikes (Hatcher, 1972).

ADCOH Site Area

The ADCOH site area is located within the Blue Ridge and Inner Piedmont geologic provinces of North Carolina, South Carolina, and Georgia (Figure 1 on page 3 and Figure 2 on page 4). The site encompasses a 7500 km² area between longitudes 82° 52' - 83° 52' and between latitudes 34° 52' and 35° 15'. The largest towns include Westminster, S.C., which was crossed by ADCOH Lines 1 and 6, and Toccoa and Clayton, Georgia, which were crossed by Seisdata Line 6. Fold coverage in these areas is lower due to the requirement of station skipping when passing through residential areas. The predominantly rural setting of the ADCOH site area helped to minimize problems associated with cultural noise.

Geology

The stratigraphy and structure determined from field mapping and the deeper geological structure revealed by seismic reflection data reflect the complex geology of the upper and lower crust. In the study area, the crust can be divided into three domains based on the displacement from the original site of formation: allochthonous (large displacement), parautochthonous (small displacement), and autochthonous (no displacement).

The allochthonous crust includes the Blue Ridge-Inner Piedmont overthrust sheet. The Hayesville thrust marks the boundary between the non-volcanic, platform-protolith sequences of the western Blue Ridge (Great Smoky Group) from the eastern Blue Ridge. The deep water Tallulah Falls Formation is the dominant rock group in the eastern Blue Ridge and consists of metagreywacke, pelitic schist, and mafic volcanic rocks (Hatcher and Zietz, 1980). The Tallulah Falls Formation is overlain by the Coweeta Group which is comprised of feldspar-quartz-biotite gneisses, metasandstone, biotite schist, and quartzite (Hatcher, 1979). The protoliths of the eastern Blue Ridge are interpreted by Hatcher et al. (1987b) to be deep water sedimentary and rift volcanic rocks deposited on oceanic crust and fragments of continental basement. The Inner Piedmont is com-

posed of an amphibolite granitic-gneissic assemblage. Several suites of rocks exposed at the surface in the Inner Piedmont of the study area resemble rocks in the Tallulah Falls Formation of the eastern Blue Ridge, and thus the eastern Blue Ridge and the Inner Piedmont are considered to contain stratigraphically equivalent rocks (Hatcher, 1978). The Blue Ridge allochthon is separated from the Inner Piedmont by the Brevard fault zone, which is located on the northwest flank of the low-grade, synformal Chauga Belt. Beneath the metamorphic allochthon is the Lower Paleozoic shelf strata, which includes, among others, the Rome, Shady, and Knox Formations. In some locations, the Lower Cambrian rocks of the parautochthonous shelf sequence rest nonconformably on Grenvillian basement; elsewhere, Upper Proterozoic-Lower Cambrian clastic and volcanic rocks, which infill extensional rift basins, intervene (Odom and Fullagar, 1984).

The entire area is underlain by Grenville-age basement. Although, as will be suggested in the discussion to follow, the basement likely experienced horizontal transport during the Grenville orogeny, it is commonly referred to as autochthonous because it serves as a reference frame for the younger orogenies. The only known exposures of Grenvillian basement in the ADCOH site area are near the Tallulah Falls and Toxaway domes, east of the Hayesville fault (Williams et al., 1987b; Fullagar and Goldberg, 1988) (Figure 2 on page 4). These Grenville-age rocks were likely incorporated into the metamorphic core during the Taconic orogeny, and were later transported northwestward. No autochthonous Grenvillian basement is exposed in the ADCOH site; indeed, to sample such basement was one of the objectives of the ADCOH scientific drilling program.

Seismic Data

Previous Work

The first seismic reflection experiment conducted near the study area was that of Clark et al. (1978) who, from a short traverse in North Carolina, interpreted the Brevard fault zone to be a shallow, gently-folded southeast-dipping zone of ductile deformation. They were the first to recognize large amplitude reflections from beneath the Inner Piedmont (2.7-3.0 s) and interpreted these as originating from Cambrian platform rocks beneath an allochthonous crust. The reflections were inter-

puted to originate from the top of the Rome Formation, the Rome-Shady contact, and the base of the Shady Dolomite. Tegland (1978) identified several key horizons in Eastern Tennessee on seismic data that correlated with the Valley and Ridge carbonate-shale-sandstone sequence. The first large-scale seismic reflection project in the southern Appalachians was initiated by COCORP (CONsortium for CONtinental Reflection Profiling). The COCORP results confirmed the earlier hypothesis of Clark et al. of high-amplitude reflections originating from the shelf strata. Their more regional data were interpreted as having the Blue Ridge thrust (Great Smoky thrust) dip steeply from the surface in the Valley and Ridge in Tennessee and to flatten out and converge with the reflective shelf sequence at a depth of 5.0-6.5 km. The interpretation of the thrust at this depth constrained the shelf sequence to a minimum thickness of 1 km and the overlying crystalline Blue Ridge allochthon to a maximum thickness of 6.5 km. Cook et al. (1979) interpreted the Brevard fault zone to dip steeply from the surface to the southeast to merge with the sole thrust at a depth of 6-9 km. Below 2.5 s, COCORP GA-2 and the portion of the GA-1 profile in the study area was reported to be relatively unreflective; reflections emanating from the crust/mantle boundary were not apparent. The COCORP interpretation of the subsurface of the southern Appalachians is often referred to as the "classic" model.

Harris et al. (1981) also recognized the allochthonous nature of the Blue Ridge-Inner Piedmont sheet and mapped the reflective shelf strata on U.S.G.S. seismic reflection data in Tennessee and North Carolina. On Seisdata line 6, Behrendt (1986) recognized reflections at 2.8 s, which were interpreted to originate from the Appalachian decollement. Southeast-dipping reflections from beneath station 800 were interpreted to emanate from the Brevard fault zone. Discontinuous southeast and northwest dipping events were recognized up to 6 s on the unmigrated data. As the data only extended to 6 s, reflections from Moho depths were not apparent.

The acquisition and subsequent interpretation of the ADCOH seismic reflection data set has resulted in the re-evaluation of earlier subsurface models. The prominent set of continuous reflections originally interpreted from the COCORP data as the master detachment (Cook et al., 1979) was reinterpreted to be sedimentary strata overlying Late Proterozoic infilled graben structures (Çoruh et al., 1987). This reflective sequence represents the base of the reflective Lower Paleozoic shelf strata and is the most continuous reflection package in the data set. Costain et al. (1986) and Çoruh et al. (1987) recognized several large-amplitude events in the 2-9 km depth range on ADCOH Line 3. These reflection packages were interpreted to be the result of wavelet tuning by constructive

interference of reflections from imbricate thrust slices within the Paleozoic shelf strata, and were termed "duplex tuning wedges" (Costain et al., 1986). Scott (1987) further investigated the characteristics of the duplex wedges by modeling them using the AIMS (Advanced Interpretative Modeling System by GeoQuest International Inc.) seismic modeling package. Çoruh et al (1987) interpreted the Blue Ridge thrust to lie above the duplex reflections, thereby constraining the thickness of the overlying Blue Ridge allochthon and the underlying Paleozoic shelf strata to 2-3 and 6-7 km, respectively. In addition, the Brevard fault zone was interpreted by Çoruh et al. (1987) to splay from the master decollement at a depth of approximately 6 km, shallower than the depth reported by Cook et al. (1979). High resolution seismic data collected at the ADCOH site imaged a distinct upper and lower boundary of the Brevard fault zone (Roy-Chowdhury and Phinney, 1987). Using both refraction and reflection arrivals from ADCOH Line 1, Laughlin (1988) delineated the detailed shallow geometry of the Brevard fault zone.

Below the crystalline allochthon and parautochthonous shelf strata, faults at the basement surface were interpreted to bound Late Proterozoic rift basins, and weak reflections emanating from 5-9 s and 11-13 s were associated with the midcrust and Moho, respectively (Çoruh et al., 1987). Favret and Williams (1988) postulated the existence of two sets of obliquely trending normal faults vertically offsetting the basement from 100 to 1300 meters on the basis of ADCOH seismic data, and potential field and earthquake data. Most recently, Hatcher (1989) interpreted the allochthonous and parautochthonous crust in the study area using ADCOH Lines 1 and 3. Although many similarities exist between his structural interpretation (which is based on ADCOH Lines 1 and 3 prior to reprocessing) and the interpretation presented herein (which is based on all reprocessed data in the study area), there are some discrepancies. Most notably among these is the interpreted geometry of the Hayesville fault, the Blue Ridge thrust between stations 300-900 on ADCOH Line 1, and the Brevard fault zone southeast of the Blue Ridge thrust-Brevard fault zone junction.

Present Work

The ADCOH, Seisdata, and COCORP data reprocessed herein are shown in Figure 2 on page 4. ADCOH Lines 1 and 3, Seisdata Line 6 and COCORP GA-1 are dip lines that are orientated SE-NW; ADCOH Lines 2, 5a, 6 and COCORP GA-2 are strike lines that run SW-NE. With the exception of ADCOH Line 3, which is located entirely in the Blue Ridge province, all dip lines

traverse both the Blue Ridge and the Inner Piedmont and cross the Brevard fault zone. ADCOH Line 3 is the only profile to cross the Hayesville fault.

Acquisition Parameters

The ADCOH seismic data were acquired by Western Geophysical under the direction of Virginia Polytechnic Institute and State University in 1985. The Seisdata set was acquired in 1981 by Seisdata Services Inc. for the U.S.G.S., and was purchased by Virginia Polytechnic Institute and State University for the ADCOH project in 1985. The acquisition parameters of the ADCOH, Seisdata, and COCORP data are shown in Table 1. Iverson (1983) reprocessed southern Appalachian COCORP profiles as part of his Ph.D. dissertation, and graciously provided stack tapes of reprocessed COCORP GA-1 and GA-2 seismic reflection lines.

Table 1. ADCOH, Seisdata, and COCORP Acquisition Parameters.

Parameter	ADCOH	Seisdata	COCORP
Station Spacing (m)	67	67	67
CDP Stack (fold)	30 and 60	24	24
Near Offset (m)	200	67	469
Far Offset (m)	4150	3350	6834
Sweep Frequency (Hz)	14-56	48-12	8-32
Sweep Length (s)	24	24	30
Source (vibs x # swps)	5x6	4x16	5x16
Source Array length (m)	67	67	206
Recording channels	120	96	96
Geophones (strs x # phs)	1x24	1x24	1x24
Recording Array length (m)	134	134	94
Record Time (s)	32	30	50
Sample Rate (ms)	4	4	8
Low Cut Filter (Hz)	12	12	9
High Cut Filter (Hz)	65	62	31

Reprocessing

As the final display of seismic data is highly dependent on the data preparation, the processing steps and parameters employed are crucial to the interpretation. An “interpretive reprocessing ” scheme is one where interpretation of seismic data is performed concurrently with the selection of the appropriate processing steps and parameters. Originally published seismic reflection data subjected to interpretive reprocessing for this study include ADCOH (Çoruh et al., 1987), Seisdata (Behrendt, 1986), and COCORP (Cook et al., 1979) profiles. The ADCOH and Seisdata data were reprocessed (from demultiplexing to final display) using both conventional and relative amplitude techniques in order to boost smaller amplitude events and also to retain relative amplitude information (Hubbard et al., 1989a). The data were initially reprocessed with amplitude balancing steps such as whitening during vibroseis correlation, spherical divergence, and automatic gain control. The amplitude manipulations resulted in well-balanced sections with good signal-to-noise ratio. These sections are referred to as the “conventionally processed” sections. Subsequently, the data were wholly reprocessed without the conventional amplitude balancing processes but with the application of an amplitude decay correction (Çoruh, 1989 unpub.). These data, referred to as the “relative amplitude” sections, yield a meaningful measurement of the relative reflection strength between reflection packages, or relative lithological information. The stacked form of the available COCORP data severely limited the types of processing that could be performed. Because a large portion of the COCORP GA-1 was outside of the ADCOH site, only stations 1-1200 were used in this study. Table 2 summarizes the processing steps and parameters employed during the reprocessing of the ADCOH, Seisdata, and COCORP seismic reflection data sets. A brief summary of some of the non-standard or more crucial processing steps is included in Appendix A.

Process	AD1	AD1	AD2	AD2	AD3	AD3	AD5	AD5	AD6	AD6	SD6	SD6	CC1	CC2
Demultiplex	x	x	x	x	x	x	x	x	x	x	x	x		
Extended correlation length (s)	17	17	17	17	17	17	17	17	17	17	16	16		
VSW during correlation	x		x		x		x		x		x			
Operator and hand edits	x	x	x	x	x	x	x	x	x	x	x	x		
Modified geometry	x	x	x	x	x	x	x	x	x	x	x	x		
Datum (m) for statics	400	400	520	520	850	850	500	500	255	255	850	850		
Spherical divergence correction	x		x		x		x		x		x			
Number of residual static applications	3	3	5	5	6	6	9	9	5	5	4	4		
Number of velocity analysis	3	3	6	6	7	7	10	10	6	6	5	5		
Pre-stack f-k filter dip pass (ms/trace)			±14		±9.5		±4.5	±14.5	±14.5		±5	±5		
NMO correction	x	x	x	x	x	x	x	x	x	x	x	x		
Amplitude decay correction	x	x		x		x		x		x		x		
Mute	x	x	x	x	x	x	x	x	x	x	x	x		
Stack	x	x	x	x	x	x	x	x	x	x	x	x		
Band pass filter (1Hz)	12-52	12-52	10-52	10-52	10-52	10-52	10-52	10-52	10-50	10-50	10-32	10-32		
AGC & conventional display	x		x		x		x		x		x			
Relative amplitude display		x		x		x		x		x		x		
AGC & automatic line drawing	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Post stack migration	x	x	x	x	x	x	x	x	x	x	x	x		
Band pass filter (1Hz)	12-52	12-52	10-52	10-52	10-52	10-52	10-52	10-52	10-50	10-50	10-32	10-32		
Post-stack f-k filter (ms/trace)								±15						
AGC & display	x		x		x		x		x		x	x		
AGC & automatic line drawing	x	x	x	x	x	x	x	x	x	x	x	x		

Table 2. Reprocessing Parameters used for ADCOH (AD), Seisdata (SD), and COCORP (CC) seismic data.

Interpretation

The interpretation to follow focuses on the allochthonous Paleozoic, parautochthonous Paleozoic, and the autochthonous Grenvillian crust separately, first discussing the interpretation based on the seismic data, then examining correlatable signatures from available gravity data that was collected in the ADCOH site. A constant average velocity of 6 km/s was employed for all time-to-depth conversions. Although interpreted strike and dip lines are displayed as automatic line drawings, the interpretations of the profiles are based on the automatic line drawing, conventional and relative amplitude displays as well as migrated and unmigrated versions of each line.

Allochthonous Crust

The Blue Ridge-Inner Piedmont allochthon is one of the largest crystalline thrust sheets in the world (Hatcher, 1989). The Blue Ridge-Inner Piedmont metamorphic allochthon was transported *en masse* up to 400 km during the Alleghanian orogeny (Hatcher et al., 1989a). The Blue Ridge is bounded on the west by the Blue Ridge thrust and on the east by the Brevard fault zone. The Brevard fault zone separates the Blue Ridge from the Inner Piedmont.

Although similarities exist between the stratigraphy of the Blue Ridge and Inner Piedmont (Hatcher, 1978; Hatcher et al., 1987b, 1988), the reflectivity of these allochthons is different. The Blue Ridge allochthon is relatively reflection free, while the Inner Piedmont has numerous continuous reflectors that parallel the geometry of the underlying Blue Ridge thrust (Figure 6 on page 29). The difference in reflectivity may be attributed to the presence of intrusive bodies within the Blue Ridge which conceivably could scatter the energy. Additionally, the subparallel reflective bands within the Inner Piedmont may be attributed to metamorphic layering (Christensen, 1989), recumbent folding of constituent amphibolites and gneisses (Hatcher et al., 1987b), to different protoliths, or to fault zones. Liu and Hatcher (1989, unpub.) recently mapped the Wahalla and Strumthouse Mountain faults in the Inner Piedmont. These faults may be associated with the re-

lections observed within the allochthon on ADCOH Line 1. Although the strength of some of the reflectors within the Inner Piedmont are similar to that of some hydrocarbon producing sedimentary reservoirs, the metamorphic grade of the Inner Piedmont and the Blue Ridge precludes the existence of hydrocarbons within the allochthonous crust. The lack of deep well information and the convoluted nature of the surface geology suggest that rock types other than those mapped on the surface may account for the high reflectivity within the the Inner Piedmont allochthon. A seismic amplitude versus offset analysis of some of the high-amplitude events within the Inner Piedmont may help to elucidate the nature and origin of the reflections.

Prior to the ADCOH survey, the Blue Ridge allochthon was interpreted to be up to 6.5 km thick (Cook et al., 1979, 1981). The higher resolution and the relative amplitude form of the data re-processed herein have enabled a more detailed "seismic mapping" of the Blue Ridge thrust which has constrained the thickness of the overlying Blue Ridge-Inner Piedmont allochthon. The thickness of the metamorphic allochthon varies from 1.8 km (0.6 s) to 3.3 km (1.1 s; Figure 11 on page 34), and the Inner Piedmont allochthon attains a maximum thickness of 7.0 km (2.3 s) above the junction of the Blue Ridge thrust-Brevard fault zone on ADCOH Line 1 (Figure 6 on page 29). A remarkably similar Blue Ridge-Inner Piedmont allochthon external geometry is apparent along strike 550 km to the northeast on the central Virginia I-64 seismic reflection profile. The thickness of the Blue Ridge allochthon on the I-64 profile is about 3 km (Pratt et al., 1988; Çoruh et al., 1988), and the Inner Piedmont is reported to be 5-6 km thick above the juncture of the Brevard fault zone-Blue Ridge thrust (Costain et al., 1989). The regional uniformity of the crystalline allochthon geometry, as exhibited from seismic reflection profiles from Virginia to Georgia, is striking.

The topography of the basement and shelf sequence might have controlled the formation of structures within the overlying allochthon. This relationship will be discussed more fully in subsequent sections.

Faults

Faults within the allochthonous crust are interpreted from the geometry of the reflectors, the amplitude and character of the reflectors, and the correlation of surface geological data with the seismic

reflectors. All the major faults associated with the allochthonous crust, including the Hayesville, Brevard, and Blue Ridge thrust are imaged on the seismic data.

Hayesville fault

The Hayesville fault, which is traversed by ADCOH Line 3, defines the northwestern boundary of the Hayesville thrust sheet (Figure 2 on page 4). According to Wooten (1980), rocks on both sides of the Hayesville fault were deposited in similar regional paleoenvironments; however, rocks on the southeast side of the fault were deposited farther from the source than the rocks on the northeast side. Rocks within the Hayesville thrust sheet (southeast of the Hayesville thrust) contain more mafic and ultramafic lithologies and less Grenville-age basement rocks than those to the northwest of the Hayesville fault (Hatcher, 1978). These disparate facies were juxtaposed along the Hayesville fault during the Taconic orogeny and later transported northwestward during the Alleghanian orogeny.

Geologic mapping indicates that both the Shooting Creek and Brasstown Bald windows, located southeast of the Hayesville fault (Figure 2 on page 4), contain rocks that may bear a resemblance to the Great Smoky Group rocks that outcrop on the northwest side of the Hayesville fault. Because of this resemblance, it has been proposed that the Shooting Creek and Brasstown Bald anticlines are windows exposed beneath the folded Hayesville fault. Hatcher (1989) interpreted the Hayesville fault to penetrate to a maximum depth of only 1.5 km, then to be overturned to roof the windows. Figure 4 is a superposition of this interpretation onto an automatic line drawing of a portion of ADCOH Line 3 that is oriented in the direction of structural dip and images the subsurface beneath the Hayesville fault. Although this interpretation is consistent with the surface geology, it does not account for the ADCOH reflector geometry, which displays reflections dipping to the southeast from beneath the surface location of the Hayesville fault and from beneath both boundaries of the Shooting Creek window on ADCOH Line 3. The southeast dipping reflections converge with the Blue Ridge thrust at a depth of about 3.0 km (1.0 s; Figure 4 and Figure 5). In order to honor both the proposed interpretation projected from the surface geology (Hatcher, 1989) and the reflector geometry exhibited by the seismic data, two possible scenarios are suggested. In one scenario, dominant stress *in the direction of structural strike* of the seismic section is invoked to account for the reflector geometry beneath the Hayesville fault. Alternatively, the majority of

Figure 4. Interpretation near Shooting Creek window and Hayesville fault: Interpretation from Hatcher et al. (1989a) based on surface geology and superimposed onto an automatic line drawing of a portion of ADCOH Line 3. Inset shows how fault plays are generated in a transpressional regime (Ramsay and Hubar, 1987). Compare with Figure 5.

the tectonic transport could have been *in the direction of structural dip*, in which case the rocks presently beneath the Shooting Creek Window are interpreted to have been brought up along thrust faults.

Strain in the Direction of Structural Strike

The events beneath the surface location of the Hayesville fault might be the seismic signature of strain induced by Alleghanian transpression in the direction of structural strike. The zone may have developed after the proposed folding of the Hayesville fault, which would account for both the presence of the rocks resembling those of the western Blue Ridge within the eastern Blue Ridge thrust sheet (rocks of the Shooting Creek and Brasstown Bald anticlines), and for the reflector geometry beneath the Hayesville fault. In this interpretation, the geometry of the Hayesville fault is similar to that interpreted by Hatcher (1989), with the addition of a deformational zone associated with transpression in the direction of structural strike and beneath the surface trace of the Hayesville fault (Figure 4). Transpression at this time would have been coeval with the formation of dextral shear along the Brevard fault zone as described by Edelman et al. (1987) and summarized by Bobyarchick et al. (1988). A deformational zone induced by stress in the direction of structural strike would have strike similar to the trend recognized by Gates et al. (1988) on interpreted Late Paleozoic transpressional fault zones in the southern and central Piedmont. Gates et al. (1988) further suggested that these shear zones reactivated older Taconic structures and that the zones tend to dip towards the southeast. Furthermore, mineral ages from within the Blue Ridge allochthon determined using $^{40}\text{Ar}/^{39}\text{Ar}$ dating techniques vary significantly from the east to the west side of the Hayesville fault (Dallmeyer, 1989). The age contrasts across the fault indicate a variation in Late Paleozoic metamorphism which implies that the tectonic boundary has experienced significant Late Paleozoic movement. An interpretation of strain in the direction of structural strike beneath the Hayesville fault implies that transpression associated with the Alleghanian orogeny may have occurred farther to the west in the southern Appalachians than has been previously documented along the Brevard fault zone by Gates et al. (1988).

Strain in the Direction of Structural Dip

An alternate interpretation is that a slice of the rocks presently beneath the Shooting Creek window was thrust up to the surface prior to or during the Late Paleozoic deformation along faults indicated

by southeastern dipping reflections bounding the Shooting Creek window on ADOCH Line 3 (Figure 5). The rocks might have experienced drag folding near the front of the thrust, and erosional exhumation (Hatcher et al., 1988) might have subsequently exposed a dome shaped feature. As the Shooting Creek window directly overlies a duplex stack as imaged on ADCOH Line 3, a slice of rocks disparate from the Eastern Blue Ridge rocks might have been emplaced into the Eastern Blue Ridge crystalline sheet along faults as the allochthon arched over the platform duplex structure. These faults may have brought up a lens of material; this would account for the isolated Shooting Creek and Brasstown Bald windows as shown on Figure 2 on page 4. Alternatively, the thrust faults may extend along structural strike and the outcrop expression may vary with topography. This interpretation would conflict with the present status of the surface geology in the vicinity of the Shooting Creek and Brasstown Bald windows.

If the rocks beneath the Shooting Creek window were brought up along faults, the reflectors that extend from the surface location of the Hayesville fault to the Blue Ridge master decollement may represent the subsurface location of the Hayesville fault. The Hayesville fault was active during the Taconic orogeny and may have originated near the brittle-ductile transition. As erosion between the Taconic and Alleghanian orogenies may have removed as much as 10 km of crustal material, the Hayesville fault may have been at a much shallower depth during the Alleghanian orogeny than the depth at which it initially detached. The convergent reflector geometry beneath the Hayesville fault suggests that as the Blue Ridge thrust ascended to the surface near the study area during its east-to-west propagation during the Alleghanian orogeny, it reoccupied a suitably oriented zone of weakness previously created by the Hayesville fault.

The rocks beneath the Shooting Creek window might be equivalent to the Western Blue Ridge Great Smoky Group rocks, as suggested by Hatcher (pers. comm., 1989); however, Wooten (1980) investigated the stratigraphy, structure, and metamorphism in the vicinity of the Hayesville fault in North Carolina and concluded that the undifferentiated rocks within the Shooting Creek window "bear little resemblance to the Great Smoky Group formations" mapped on the northeastern side of the fault. The rocks within the Shooting Creek window were interpreted by Wooten to be constituents of the Hayesville thrust sheet. The determination of the correct correlation of rocks beneath the Shooting Creek window is not within the scope of this study. It is emphasized that the seismic datum (time = 0 on the seismic sections) may differ up to 500 m from the surface at which field mapping is performed. The poor outcrop exposure and condition, the variation of topography

Figure 5. Alternate interpretation Near Shooting Creek window and Hayesville fault: A.D portion of ADCOII Line 3. EBR = eastern Blue Ridge rocks, WBR = rocks of or resembling those of the western Blue Ridge. Proposed thrust solution honors geological and geophysical evidence. Compare with Figure 4.

along the traverse of the seismic line, and the difference between the surface and the seismic datum suggest that what is imaged in the subsurface on the seismic data may not necessarily correlate with the surface geology. It will suffice to conclude that both solutions presented honor the reflector geometry and would support either Hatcher's or Wooten's geologic correlation. Both models attempt to account for the reflector geometry and the platform protolith rocks beneath the Shooting Creek window; however, the models are incomplete without verification from surface mapping. A closer examination of the Hayesville fault in the study area may help to determine the style of faulting at the Shooting Creek window and if the Hayesville fault has indeed been subjected to Alleghanian transpression.

Brevard fault zone

The Brevard fault zone is located 55 km to the southeast and parallel to the Hayesville fault in the study area (Figure 1 on page 3). Geologic and geochronologic data indicate that the Brevard fault zone is a complex structure that has experienced different episodes and senses of movement (Edelman et al., 1987). The present form of the Brevard fault zone probably began to develop during the Early Alleghanian with the formation of a mylonite zone that was controlled by pre-existing stratigraphy and by Taconic/Acadian structure (Edelman et al., 1987; Bobyarchick et al., 1988). Edelman et al. (1987) proposed that the mylonite zone formed in response to low angle dextral shear. Subsequently, large scale thrusting during the later Alleghanian orogeny cut through and displaced the Taconic/Acadian/Early Alleghanian structural assemblage. The Brevard fault zone reactivated brittlely along the mylonite zone during the late phase of the Alleghanian orogeny, ramping up to the surface to yield the present day structure (Edelman et al., 1987). At the surface, the brittle fault within the Brevard fault zone is called the Rosman fault.

The reflector geometry revealed by the seismic data suggest that the present day form of the Brevard fault zone has been controlled by the underlying basement topography. As revealed by Figure 6-Figure 8, the Brevard fault zone splays from the Blue Ridge thrust directly above a basement high at depths of approximately 5.5-7.0 km (1.8-2.3 s). The reflector geometry of ADCOH Line 1, Seisdata Line 6, and COCORP GA-1 suggests that, during the Alleghanian orogeny, the stress trajectories within the allochthon were bent upward as the overthrust sheet encountered a linear topographic basement high presently beneath the Inner Piedmont. Northwest

directed stress resulted in the brittle reactivation of the previously weakened Brevard fault zone along the curved stress trajectories to form a ramp up to the surface. A time-structure contour map of the basement surface clearly displays the basement topographic high responsible for the stress field (Figure 9); the basement relief beneath ADCOH Line 1 is labeled *a* on the contour map; the basement offsets beneath Seisdata Line 6 and COCORP GA-1 are labeled *b* and *c*, respectively. The surface trace of the Brevard fault zone is projected down onto the basement contour map to show the relation between the basement topographic high and the resulting surface expression of the Brevard fault zone. The proposed genetic relationship between the basement topography and the the Brevard fault zone ramp is consistent with the modeling of Wiltchko and Eastman (1983), who suggested that basement warps and faults result in a differential stress field that influences fault patterns (Figure 10a), and that directed stress may facilitate failure in the form of faults that deflect from the basement high to the surface along the curved stress trajectories (Figure 10b). Another observation of Wiltchko and Eastman that is consistent with the ADCOH seismic data is the concentration of low stress on the side of the basement high farthest from the directed stress and the corresponding retardation of the formation of faults in that area.

The ramp along which the Rosman fault reactivated is imaged on the reflection data in the ADCOH site and also in central Virginia on the I-64 reflection profile (Çoruh et al., 1988), suggesting that it is a prominent feature for at least 550 km (Costain et al., 1986). By implication, the basement topography that is interpreted to have controlled the formation of the ramp, may also be a regional feature.

Blue Ridge thrust

The Blue Ridge thrust, often referred to as the Blue Ridge master decollement, defines the boundary between the Blue Ridge and Valley and Ridge and is the frontal fault of the overthrust system. On the basis of the the reprocessed data, all major faults within the allochthonous crust, including the Hayesville fault and the Brevard fault zone, are interpreted to sole in the Blue Ridge master decollement. It was along this fault that the Blue Ridge-Inner Piedmont allochthon was displaced northwestward during the Alleghanian orogeny. The Blue Ridge thrust likely originated east of the study area near the brittle-ductile transition during the Late Paleozoic continent-continent collision, and subsequently propagated upward through the basement, through the Upper Proterozoic

Figure 6. Interpretation of ADCOH Line 1 ALD: BRT = Blue Ridge thrust, BFZ = Brevard fault zone, IPA = Inner Piedmont allochthon, BRA = Blue Ridge allochthon, LPSS = Lower Paleozoic shelf strata, LPB = Late Proterozoic basin, WG = Westminster gap, I(?) = intrusion, MCR = midcrustal reflections, BOC(?) = base of crust, and a refers to basement topography and corresponds with the same letter on Figure 9 on page 32.

Figure 7. Basement offset on Seisdata Line 6: Ramp geometry of Brevard fault zone and Blue Ridge thrust is related to basement offset. *b* refers to basement topography and corresponds with same letter as on Figure 9 on page 32.

Figure 8. Basement offset on COCORP Line 1: Ramp geometry of Brevard fault zone and Blue Ridge thrust is related to basement offset. c refers to basement topography and corresponds with same letter on Figure 9 on page 32.

Figure 9. Time Structure Contour Map, Top of Basement: Features discussed in text: *a*=intrusion on ADCOH Line 1, *b*=basement offset beneath Seisdata Line 6, *c*= basement offset beneath COCORP Ga-1, *d*=Tallulah Falls Dome, *e* =intrusion on ADCOH Line 3, *f*=intrusion on COCORP GA-1. The Brevard fault zone ramp and the Blue Ridge thrust are interpreted to be genetically related to the basement high created by features *a*, *b* and *c*.

a)

Basement Warp

Principal Stress Directions

—— σ_1
 - - - σ_3

b)

Basement Warp

Potential Fault Orientations

Figure 10. Stress field and fault patterns: a) Hypothetical basement high and resulting stress field
 b) Fault patterns induced by the stress field. Figures from Wiltchko and Eastman, 1983.

Figure 11. Interpretation of ADCOH Line 3 ALD: BRT = Blue Ridge thrust, HVF = Hayesville fault, CGMF = Chunky Gal Mountain fault, SFF = Shope Fork fault, SCW = Shooting Creek window, BRA = Blue Ridge allochthon, LPSS = Lower Paleozoic shelf strata, DS = Duplex structure, LPB = Late Proterozoic basin, I(?) = intrusion, MCR = midcrustal reflections, BOC(?) = base of crust, and *e* refers to basement topography and corresponds with the same letter on Figure 9 on page 32.

rift/drift facies, and finally through the Lower to Middle Cambrian sequences to the surface (Hatcher and Thomas, 1989). Near the study area, the Blue Ridge thrust is interpreted to demarcate the boundary between underlying shelf strata and the overlying Blue Ridge-Inner Piedmont crystalline allochthon.

Relative amplitude data helped to discriminate Blue Ridge and Inner Piedmont crystalline rock from Lower Paleozoic shelf strata, thereby delineating the Blue Ridge thrust. On the relative amplitude sections, the shelf strata are characterized by higher amplitude reflections indicative of sedimentary rocks and by the presence of duplex structures that induce wavelet tuning (Costain et al., 1986). The Blue Ridge allochthon, on the other hand, is relatively seismically transparent on the relative amplitude sections. On the basis of the relative amplitude data, the Blue Ridge thrust on ADCOII Line 1 is interpreted to ramp up from depths of approximately 6.0-7.0 km (2.0-2.3 s) beneath the Inner Piedmont, and to flatten out 30 km to the northwest at depths less than 3.0 km beneath the Blue Ridge (1.0 s; Figure 6 on page 29 and Figure 11 on page 34). A similar Blue Ridge thrust reflector geometry is present along strike the southwest beneath Seisdata Line 6 (Figure 7 on page 30), and COCORP GA-1 (Figure 8 on page 31), and surprisingly, along strike beneath the central Virginia I-64 reflection profile (Çoruh et al., 1988).

Time structure contour maps of the basement surface and the Blue Ridge thrust in the study area (Figure 9 on page 32 and Figure 12) suggest that the thrust is controlled by the topography of the basement surface. The reflector geometry suggests that the collision of the advancing allochthon with the same basement ridge that is interpreted to have affected the Brevard fault zone also caused the Blue Ridge thrust to ramp upward to a shallower level along curved stress trajectories. Southeast of the Blue Ridge thrust-Brevard fault zone juncture on ADCOII Line 1, Seisdata Line 6 and COCORP GA-1, the Blue Ridge thrust is interpreted to dip to the west. Geological maps (Hatcher unpub., 1989) indicate that the surface expression of this concave-up portion of the fault is the Six Mile Synform. Along strike to the northeast, westward dipping reflectors on the I-64 profile are interpreted to represent the west flank of a large antiform (Çoruh et al., 1988). In this location, the westward dips have been interpreted to be the result of Mesozoic tilting along reactivated Paleozoic decolléments (Costain et al., 1989).

Figure 12. Time Structure Contour Map of the Blue Ridge thrust: Contour interval = 100 ms.

Other faults

Figure 11 on page 34 displays other faults that are imaged on ADCOH Line 3, including the Chunky Gal Mountain fault, which dips to the southeast approximately beneath station 1400, and the Shope Fork fault, which dips to the northwest beneath station 800. Both faults appear to root in the Blue Ridge thrust at depths of approximately 3 km. The reflector geometries of the Chunky Gal Mountain and Shope Fork faults suggest that prior to the Alleghanian orogeny, the faults were united at depth or may have actually been rooted in the Taconic Hayesville fault. According to Lacazette and Rast (1989), the Chunky Gal Mountain fault consists of a polydeformed shear zone, which is recognizable on ADCOH Line 3 between stations 1400-1600 in the form of multiple southeast dipping reflectors. As discussed, the reflections that dip to the southeast from beneath both sides of the Shooting Creek window may represent thrust faults. The surface trace of the Chattahoochee fault is mapped near station 700 on ADCOH Line 3 (Hatcher, unpub. 1989) but is not imaged on the seismic section, possibly due to a shallow depth of penetration.

Parautochthonous Shelf Strata

The Lower Paleozoic shelf strata are roofed by the Blue Ridge master decollément and floored by an unconformity marking the break up of the continents during the Late Proterozoic-Early Cambrian. The shelf sequence was deformed prior to and during the emplacement of the metamorphic allochthon in the Alleghanian orogeny. Foreland deformation consisted of thrusting of the shelf strata toward the interior of the craton, resulting in duplex structures that open to the west. The shelf strata is a reflective package because of the velocity contrasts of the postulated constituent formations; the Knox Formation dolomites have a velocity of approximately 6.3-6.5 km/s, and the Rome Formation shales have a velocity of approximately 3.7 km/s (Edsall, 1974; Kolich, 1974; Gresko, 1985). The reflection coefficients of the shale and sandstone interfaces of the Lower Cambrian Rome Formation range between 0.2-0.4, where 0.25 is usually considered to be a reflection of "bright spot" intensity. Thus, the Lower Paleozoic shelf strata or, in particular, the Rome Formation and the Rome-Shady interval, are distinctive seismic markers. Although no wells penetrate through the overthrust terrane to verify these correlations, the seismic response of the

sequence has been successfully modeled (Scott, 1987), and some of the horizons may be correlative with the Paleozoic sedimentary rocks of the Valley and Ridge in Tennessee (Cook et al., 1979; Harris et al., 1981).

Prior to the results of the ADCOH seismic survey, the shelf strata were interpreted to be a thin (1 km), relatively undeformed sequence (Cook et al., 1979, 1981). Recognition of large amplitude events on the higher resolution ADCOH seismic data that are interpreted to originate from within the shelf strata has led to a reassessment of the thickness of the foreland sequence and of the overlying crystalline allochthon (Costain et al., 1986; Çoruh et al., 1987). Costain et al. (1986) proposed that the high reflectivity of the duplex structures might result from wavelet tuning of tectonically imbricated thin layers. Çoruh and Costain (1987) suggested that the thrust stacking of the thin beds resulted in reflections with a 2- to 3-fold increase in amplitudes. Reflections, which on conventionally processed data might have been ambiguous (Figure 13), are clearly resolvable as a thick package of shelf strata on the relative amplitude data (Figure 14). Relative amplitude data were utilized to elucidate the internal and external geometry of the shelf strata including the thickness, lateral continuity, and the presence of high amplitude packages within the sequence which might result from duplex structures, from gas pockets, as discussed below, or from both.

Undulations of the top of the shelf strata caused by internal duplexing might have influenced the geometry of the overlying allochthon. Hatcher et al. (1987b) and Hatcher et al. (1989b) proposed that the formation of domal map patterns in the thrust sheets was influenced by the presence of duplex structures in the platform sequence beneath the allochthon. The Tallulah Falls Dome was interpreted to overlie a thick sequence of duplex structures (Williams et al., 1987a; Hatcher et al., 1987b; Hatcher et al., 1988; Hatcher and Thomas, 1989; Hatcher et al., 1989b). Although the data quality is only fair, no clear indication of duplex stacking beneath the Tallulah Falls Dome is evident on the conventional or relative amplitude processed Seisdata Line 6, which passes directly over the dome (Figure 29 on page 69); however, seismic mapping of the Blue Ridge thrust does reveal an undulating fault surface that gently arches over *other* duplex structures in the foreland sequence, such as beneath the Shooting Creek window on ADCOH Line 3 (Figure 11 on page 34).

Figure 14. Thick sequence of shelf strata: Relative amplitude portion of ADCOH Line 3.

Hydrocarbon Potential

Few wells have penetrated the Cambrian-Ordovician section in the southern Appalachians and thus the sequence remains relatively unexplored (Harris and Milici, 1977). The prime target for hydrocarbon exploration is the Knox Group, a Cambrian-Ordovician age constituent of the shelf sequence. On reflection seismic data, the Knox Group is generally unreflective except for a locally developed basal reflector (Milici et al., 1979). The Knox unconformity separates the karsted Lower Ordovician Knox Group from overlying Middle Ordovician shaley carbonate strata (Harris, 1969). Erosion associated with the Knox unconformity during the Late Ordovician controlled the karst paleotopography of the uppermost Mascot and underlying Kingsport members of the Knox Formation (Harris, 1969). The Knox unconformity, as well as the permeable upper part of the Mascot Dolomite, served as a zone of hydrocarbon migration (Baird and Dennen, 1985). The impermeable Middle Ordovician rocks, together with weathering products, served as the cap rocks for the fluids beneath the Knox unconformity (Baird and Dennen, 1985). Harris et al. (1981) interpreted the Ordovician Sevier Shale to overlie the Knox Group 200 km to the northeast of the ADCOH site area along strike. In the ADCOH site area, Hatcher (1989) interpreted the youngest constituents of the Lower Paleozoic shelf strata to be Middle Ordovician rocks. Both interpretations support the presence of the Middle Ordovician cap rocks below the crystalline overthrust sheet and above the Lower Ordovician Knox Formation. The top 30 meters of the Mascot Dolomite is known for hydrocarbon production in the Valley and Ridge province of Tennessee (Hoagland, 1971; Stearns, 1971). Harris and Milici (1977) suggested that porous zones located at 180-240 meters below the unconformity are also favorable for hydrocarbon exploration. Natural gas pockets in the Mascot and Kingsport units of Tennessee indicate the latter day abundance of petroleum (Hoagland, 1971). Others (i.e., Cramer, 1980) also reported gas finds from deep drilling.

The Lower Paleozoic shelf strata in the study area were overthrust by the metamorphic allochthon during the Alleghanian orogeny. The emplacement of the thrust sheet deformed the Cambrian through Middle Ordovician platform rocks into duplex structures. Although exposed Blue Ridge and Inner Piedmont crystalline rocks are of at least greenschist facies, the metamorphic grade of the shelf strata beneath the allochthonous crust may be considerably lower. Epstein et al. (1977) related color changes in conodonts to alterations of trace amounts of organic matter within the fossil. The irreversible color change is related to increased temperature, overburden thickness, and burial du-

ration. The color changes, termed conodont alteration indices (CAI), range from 1-5 and are directly associated with a fixed carbon ratio range. The CAIs have been used to estimate the hydrocarbon potential in the southern Appalachians. Comparison of hydrocarbon production and isograd maps in the Appalachian Basin led Harris and Epstein (1978) to associate CAIs of 2 or lower with major commercial production of oil and CAIs of 4.5 or lower with commercial production of gas. CAIs and estimated maximum burial depths led Harris (1979) to propose maximum burial temperatures of 150°C to greater than 300°C. Epstein et al. (1977) suggested that the tectonic burial of the shelf strata by the overthrust allochthon had little influence on the degree of organic metamorphism of the underlying rocks, and that the CAIs reflect overburden prior to deformation; however, maximum burial temperatures in the Mascot-Jefferson city zinc District in Tennessee would require an unusually high geothermal gradient (615° to 1100°C/km) if the elevated temperatures are not attributed to thrust related overburden (Caless, 1983). The preservation of methane and possibly other light hydrocarbon fluid inclusions in the rocks of the Knox Formation in Tennessee (Roedder, 1971; Taylor et al., 1983a, 1983b) indicate that maximum burial temperatures might not have exceeded 170°. Other studies (Montanez, 1989) also suggest similar maximum burial temperatures on the basis of radiometric and fluid inclusion studies and $\delta^{18}\text{O}$ data from dolomites immediately pre-and post-dating precipitation of the thermal peak minerals. These maximum burial temperatures are less than those reported using CAIs. The discrepancy between the maximum burial temperatures can be attributed to the fact that the conodonts record the thermal affect of long term pre-thrusting burial, whereas the other data reflect only the thermal peak fluid temperatures induced by the emplacement of the thrust sheets (Montanez, 1989).

Overthrusting of large rock sheets increases the temperature and pressure of underlying units and consequently results in the thermal maturation of kerogene to hydrocarbons as described by Angevine and Trucotte (1983). Montanez (1989) proposed that the overthrusting associated with the Alleghanian orogeny was responsible for the elevated burial temperatures and for the subsequent formation of hydrocarbons in the southern Appalachians. Recent work of Haynes and Kesler (1989) suggests that zones with abundant organic content in the Mascot Dolomite of eastern Tennessee show strong spatial associations with Middle Ordovician paleotopographic highs and little spatial association with present day topography. They interpret this to indicate that the physical entrapment of the hydrocarbons migrating through the karsted Mascot Dolomite occurred prior to the Alleghanian orogeny; however, this study was conducted over a localized area and might not reflect regional hydrocarbon formation and migration trends. Furthermore,

hydrocarbons that formed within the Knox Formation during the Alleghanian orogeny migrated beneath, and were capped by, Middle Ordovician rocks. Thus, the locations of hydrocarbons that were generated during the Alleghanian may still be associated with Middle Ordovician paleotopography, especially if Alleghanian deformation of the Lower Paleozoic units was not locally severe.

In the site area, thrusting was initiated earlier and overburden was greater than some of the (previously mentioned) studies in undertaken in Tennessee. Angevine and Trucotte (1983) suggested that the thickness of the overthrust sheet is directly related to oil generation: a 4 km thrust plate will induce hydrocarbon maturation after 2 my that will have up to a 100 my residence time, whereas an 8 km thrust plate will induce oil maturation after 0.7 km and will have only a 5 my residence time. As original burial depths of the shelf strata may have been 6-12 km deeper than present depths (Dallmeyer, 1975; Ellwood et al., 1980), the shelf strata in the site area have exceeded the oil generation window even if the hydrocarbons were formed during the Alleghanian orogeny; however, some portions of the shelf strata within the site area are quite favorable for gas production.

Interpretation of the ADCOII seismic data suggests that the shelf sequence is presently at a depth of 4.5-7.5 km (1.5-2.5 s) beneath the Inner Piedmont, which implies that the shelf strata may have been at a depth of approximately 18 km at the time of burial. Paleotemperatures derived from biotite ages and postulated thermal gradients were used by Ellwood et al. (1980) to estimate the temperature and pressure of the sedimentary rocks below the Inner Piedmont allochthon after the Late Paleozoic compressional event. Their estimates of 350-400° C temperatures and of 4-6 kbars pressures indicate a low probability of the existence of economically significant amounts of hydrocarbons in the shelf strata beneath the Inner Piedmont; although Friedman and Reeckman (1980) pointed out that several other prospects (i.e., Anadarko Basin, some Gulf Coast Basins) that are associated with high temperatures and pressures have proven to be quite productive. Harris et al. (1981) concluded that natural gas potential in the southern Appalachians probably does not extend east of the Brevard zone in North Carolina.

The hydrocarbon potential is more auspicious beneath the Blue Ridge in the study area. CAIs of 3.5 beneath the Blue Ridge led Harris et al. (1981) to propose a potential for natural gas beneath the Blue Ridge allochthon. Iverson (1983) discussed the hydrocarbon potential of the rocks within the southern Appalachians and concluded that the eastern Blue Ridge should be "cautiously con-

sidered for minor gas production in isolated areas, and that hydrocarbon exploration should be seriously considered in the western Blue Ridge". The cautious consideration of Iverson (1983) and the apprehension of Ellwood et al. (1980) toward hydrocarbon exploration in the southern Appalachians was based primarily on the depth to the top of the shelf sequence as interpreted from pre-ADCOH seismic data. As noted earlier, interpretation of the ADCOH seismic data has revealed that to the northwest of the Blue Ridge thrust-Brevard fault zone juncture, the Blue Ridge thrust, which constrains the depth to the top of the shelf sequence, ramps up from depths (similar to previous interpretations) of 6.0-7.0 km beneath the Inner Piedmont to shallower depths of 1.8-3.0 km beneath the Blue Ridge. An isopach map of the Lower Paleozoic shelf strata (Figure 15) indicates that the shelf strata is thinnest (1.8 km) beneath the Inner Piedmont allochthon, and reaches a maximum thickness of 7.5 km near ADCOH Line 3 between stations 300-700. Read (Rankin et al., 1989) suggested that the total Cambrian-Ordovician section during the Early Paleozoic was 3 km thick. The present day maximum thickness of 7.5 km beneath the Blue Ridge is more than double that of the original section thickness, suggesting that the Alleghanian overthrusting of the crystalline allochthon has significantly shortened the underlying shelf strata. The minimum thickness of the shelf strata of 1.8 km beneath the Blue Ridge thrust-Brevard fault zone splay is 1.2 km less than that of the proposed original section. This comparison suggests that a significant portion of the sequence has been removed in this location, possibly during Alleghanian compression, and thus supports the proposition of Hatcher (1971), Hatcher et al. (1973), and Liu and Hatcher (1989) that carbonate slices located along the Brevard fault zone-Blue Ridge contact are portions of the Lower Paleozoic shelf sequence that have been brought up along the Brevard fault zone during dip-slip (thrust) Alleghanian displacement. The reinterpretation of the shelf strata geometry in the study area results in a sequence that is up to 6 km thicker and up to 6 km shallower beneath the Blue Ridge than interpretations based on pre-ADCOH seismic data. The shallower location implies less overburden, and hence, lower burial temperatures and an increased possibility of extant hydrocarbons within the shelf sequence beneath the Blue Ridge.

The reprocessing of the ADCOH seismic data in relative amplitude form has revealed high amplitude bright spots within the shelf strata (Figure 16), indicating either the tuning phenomenon associated with duplex wedges (Figure 17) or, where the bright spots are not associated with duplex structures, abrupt lateral variations in reflection amplitude due to velocity and density variations induced by changes in the rock porosity, permeability, or pore fluid composition. Gas within the pore space of a rock lowers the velocity as compared with water, and thus localized amplitude

Figure 15. Isopach between basement surface and Blue Ridge master decollement: Maximum and minimum thicknesses of Lower Paleozoic shelf strata are 7.5 and 1.8 km, respectively. A constant average velocity of 6 km/s was used for the time-to-depth conversion.

Figure 16. Bright Spot within the Shelf Sequence: Relative amplitude data reveals high amplitude reflectors that may indicate the presence of gas accumulations.

Figure 17. Duplex Structure: Duplex structures, such as this one on ADCOH Line 3, are often fractured and serve as favorable hydrocarbon traps.

variations may indicate the presence of hydrocarbons, as has been demonstrated by numerous Gulf of Mexico reflection profiles. This is supported by the presence of methane fluid inclusions in the rocks farther to the northeast (Taylor, 1983a, 1983b). The deformational style of the shelf strata is also an encouraging factor for hydrocarbon exploration. Harris and Milici (1977) proposed two prevailing types of traps in Kentucky and Virginia: isolated and blanket reservoirs, both of which might be enhanced by fracturing. Mitra (1986) described the subthrust geometry of the Lower Paleozoic shelf strata units in Virginia and West Virginia as overlapping ramp anticlines. He suggested that this type of duplex constitutes the best hydrocarbon trap because of the multiple stacking of the reservoir unit (Figure 17). In general, the duplexes are potentially good reservoirs because they usually have higher confining pressures than the more common shallower traps, and they are less susceptible to invasion and flushing by surface waters (Mitra, 1986). Additionally, the curvature of the rock units produced during duplex stacking enhances fracturing and induces secondary porosity (Mitra, 1986). The Rose Hill oil field in the southern Appalachians is an example of a producing structural trap consisting of fractured, overlapping anticlines. The well at the Rose Hill field penetrated two thrust sheets to a depth of 2135 m. Only the upper ramp was productive, however, possibly due to increased fracturing resulting from increased curvature of the unit.

Summary

The Mascot and underlying Kingsport units of the Knox Formation are known to be productive east of the study area (Hoagland, 1971; Stearns, 1971; Baird and Dennen, 1985). Lower Ordovician karst erosion has rendered the carbonates permeable, and fluids within the Knox Formation are sealed by overlying Middle Ordovician shaley carbonates. Although paleotemperature studies indicate a low probability of hydrocarbons beneath the Inner Piedmont allochthon in the study area, other studies (Harris et al., 1981; Taylor, 1983a, 1983b; Friedman and Reeckmann, 1980; Mitra, 1987; Montanez, 1989) support the presence of hydrocarbons in the shelf strata west of the Brevard fault zone. The duplex style of deformation provides a favorable hydrocarbon trap and may have induced secondary porosity. Bright spots, as revealed by ADCOH relative amplitude data, may indicate the presence of hydrocarbons. The revised depth to the Blue Ridge master decollement in the ADCOH site determined from the relative amplitude data yields a thicker and shallower sequence of shelf strata than heretofore reported, and could prove to have significant economic implications if the Knox Formation in the study area does indeed contain hydrocarbons. Especially favorable exploration sites, where the sequence is within reachable depths for an exploration hole

of about 2 km, include the duplex structures within the shelf strata beneath the Shooting Creek window, as originally suggested by Hatcher et al. (1987b), and beneath stations 850 and 1000 on ADCOII Line 3. On the basis of new information provided by recent studies and revealed by the ADCOII seismic data, hydrocarbon exploration beneath the Blue Ridge province in the study area should be seriously reconsidered.

Autochthonous Crust

Midcrust

A velocity discontinuity in the midcrust was observed on earthquake records by V. Conrad in 1925 and was termed the Conrad discontinuity. Jeffreys in 1926 interpreted the discontinuity as a boundary separating a granitic upper crust from a basaltic lower crust. Deep continental drilling and reflection data have since altered this simple two layer, granite-over-basalt model. The Kola superdeep well in the Soviet Union, the only well to penetrate to midcrustal depths, encountered exactly the opposite layer composition: metamorphic rocks of predominantly basic composition overlying a migmatite-plagiogneiss complex (Kozlovsky, 1984). The well did, however, confirm the theory of tectonic layering (different rock layers at different depths) of the lithosphere. Seismic reflection studies have shown that the detailed structure of the crust seems to differ dramatically from region to region; often midcrustal reflections dominate the section, while at other times they are absent. Other evidence, such as earthquake data, supports the theory of a distinct midcrustal feature. Fault rupture is confined to the upper, rigid crust (usually < 15 km), suggesting that the upper brittle crust overlies a ductile lower crust (Sibson, 1982). This varying crustal rheology helps to explain crustal reflections in young convergent terrains such as the Himalayas and the Caldonides, where upper (brittle) faults seem to sole within the lower (ductile) crust. According to Litak and Brown (1989), "the variable and elusive nature of the Conrad suggests that, where it is observed, it is a feature of regional or local extent and diverse origins". The location of a brittle-ductile transition may be dependent on the composition of the crust and may vary with depth, fluid content, grain size, strain rate, pressure, and temperature gradient (Sharry et al., 1986). Processes that

might affect the deep crustal rocks include extension, compression, underplating, anatexis, and metasomatism (Smithson, 1986).

It is not known if the reflective midcrust is an inherited feature or a recently formed feature. The origin of mid-lower crustal reflections is presently the subject of many studies. Possible sources of mid-lower crustal reflectivity include metamorphic banding, intrusive or magmatic layering, fluid filled lenses from metamorphism or mantle outgassing, metasediments guided into lower crustal depths along large faults, and shear zones. Zones of mylonite are often cited as a cause of crustal reflectivity due to their compositional layering and fabric, continuous and planar geometry, and their concentration and preferred orientation of biotites and other phyllosilicates (Sharry et al., 1986). Some investigators (Wever and Meissner, 1987; Meissner and Kuznir, 1987; Trappe et al., 1988; Meissner, 1989) believe the reflectivity of the mid-lower crust is a function of age and heat flow; the younger, warmer, and thus less viscous crusts such as the Variscan (Alleghanian) areas exhibiting strong reflections while the colder, older and more viscous shield areas are generally reflection poor. Others noted that rocks deformed during different orogenies, such as the Lewisian-, Caledonian-, and Hercynian-age BIRPS profiles, are all underlain by a reflective lower crust (Matthews and Cheadle, 1986; Wright et al., 1989). Meissner and Wever (1986) suggested that, in general, the lower crust of shield and platform areas seems to be unreflective, with the exception of those areas that have been affected by later orogenic events. Matthews and Cheadle (1986) stated that the reflective lower crust in the United States is observed only where the crust has experienced major extension since the last orogenic event. Meissner (1989) suggested that compressional structures (which he termed "crocodiles") in the mid-lower crust and below plane thrusts can survive a long time possibly due to strain hardening, whereas Moho lamellae, which require a high temperature, low viscosity condition for formation and a medium temperature, medium viscosity environment for survival, will only be present in younger (and therefore warmer and more viscous) crusts. This temperature-viscosity hypothesis seems to be consistent with most seismic observations.

Grenvillian Crust

The entire study area is underlain by rocks that were deformed during the Grenvillian orogeny. Grenvillian crust has experienced a series of deformational events, spanning from the Archaean

through the Proterozoic. The Grenville front delineates the northeastern boundary of the Grenvillian metamorphism and deformation, separating predominantly Grenville Proterozoic basement terranes to the east from other Precambrian basement provinces to the west (Figure 18).

The front is approximately 4000 km in length and extends from Lake Huron in Canada across Michigan, and then southward through central Ohio and Kentucky. From Ohio southward, the front is concealed and must be located by drill cores, and by radiometric and aeromagnetic data. The exposed front has been seismically imaged near Lake Huron in Canada by the GLIMPCE (Great Lakes International Multi - disciplinary Program on Crustal Evolution) consortium as a remarkable 32 km wide band of reflectors dipping approximately 25-35° SE (Green et al., 1988). The reflections extend from the surface to the Moho and are interpreted to have formed in response to southeast over northwest thrusting during the Grenville orogeny (Green et al., 1988). The high reflectivity is attributed to impedance contrast between thrust stacked microterranes (Green et al., 1988, Burke, 1989, pers. comm.). Where the basement rocks have been dated in the Blue Ridge geologic province, the ages range from 1000-1300 Ma (Rankin, 1975; Fullagar and Goldberg, 1988)

and are similar in age to those of the Grenville Province of eastern Canada and other Grenville basement localities in the Appalachians.

Perhaps one of the most important results of this investigation is the recognition of pronounced reflectivity within the midcrust in the study area as displayed by the ADCOH profiles. Although other deep reflection profiles in Tennessee, Virginia, West Virginia and the Grenville crust in Canada has been shown to be highly reflective, the midcrust in the study area was heretofore believed to be relatively reflection free, primarily on the basis of earlier seismic reflection interpretations (Cook et al., 1979; Brown, 1987; Harris et al., 1981; Behrendt, 1986). Some investigators (Harris et al., 1981; St.-Julien et al., 1983; Thomas, W.A., 1983; Lillie, 1986; Çoruh et al., 1987; Favret and Williams, 1988) recognized faults at the Grenville basement surface that were interpreted to be normal, upper crustal faults that formed in response to Late Proterozoic extension. Interpretation of the reprocessed ADCOH, Seisdata and COCORP reflection data suggests that the Grenville basement in the study area has indeed been affected by Late Proterozoic extension, but has as well been affected by Grenville compressional and possibly Paleozoic orogenesis.

Compressional Features

The ADCOH seismic data display coherent reflections between depths of 15-30 km (5-10 s) on all strike and dip lines. The reflections are strong and continuous both on the conventional and relative amplitude sections (Figure 19); however, a single layer, horizontal reflection band indicating an abrupt midcrustal discontinuity is not observed. Instead, bands of reflections are observed which are up to 16 km in length and 1.5 km thick. On the southeasternmost end of ADCOH Line 1, the reflections are evident from beneath the shelf strata to Moho depths (Figure 6 on page 29). The reflections are semi-continuous and have a layered appearance. These reflections terminate abruptly to the northwest, approximately under station 300 on Line 1 and continue on the northwestern side of a reflection-free zone, approximately beneath station 500. ADCOH strike Line 6 (Figure 20) intersects ADCOH Line 1 at the town of Westminster. The midcrust on ADCOH Line 6 is also devoid of reflections at the intersection. Subhorizontal midcrustal reflections on ADCOH Line 6 commence abruptly under station 200 and continue from 3-13 s to the southwest. ADCOH strike Lines 2 and 5a tie with ADCOH dip Lines 1 and 3 (Figure 21 and Figure 22). These strike lines display the largest amplitude and most continuous group of midcrustal reflections in the data set (Figure 23). As with ADCOH strike Line 6, the reflections on these strike lines are predominantly

Figure 19. Relative amplitude midcrustal reflections: Portion of ADCOH Line 3. Midcrustal events display significantly strong reflection strengths.

Figure 20. Interpretation of ADCOH Line 6 A/D: BRT = Blue Ridge thrust, BFZ = Brevard Fault zone, LPSS = Lower Paleozoic shelf strata, WG = Westminster gap, LPB = Late Proterozoic basin, I(?) = intrusion, MCR = midcrustal reflectors, BOC(?) = base of crust, and a refers to basement topography and corresponds with same letter on figure 9 on page 32.

Figure 21. Interpretation of ADCOH Line 2 ALD: BRT = Blue Ridge thrust, BRA = Blue Ridge allochthon, LPSS = Lower Paleozoic shelf strata, LPB = Late Proterozoic basin, B = base of crust, MCR = midcrustal reflectors, and BOC(?) = base of crust.

Figure 22. Interpretation of ADCOH Line 5a ALD: BRA = Blue Ridge allochthon, BRT = Blue Ridge thrust, LPSS = Lower Paleozoic shelf strata, B = basement, MCR = midcrustal reflectors.

Figure 23. Midcrustal reflections on ADCOH Line 2: Automatic line drawing reveals continuous reflections at midcrustal depths.

subhorizontal. The reflections that are prominent in the midcrust of ADCOH Line 1 continue to the northeast on ADCOH Line 3 until approximately beneath station 800, where they ramp up to the basement surface (Figure 24). An automatic line drawing of the reprocessed COCORP GA-1 reveals reflections that ramp up to the basement surface from depths of 15 km (Figure 25) and that are similar to those events observed at the basement surface on ADCOH Line 3 between stations 1200-1700. The increased resolution at midcrustal depths of the ADCOH seismic data, as compared to the COCORP and Seisdata profiles, can be attributed to use of a higher and broader band during vibration.

On ADCOH Line 3, events at the basement surface define the boundaries of Late Proterozoic-Early Cambrian extensional basins (Figure 24). Because the events do not extend upward through the shelf sequence, the last activity along the reflectors is interpreted to be Late Proterozoic-Early Paleozoic. These events can be followed downward to midcrustal depths of 15-25 km where they flatten out to subhorizontal dips. The extension of the events from the basement surface to midcrustal depths, the high amplitude and variation of dip along the reflectors, and the tectonic analogy to other Grenville basement localities suggest that the reflectors did not originate under a purely extensional stress regime. Although speculative, the reflectors are interpreted to have originated prior to the Late Proterozoic, possibly during the 1100 Ma Grenville compressional event, and to have been reactivated at the basement surface during Late Proterozoic-Early Cambrian extension. This conclusion is consistent with that of Beardsley and Cable (1983), who suggested that Grenvillian faults under the Appalachian Basin in West Virginia were reactivated during the Cambrian and consequently controlled the location and thickness of sediment deposition within the basin (Figure 26).

The reflectors are interpreted to be tectonic boundaries, versus phase changes at the brittle ductile zone, immiscible fluid contacts, or sills. This interpretation is mainly supported by the attitude of the reflectors, which dip as much as 20° to both the northwest and southeast. The varying dip direction of the basement reflectors suggests that the reflectors may represent decolléments that formed during a compressional event, similar in origin and style to the Grenvillian Monocyclic Belt Boundary Zone in the Grenville province (Rivers et al., 1989) and to the more recently formed Blue Ridge master decollement. Dewey (1986) suggested that compressional thrust stacking enables sediments and water to penetrate to lower crustal depths, aiding in the generation of fabric which may produce reflections. Since the Grenville compressional event, however, other activity (exten-

Figure 24. Extensional Basin: Reflectors bound a Late Proterozoic-Early Cambrian extensional basin. Reflectors may be preserved Grenvillian structures that were reactivated during Late Proterozoic extension, as shown by the inset (Daly et al., 1987).

REPROCESSED COCORP GEORGIA-LINE 1

SE

NW

0.0

1.0

2.0

3.0

4.0

5.0

Figure 25. Reflections from within Grenvillian basement: Reflections ramp upward to the basement surface on COCORP GA-1.

Figure 26. Reactivation of interpreted Precambrian thrust: Figure from Beardsley and Cable, 1983. Proposed reactivation of Grenvillian structures at the basement surface, as revealed by the ADCOH seismic data, is consistent with the interpretation of Beardsley and Cable (1983) beneath the Appalachian Basin in West Virginia.

sion, sill emplacement) may have occurred along the interpreted zones of weakness and may have contributed to the high reflectivity.

Further supporting the suggestion that the reflectors are structural in origin is the observation that dipping midcrustal events appear only on dip lines, while the reflections on the strike lines are subhorizontal. Reston (1987) modelled lower crustal reflectors and determined that if a reflecting surface is more elongated in one direction than in another, the reflections from the profiles in the two directions would differ in length, flatness, and continuity. In general, he concluded, the profile in the strike direction will contain more relatively flat out-of-plane reflections, and consequently the imaged reflector will be flatter and more continuous than the same reflector imaged on the dip lines, which will include many dipping reflections. The ADCOII seismic data display these characteristics: the flattest and most continuous reflections from the midcrust are imaged on the strike Lines 2 and 5a, and the reflections are also horizontal on strike Line 6. The dip lines, which exhibit dipping reflectors, are not as continuous as ADCOII strike Lines 2 and 5. The attitude of the midcrustal reflectors on the strike and dip lines suggest that the trend of the autochthonous crustal structures is similar to that of the Appalachian structure. The trend of the Grenville front also coincides with the Appalachian structural strike. The apparent similarity of trends between the midcrustal reflectors observed on the seismic data and the Grenville front further supports the suggestion that the structures may be Grenvillian in origin. This interpretation is consistent with that of the GLIMPCE consortium, who recognized crustal penetrating southeast dipping fabric in surface outcrop and on seismic data, and interpreted the structures to be the response of northwest directed compressional Grenville orogenesis (Green et al., 1988). In situ and laboratory velocity studies of rocks at the Grenville front indicate that the reflectivity observed on the GLIMPCE data is the result of lithological contrasts (M. Burke, 1989, pers. comm.). The interpretation of the midcrustal reflections as preserved Grenvillian structures unaffected by Late Paleozoic deformation implies that the majority of the compressional strain from the Alleghanian orogeny in the study area was released within the allochthonous and parautochthonous upper crust only; the Paleozoic orogenies do not seem to have affected the autochthonous Grenvillian basement.

The possibility remains that the midcrustal reflectors originated during Late Proterozoic extension, just prior to the intrusion of the proposed plutons. The offsets along the normal faults at the basement surface appear to be less than 900 m, which suggests that Late Proterozoic extensional stress was not extreme in the study area. The amplitude strength and continuity of the midcrustal

events, however, indicate that a crustal penetrative deformational event did indeed occur. The reflectors that bound the Late Proterozoic extensional basins have apparent dips of approximately 20° at the basement surface and decreases to subhorizontal dips in the midcrust whereas dips of 45° or greater are indicative of extensional strain (Anderson, 1951). Given an appropriate stress orientation, Donath and Cranwell (1981) have shown that failure is likely to occur along a pre-existing fault. Brun and Choukroune (1983) suggested that low angle normal faults, such as those observed at the Grenvillian basement surface, might be controlled by pre-existing, low angle mechanical interfaces. The dip and continuity of the reflectors and the tectonic analogy to other Grenvillian localities suggest that the faults at the basement surface in the study area might have been reactivated in an extensional regime along zones of weakness that initially formed in response to Grenvillian compression.

Extensional Features

As previously discussed, some reflections can be followed upward from midcrustal depths to the basement surface where they bound Late Proterozoic extensional basins. Normal faults offset the Grenvillian basement surface beneath the Blue Ridge thrust-Brevard fault zone juncture on Seisdata Line 6 and COCORP GA-1 (Figure 7 on page 30 and Figure 8 on page 31). These normal faults are interpreted to have formed during Late Proterozoic extension, and are similar in attitude and timing to those observed by St.-Julien et al. (1983) within autochthonous Grenville basement near Quebec City. Alternatively, the normal faults observed on the COCORP and Seisdata profiles could have formed from the lithospheric response to the load of the advancing thrust sheets during the Alleghanian orogeny, as described by Lillie et al. (1986, 1987).

On the ADCOH seismic data, the midcrust is highly reflective with the exception of a few distinct near vertical areas of low energy return. The generally high reflectivity of the midcrust encourages speculation about the nature of these poorly reflective zones. One particular reflection-free zone on ADCOH Lines 1 and 6 is interpreted to be an intrusion with a diameter in the dip direction of about 12 km and a surface area of at least 70 km². Support for this interpretation includes:

- abrupt reflection terminations on ADCOH Line 1 approximately between stations 300 and 500 at 3.5-13.0 s (Figure 6 on page 29),

- abrupt reflection terminations on ADCOII strike Line 6 between stations 100-200 at 3.8-14.5 s,
- reflection-free zone within the area delineated by the reflection terminations on both ADCOII dip Line 1 and strike Line 6 (Figure 27 and a on Figure 9 on page 32). That is, the reflection-free zone is traversed by both dip Line 1 and strike Line 6.
- 1.5 km topographic basement relief indicated by the warped, overlying shelf sequence on ADCOII Line 1, and
- the coincidence of the reflection-free zone with a Bouguer gravity low (Figure 27) and
- the coincidence of the reflection-free zone with a low aeromagnetic anomaly (Figure 27).

Simple two-dimensional gravity and magnetic modeling suggests that the observed potential field signatures can be produced by a low density intrusion at a depth of about 11 km, as suggested by the seismic data. Preliminary magnetic modeling following Talwani and Heirtzler (1964) was performed by William Domoracki (VPI & SU, unpub., 1990). Using a susceptibility contrast of -0.0045 emu between the proposed intrusion and the surrounding material, the modeling suggests that the body is about 10 km wide and 5 km thick. Gravity modeling indicates that the Bouguer gravity low can be modeled if the body has a maximum density contrast of $\pm 0.07 \text{ g/cm}^3$ with the surrounding rocks. Although these potential field models are not conclusive, they demonstrate that the interpretation of the reflection-free zone as a low density intrusion is a viable hypothesis.

A portion of the reflection-free zone does coincide with the Westminster low fold data zone; however, this zone occurs only beneath the Westminster seismic gap on ADCOII Line 1 and 6, as indicated by the low reflectivity of the section directly beneath, and cannot account for the poor reflectivity extending for up to 6 km on either side of the low fold zone. Other low fold areas, such as the tapered ends of ADCOII Lines 1 and 6 (Figure 6 on page 29 and Figure 20 on page 54), display strong midcrustal reflections, indicating that the areas of low energy return are not solely a function of fold coverage.

ADCOII Line 1 was "de-extended" by removing the reflection-free zone and subsequently splicing the section together (Figure 28). The continuity of the reflectors on the de-extended profile indicates that the reflectors were continuous prior to the proposed intrusive event. Because the reflection-free zone cross cuts reflections which are interpreted to have a maximum age of Grenvillian, the intrusion is interpreted to be post-Grenvillian. To constrain the later timing of the

Figure 27. ADCOH Line 1 and associated potential field profiles: Potential field profiles from Favret and Williams, 1988.

Figure 28. De-extended ADCOH Line 1: Portion of ADCOH Line 1 after reflection-free zone has been removed and section spliced back together. Arrows represent reflector packages that may have been continuous prior to intrusion.

intrusion, the nature of the overlying events are considered. The reflection-free zone does not penetrate the Lower Paleozoic shelf sequence, but has instead warped the base of the shelf strata to delineate the basement high on ADCOH Line 1 (Figure 6 on page 29). The reflector geometry of the allochthonous crust suggests that the basement relief influenced the formation of Alleghanian structure. If the reflective structures in the midcrust are indeed preserved Grenvillian structures, and the basement high did control Alleghanian structure, then the emplacement of the intrusion is constrained to a post-Grenvillian, pre-Alleghanian time of emplacement.

Other zones within the autochthonous Grenvillian crust are suspected to be intrusions because of the coincidence of potential field anomalies with basement relief, or with reflection-free zones, or with both. Seisdata Line 6 traverses the surface location of the Tallulah Falls Dome, and beneath the surface expression of the dome, the reflective shelf strata are warped to yield a 1.2 km basement high (Figure 29 and *d* on Figure 9). This dome dominates the time-structure contour map of the basement surface and both the Bouguer and residual gravity fields. The dome exhibits a prominent Bouguer gravity low of -80 mgals in an average field of -55 mgals. Although resolution on the Seisdata profile is admittedly poor, seismic mapping of the Blue Ridge thrust and the base of the shelf strata indicate that the shelf sequence does not thicken substantially beneath the surface exposure of the Tallulah Falls Dome. This is not in agreement with the interpretation of Williams et al. (1987a) and Hatcher et al. (1988, 1989b) who suggested that the gravity low is a result of an increased thickness of thrust stacked shelf strata beneath the Tallulah Falls Dome. Because the midcrustal reflectors, which are so prominent on the ADCOH seismic data, are not resolved on the Seisdata line (due to the narrower frequency band) the presence of an intrusion cannot be inferred from midcrustal reflection terminations; however, the warped platform sequence and a significant gravity anomaly over the Tallulah Falls Dome indicate that the basement was likely intruded by a pluton of lower density. Correlation of the basement structure contour map and the gravity data indicate that a nose of the Tallulah Falls Dome extends from Seisdata Line 6 along strike to an area between stations 500-700 on ADCOH Line 3 (Figure 11 on page 34 and *e* on Figure 9 on page 32). Although the basement warp is not prominent in this location, the reflection-free zone beneath ADCOH Line 3 may be associated with the interpreted Tallulah Falls Dome intrusion. Another intrusion is interpreted to be on COCORP GA-1, 20 km to the southeast of the large basement offset (Figure 30 and *f* on Figure 9 on page 32). This intrusion is inferred from the presence of a reflection-free zone beneath a warped basement surface.

Figure 29. Tallulah Falls Dome: Base of reflective shelf strata on Seisdata Line 6 warped up under surface location of Tallulah Falls Dome. *d* refers to basement topography and corresponds with same letter on Figure 9 on page 32.

Figure 30. Intrusion of COCORP Line 1: Inferred from reflection-free zone beneath warped basement surface. *f* refers to basement topography and corresponds with same letter on Figure 9 on page 32.

Do the proposed intrusions occupy the midcrust as well as the upper crust, or do they occupy only the upper crust but the pluton base is not seismically resolved? The velocity contrasts between the granitic Grenville basement and the proposed low density intrusions are not expected to be great. Thus, the scatter of energy from the top of the plutons is not expected to be sufficient to disguise the true boundaries of the intrusions. A likely explanation is that the emplacement of the pluton has disturbed the rocks presently beneath the intrusive body during its ascent toward the surface. This would disrupt acoustic boundaries, forming a near vertical reflection-free zone that cross-cuts the midcrustal reflectors. This interpretation is consistent with the results of the magnetic modeling, which suggests that the pluton interpreted on ADCOH Line 1 is only 5 km thick. Alternatively, the intrusion may indeed occupy portions of the midcrust. Although an intrusive body of this size would occupy a large crustal volume, several previous investigators have reported the existence of such bodies on the basis of surface mapping, drill cores, seismic reflection and refraction data, and gravity and magnetic data. Pratt et al. (1985) delineated the existence of a concealed granitoid beneath Lumberton, North Carolina using seismic and gravity data, and interpreted the body to have a diameter of 45 km and extend to depths of 12.5 km. Vigneresse (1988) reported that typical anorogenic granitic plutons are cylindrical in shape and are vertical, as the intrusion delineated on ADCOH Line 1 appears to be, and often have a diameter of approximately 14 km and a depth of 10-12 km. Pitcher (1979) reported that the most typical shape of a pluton top is circular or elongated along the structural grain of the country rock and that a cylindrically shaped plutonic volume is characteristic of emplacement in brittle crust. Pitcher (1979) suggested that although the surface area of plutons are sometimes as large as 1000 km², a more average dimension is 150 km². He further suggested that granite bodies may typically only penetrate one third of the crust. The delineation of the base of the intrusive body using seismic or gravity data is dependent on the velocity and density contrast and gradient near that depth. Bott et al. (1970) found that below 10-12 km, a density gradation within some granitic plutons existed. The roof of the intrusive body delineated on ADCOH Line 1 appears to be at a depth of 12 km. If the pluton has an "average thickness" of 12 km, as suggested above, then the body would extend to approximately 24 km. Midcrustal reflection terminations are evident at depths of 36 km, however, which suggests that the proposed intrusion may extend to that depth. At a depth of 36 km, it is likely that either a density gradation may exist, as suggested by Bott et al. (1970), or that stoping of the country rock occurred, disrupting the acoustic boundaries during pluton ascent. Either case would render the pluton base acoustically transparent.

It is worth mentioning how well the automatic line drawing algorithm (Çoruh et al, 1987) delineates features in the midcrust, such as the proposed intrusions. These are not apparent on conventional displays. Prior to the automatic line drawing algorithm, Matthews (1987) reported that granite plutons were not identifiable on reflection sections due to a lack of velocity contrasts. The use of the automatic line drawing algorithm on the ADCOH seismic data, however, has improved the resolution and has permitted the discrimination between the interpreted Grenvillian crust and acoustically transparent intrusive bodies. Similar seismic signatures of crustal extension have also been recognized on automatic line drawings of seismic reflection profiles from Virginia and New Jersey (Çoruh et al., 1989).

The seismic and gravity data suggest that the only two poorly reflective midcrustal zones on the highly reflective ADCOH data coincide with low density, acoustically transparent post-Grenvillian, pre-Alleghanian intrusions. In addition, other autochthonous crustal zones, such as the Tallulah Falls Dome, are suspect intrusions based on a coincidence of a gravity anomaly with basement relief, or with a reflection-free zone, or with both. Seismic mapping of the basement surface indicates that the intrusions and basement faults are aligned along a basement strike of N50°E. Although no definite correlation can be made without drilling, the size, density, and timing of some of the proposed intrusions are interpreted to be similar to some of those of the Late Proterozoic-Early Paleozoic Crossnore Plutonic Suite, such as the Striped Rock and the Robertson River Plutons.

Mohorovicic Discontinuity

The Mohorovicic discontinuity, or the Moho, was discovered by Mohorovicic in 1910 while studying earthquake body wave travel times. This crust/mantle boundary was defined from refraction data as a first order discontinuity below which existed material of velocities 7.6-8.6 km/s. In recent years, seismic reflection studies have introduced new questions about the Moho by imaging bands of reflections between 8-14 s. The seismic data suggests that the Moho may consist of thin laminations of varying velocity material underlain by a relatively seismically transparent mantle, possibly marking the transition zone from average crustal to olivine mineralogy. The observed laminated seismic character of the zone may be attributed to interference effects within the varying velocity layers (Braile and Chiang, 1986). The Moho transition zone may be 0-5 km thick and laterally variable.

The Moho seismic signature is associated with the age, tectonic style, heat flow, and viscosity of the geologic province. Reflection profiles in young, extensional terrains, such as the Basin and Range, often have highly reflective Moho signatures, and profiles from young convergent terrains, such as the Himalayas and the Caledonides, may display multiple or offset Moho signatures (Matthews and Cheadle, 1986). Moho signatures in older terrains, such as the North American craton, usually do not exhibit distinct reflections but are instead marked by a cessation of lower crustal reflectivity. Often Moho signatures are observed to be relatively continuous beneath a complexly deformed upper crust, appearing as a laminated zone or truncating lower crustal reflections. This suggests two possible scenarios: 1) the Moho is a stable feature that is unaffected by tectonic events, or 2) the Moho is a young feature that re-establishes itself after an orogenic event. Evidence from deep reflection studies, such as the presence of laminated, offset, and duplicated Moho signatures, supports the latter scenario. An argument in favor of a young, mobile Moho is the fact that the oceanic Moho must reestablish itself once every 100-200 million years, depending on which ridge-trench system is being considered, as crust is continuously created and destroyed. Among the suggested mechanisms by which the Moho may reestablish itself after a crustal scale orogeny are viscous relaxation, detachment or shear zone decoupling, and igneous underplating.

Southern Appalachian Mohorovicic Discontinuity

Various seismic expressions of the Moho have been observed on seismic reflection data sets in the southern Appalachians. In general, on the basis of the ADCOII and I-64 seismic data, the Moho is westward dipping in and along strike of the study area, defining a crustal thickness of 36-45 km. Farther to the east, Nelson et al. (1985) reported that the crust has a roughly uniform thickness of about 33-36 km, on the basis of COCORP data. Costain et al. (1989) generated a crustal thickness map for the Appalachian orogen using available seismic and gravity data.

Reprocessing of the central Virginia I-64 reflection profile (Pratt et al., 1987) has revealed strong, to westward dipping reflection packages at 9-12 s that are up to 5 km thick and are interpreted to be from lower crustal layering just above the Moho. Sub-vertical reflection-free zones which are delineated by reflection terminations and coincide with potential field anomalies are interpreted to be signatures of Mesozoic dikes (Çoruh et al., 1989). The dikes appear to cross cut the entire crust beneath the I-64 profile, including the Moho, which indicates that the Moho pre-dates the

Mesozoic orogeny. Brown (1987) and Brown et al. (1987) suggested that because the Moho on the southern Appalachian COCORP profiles appears to have been undisturbed by the upper crustal deformation, it post-dates the crustal deformational event that was responsible for the surface structure; however, increased resolution provided by automatic line drawings of COCORP GA Lines 5 and 8, which were produced at Virginia Polytechnic Institute and State University, reveals that the Moho has been disturbed, although it is not clear which deformational event is responsible for the disturbance. The COCORP GA Lines 5 and 8 traverse the Coastal Plain of Georgia 200 km to the southeast of the study area and exhibit reflections at 11.5-13.2, which likely indicate the base of the crust (Costain et al., 1989). An abrupt 2 km offset near the southeast end of the COCORP GA Line 5 does not correlate with any shallower feature, indicating that the offset may pre-date the Alleghanian orogeny responsible for deformation of the upper crustal structures.

Also east of the study area, Nelson et al. (1985) proposed that a broad group of southeastward dipping reflectors observed from 2 to 10-11 s on COCORP GA-14 and 15, respectively, marks the Alleghanian suture that juxtaposes Grenvillian crust on the west with African basement rocks on the east. These reflectors dip down to a thick package of westward dipping reflections at 11-12 s, which may represent the base of the crust or the Moho. Because the southeast dipping reflectors intersect the interpreted Moho at an acute angle, Nelson et al. (1985) suggested that the Moho cross cuts and thus post-dates the interpreted Alleghanian suture. Nelson et al. (1985) cited the interpreted undeformed state of the Moho as supporting evidence for the post-Alleghanian age of the Moho. The suggestions that the Moho actually cross cuts the dipping reflectors, and that the Moho is undeformed in the COCORP GA-14 and 15 area are debatable. Automatic line drawings of COCORP GA Lines 13 and 14 which were produced at Virginia Polytechnic Institute and State University reveal a band of west dipping reflections at Moho depths. The band is not one continuous package but is instead a series of discontinuous reflection packages with associated diffractions, bowties, and possibly even offsets. On the basis of these observations, the Moho may be pre-Alleghanian in age rather than post-Alleghanian.

The southern Appalachian COCORP GA-1 and 2 are reported to display no obvious reflections from Moho depths (Nelson et al., 1987). On ADCOII Lines 1 and 3, Çoruh et al. (1987) observed short segments of reflection packages at 11-13 s that were interpreted to be associated with the Moho. Reprocessing of the ADCOII seismic data has enhanced westward dipping deep reflections emanating from depths of 36-42 km (12-14 s). Reflections from Moho depths are still unidenti-

able on the reprocessed COCORP GA-1 and 2 and Seisdata Line 6. On the basis of refraction data, Prodehl et al. (1984) proposed a Blue Ridge crustal thickness of 47-51 km in Georgia, less than 100 km to the southwest along strike from ADCOH Line 3. In their model, the velocity increased by ramps from 6.1 km/s on the surface to 6.7 km/s at a depth of 34 km. From 34-47 km, thin layers with velocities of 6.7-7.8 km/s have been interpreted to be the lower crust. If this model is correct, then the reflections observed on the ADCOH seismic lines represent crustal layering just above the Moho, within the lower crust. Alternatively, the thin layers on the refraction model could represent a thick Moho transition, in which case the crustal thickness derived from the reflection data and the refraction data would be in agreement.

Individual reflection packages from Moho depths on the ADCOH seismic data are up to 1 km thick and are continuous for up to 10 km. The reflections are interpreted to be associated with the Moho on the basis of their depth and laminated character; they do not define a single, continuous horizon. Perhaps due to better signal penetration, the reflections are most evident in the vicinity of ADCOH strike lines 2 and 5A, including the southeast end of ADCOH Line 3 and the northwest end of ADCOH Line 1. The reflections appear to have a component of dip on both the strike and dip lines (Figure 31 and Figure 32). The true strike and dip of reflections from Moho depths as determined from individual reflection packages on the ADCOH lines is about N15°E, 15°NW. A similar dip is observed on the I-64 reflection profile. These large dips suggest that both the I-64 and the ADCOH seismic data may be located over a wide, west dipping ramp at the base of the crust; the ramp may partially contribute to the observed Appalachian gravity gradient. Other investigators (Hutchinson et al., 1983; Cook, 1984; Costain et al., 1989) have also discussed the correlation of the Appalachian gravity gradient with a oceanward thinning of the continental crust. The discrepancy between the strike of the Moho at the ADCOH site area and the regional Appalachian trend of approximately N45°E may indicate differential response to tectonic events; however, the crustal thickness variations over the entire Appalachians indicate that the discrepancy between trends is more likely localized and insignificant.

Because the crust-mantle boundary is not a highly resolved feature on the seismic data in the study area, the age of the Moho is difficult to ascertain. On the northeast end of ADCOH Line 3, southeasterly dipping reflections that are evident down to 11 s are discordant with west dipping reflections that emanate from Moho depths. As the midcrustal reflectors are interpreted to be Grenvillian in age, the data can only constrain the age of the Moho to a post-Grenvillian time

Figure 31. Reflections from Moho depths: Component of westward dip observed on ADCOH dip Line 1.

Figure 32. Reflections from Moho depths: Component of westward dip observed on ADCOH strike Line 2.

frame. The age relationship between the proposed intrusions and the Moho is not as apparent as the relationship between the interpreted dikes and the Moho on the I-64 profile.

The age of the Moho in the southern Appalachians is presently indeterminate. Some investigators suggest that the Moho thins oceanward and coincides with the Appalachian gravity gradient, marking a lateral change from Grenvillian crust on the west to another crust on the east. Cook (1984) suggested that the crustal thinning is associated with the development of a Precambrian-Cambrian continental margin. Others suggested that the present Moho structure may be a result of Paleozoic collisional or extensional events (Nelson et al., 1985; Brown, 1987; Brown et al., 1987; Çoruh et al, 1989). In most cases, the present state of the Moho (i.e., disturbed or undisturbed, cross cut or offset) is inconclusive given the available resolution. Proposed ages of the southern Appalachian Moho have for their basis speculative relationships between reflections from Moho depths and either lower crustal reflections or intrusions. A pre-Mesozoic Moho age is consistent with the data in and along strike of the study area; the later time constraint, however, is unknown. To the east of the study area, the lower crust may have been more involved in the Alleghanian orogeny, and the Moho may have been correspondingly more responsive to this deformation than in the study area.

Potential Field Data

The gravity field beneath the eastern Valley and Ridge, the Blue Ridge, and the western Inner Piedmont is dominated by a broad low with Bouguer values typically lower than -50 mgals. The negative anomaly, herein referred to as the Appalachian gravity anomaly, is paired with a positive anomaly which is parallel to and east of the low and is situated beneath the Inner Piedmont with maximum Bouguer values of +50 mgals (Hutchinson et al., 1983). The paired anomalies are separated by a steep gravity gradient, the Appalachian gravity gradient, which is approximately 100 km wide and is continuous for the length of the Appalachians (Figure 33). The Appalachian gravity anomaly has been attributed to a 7-10 km increase in crustal thickness (Hutchinson et al., 1983). Using gravity models, Hutchinson showed that the steep gradient and the positive part of the anomaly can be attributed to smaller positive density anomalies superimposed on the thickened crust. The depth of the density anomaly, however, was indeterminate.

Figure 33. Southern Appalachian Gravity Field: Major features include the Appalachian gravity gradient, Appalachian gravity anomaly and a low gravity anomaly. Figure modified from Haworth et al., 1980.

Gravity Field in the Study Area

Contour maps of the Bouguer, regional and residual gravity fields in the study area were generated by R.T. Williams for the ADCOH project (Hatcher et al., 1988). The Bouguer field is dominated by a gravity low extending from the northeast to the southwest and a gravity high in the northwestern corner (Figure 34). The gravity high was attributed to high density mafic and ultramafic rocks (Favret and Williams, 1988). The gravity low is the southwestern terminus of an anomaly that extends along structural strike for 400 km from the northeast into the study area, and is located on the northwestern edge of the Appalachian gravity gradient.

Correlation of Gravity and Seismic Data

Time-Structure Contour Maps.

Time-structure contour maps of the base of the reflective shelf sequence, the Blue Ridge thrust, and an isopach between the two were constructed using the available seismic data (Figure 12 on page 36, Figure 9 on page 32, and Figure 15). The isopach map was constructed using a constant average velocity of 6 km/s for the time-to-depth conversion. The base of the reflective shelf sequence represents the basement topography, although there may be as much as 1 km of Upper Proterozoic-Lower Cambrian sediments between the Rome/Shady reflective marker and the top of the Grenville basement (Rankin, 1976; Harris et al., 1981). The time structure contour maps and isopach maps provides a means to determine if the lateral thickness variations within the crystalline allochthon or within the shelf strata exhibit any correlations with the observed gravity anomalies. Comparison of gravity data, seismic contour maps, and surface geology indicate the following:

- Gravity highs on both the Bouguer and residual gravity maps correlate with high density rocks mapped at the surface.
- Neither the thickness variations nor the structural geometry within the shelf strata or overlying allochthon are correlatable with the gravity data.
- The basement topography *does* correlate with the gravity field: the Bouguer gravity low that dominates the gravity field bifurcates at its southwestern terminus, indicating that the gravity

Figure 34. Bouguer Gravity field at ADCOH site: Field is dominated by a low gravity anomaly. Figure from Hatcher et al., 1988.

field has been disturbed in two different directions. These disturbances coincide with the basement relief associated with the Tallulah Falls Dome and with the intrusion delineated on ADCOH Line 1.

- Tallulah Falls Dome extends northwestward on the time structure contour maps, and this extension is coincident with a linear residual gravity low. The gravity and topographic trends extend from Seisdata Line 6 into the area between stations 500-700 on ADCOH Line 3. This indicates that the reflection-free zone on ADCOH Line 3 may be associated with the interpreted Tallulah Falls Dome intrusion.

This comparison suggests that heretofore unexplained perturbations in the gravity field in the ADCOH study area can be attributed to features within the autochthonous Grenvillian crust, rather than to variations within the allochthonous and parautochthonous crust, as suggested by earlier workers.

Low Gravity Anomaly

Bouguer gravity profiles of Hutchinson et al. (1983) and Cook (1984) suggest that the low gravity anomaly that dominates the gravity field in the site area is associated with the Appalachian gravity anomaly, and can therefore be attributed to an increase in crustal thickness. Because the gravity anomaly is at a minimum beneath the Blue Ridge and tapers to higher values to the northwest and to the southeast, one might expect the crust to correspondingly thicken beneath the Blue Ridge. It is disconcerting, then, that the seismic data analyzed herein do not display a Moho that dips toward the center beneath the low gravity anomaly, but instead dips consistently to the northwest throughout the study area. Thus, the low gravity anomaly which dominates the gravity field in the site area cannot be attributed to a crustal root beneath the Blue Ridge. The regional gravity map (Figure 33 on page 79) reveals that the Appalachian gravity anomaly exists 50 km to the northwest of the low gravity anomaly that dominates the ADCOH site area. The Appalachian Gravity anomaly *does* extend the length of the Appalachian orogen and *is* most likely an expression of westward crustal thickening.

What is the cause of the low gravity anomaly that dominates the study area? Although speculative, a correlation does exist between the basement reflectors revealed by ADCOH Lines 1 and 3 and the low gravity anomaly. On the southeastern end of ADCOH Line 1 (Figure 6 on page 29), the reflections dip to the northwest from beneath the shelf strata. The basement reflections flatten out

on the northwest side of the intrusion delineated on Line 1. The upper basement reflections continue to the northwest subhorizontally until approximately beneath station 500 on ADCOH Line 3 (Figure 11 on page 34) where they begin to dip to the southeast and eventually ramp back up to the basement surface. The gravity low that dominates the ADCOH site gravity field also has a similar signature; the gravity is at a minimum where the reflections are subhorizontal on the northwest end of ADCOH Line 1 and the southeast end of ADCOH Line 3, and tapers to higher gravity values as the reflections ramp up to the basement surface. These basement reflections are interpreted to be the result of Grenvillian orogenesis, which, by analogy with the Alleghanian orogeny, may have involved the overthrusting of large rock masses. Overthrusting may have resulted in the juxtaposition of materials with varying densities, and thus the material between the base of the shelf strata and the Grenvillian basement reflectors may be a low density body that may be responsible for the low gravity anomaly. The possibility remains that the low density body is a large late Proterozoic sedimentary basin, with an apparent width and depth of 60 km and 3.7 km, respectively.

Modeling

Simple two dimensional gravity modeling was executed to test the hypothesis of low density bodies within the autochthonous crust. Prior to this study, the gravity field had been modeled in detail by varying densities from -0.1 to +0.17 g/cc within the upper 10 km of the crust (Williams, unpub.). The reprocessed seismic data suggests that potential field models should account for the presence of the autochthonous crustal structures. The two-dimensional gravity modeling of the upper-to-lower crust, undertaken as part of this study, reveals that the Bouguer field in the study area can be modeled using a three layer crust with intrusions. The crystalline allochthon, parautochthonous crust, and the Grenvillian crust are modeled as three distinct but homogeneous layers. The Moho dips to the northwest throughout the entire profile, as indicated by the seismic data, and the low density intrusions, which were discussed earlier occupy portions of the autochthonous crust. This simple model, inferred from the seismic data, requires a density variation of only $\pm 0.07 \text{ g/cm}^3$ to obtain a good fit to the observed Bouguer field, well within the density range of $\pm 0.1 \text{ g/cm}^3$ proposed by Thomas, M.D. (1983) for the rocks in the area near the ADCOH site.

Conclusions

All of the major faults within the allochthonous crust are interpreted to root in the Blue Ridge master decollement. In the northwestern portion of the study area, events extending from the surface location of the Hayesville fault to the Blue Ridge thrust may be the seismic signature of an Alleghanian transpressional zone in the direction of structural strike. Alternatively, the reflectors may represent the subsurface location of the Hayesville fault, in which case the convergent reflector geometry beneath the Hayesville fault suggests that the Blue Ridge thrust may occupy a zone of weakness created earlier by the Taconic-age Hayesville fault. The formation of allochthonous crustal features, including the Blue Ridge and Brevard fault zone ramps, the Tallulah Falls Dome, and the Shooting Creek Window are interpreted to have a genetic relationship to the underlying parautochthonous or autochthonous topography. Relative amplitude data enabled the discrimination between crystalline Blue Ridge and Inner Piedmont rocks and shelf strata, thereby delineating the Blue Ridge thrust. The revised geometry of the Blue Ridge thrust has constrained the top of the shelf sequence to depths less than 3 km. This shallow depth to the top of the shelf strata, and the presence of duplex structures and bright spots within the sequence suggest that hydrocarbon exploration beneath the Blue Ridge should be reconsidered.

On the basis of the reflection strength as revealed by new relative amplitude data, the strike and apparent dips, the basin bounding locations of the midcrustal events, and the tectonic analogy to other Grenville basement localities, upper-to-lower autochthonous crustal reflectors are interpreted to be preserved Grenvillian structures that were reactivated at the basement surface during Late Proterozoic-Early Cambrian extension. The reflectors are cross-cut by reflection-free zones, which are coincident with potential field anomalies and basement relief. The reflection-free zones are interpreted to be low density, acoustically transparent intrusive bodies. Because the proposed intrusions cross cut interpreted Grenvillian structures but do not penetrate the allochthonous crust, the time of emplacement is constrained to post-Grenvillian, pre-Alleghanian.

The comparison of seismic time structure contour and isopach maps with gravity data suggests that the structures or thickness variations within the allochthon or within the shelf strata show little

correspondence with the gravity fields. There were, however, correlations between basement topography and gravity disturbances. This comparison of the seismic data and simple two dimensional gravity modeling, constrained by the seismic data, suggests that Bouguer field anomalies in the site area can be attributed to structures within the autochthonous crust.

The Moho in the study area is interpreted to be at a depth of approximately 36-42 km, with a strike and dip of N15°E and 15°NW, respectively.

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Appendix A. Seismic Data Processing

Seismic data processing was performed at the Regional Geophysics Lab at VPI&SU using a VAX 11/780 and an FPS-120 array processor. The software utilized included the Cogniseis Disco seismic data processing package and modified and additional modules developed at Virginia Polytechnic Institute and State University. A brief description of some of the processes performed during the reprocessing of the seismic data is presented below. Standard processes which are not highly parameter-dependant are not discussed.

Extended Vibroseis Correlation

The extended vibroseis correlation provides reflection data at times greater than the originally recorded length for the purpose of observing deeper crustal reflections. The method was invoked at VPI & SU as early as 1985 (Pratt, 1985) and has more recently been discussed by Okaya (1989). The length of the trace after full correlation is equal to the length of the recorded trace minus the length of the vibroseis sweep. The full correlation length can be extended without affecting the original data by allowing the correlation operator to continue past the original length of the data during correlation. The extended correlation process will result in recovered signal at travel times greater than those of the original full correlation time, thus allowing for deeper crustal imaging at a cost of partial processing.

The extended correlation process utilized herein preserves the full-frequency band over the original (unextended) length of the data. The extended correlation process can theoretically continue as long as the correlation operator overlaps with non-zero uncorrelated data. During extended correlation, however, the frequencies present at the tail of the sweep are lost; the bandwidth decreases

in a predictable manner for times greater than the original length of the full-correlation data which results in a narrow bandwidth at great extended correlation times. For linear upsweep data, such as the ADCOH data, the higher frequencies are lost, and the band for times greater than the original length of data can be determined using the following equation:

$$f(t) = f_1 - \frac{f_1 - f_0}{\text{sweeplength}} (t_{\text{extended}} - t_{\text{original}})$$

where

f_0 = frequency at beginning of sweep band

f_1 = frequency at end of sweep band

f = the minimum frequency for linear downsweep or the maximum frequency for linear upsweep data.

A 32 s recording time of a 24 s 14-56 Hz linear upsweep resulted in 8 s of full correlation time for the ADCOH data. The recorded traces were extended before correlation to yield 17 s of correlated data. The extended correlation process retained the full 14-56 Hz bandwidth over the first 8 s of the data. After 8 s, the bandwidth is narrowed according to the above equation. The bandwidth at 10 s was reduced to 14-52.5 Hz, at 13 s to 14-47 Hz, and at 16 s, one and one half octaves remained in the 14-42 Hz bandwidth. Reflections from Moho depths on the ADCOH data are observed at 12-14 s; the bandwidth at this depth was 14 to 49-45.5 Hz, respectively, a range which should provide the resolution necessary to image the crust-mantle boundary. The bandwidth of the ADCOH data is wider than that of the COCORP or Seisdata at all depths. The larger bandwidth may be responsible for the increased resolution of the ADCOH data at midcrustal and lower crustal depths as compared to the COCORP and Seisdata profiles.

A 30 s recording time of a 24 s 48-12 linear downsweep resulted in 6 s of full correlation time for the Seisdata set. The recorded traces were extended before correlation to yield 16 s of data. The full 48-12 Hz band was preserved in the first 6 s of data. Because of the downsweep, the lower frequencies are lost during the extended correlation process. At 10 s the bandwidth was narrowed to 48-18 Hz, at 13 s the bandwidth was reduced to 48-22.5 Hz, and at 16 s to 48-27 Hz. The narrow

bandwidth of the extended Seisdata profiles contributed to the decreased resolution of the Seisdata at deeper depths as compared with the ADCOH data.

Vibroseis Whitening

A process called vibroseis whitening (Çoruh and Costain, 1983) was applied to the conventionally processed data by applying AGC to the data prior to correlation in order to balance (whiten) the spectral content. Vibroseis whitening partially compensates for the effects of geometrical spreading and intrinsic dampening.

Modified Geometry

Due to the rough terrain encountered in the ADCOH site region, the survey route was often tortuous. As a result, portions of the dip lines were actually parallel to strike. The geometry of the line was modified to compensate for the deleterious effects of the crooked line by choosing straight line segments through the areas where the CDP coverage was the densest in a direction perpendicular to strike (Figure 35). The result was an increased fold for most CDP gathers and hence an increase in resolution.

Datum Statics

In order to obtain a seismic section in which the reflectors represent true geologic structures, the seismic arrival times must be reduced to a common reference time to remove the effects of the weathered layer and varying topography along the seismic line. The objective is to choose a suitable

Figure 35. ADCOH Line 3 Line Geometry: Dots represent modified CDP locations

horizontal plane and to subsequently reduce the travel times to simulate the location of the shots and receivers along the datum plane. Analysis of the shot gather first breaks was performed to determine the approximate replacement velocity of the weathered layer. The chosen velocities determine the amount of shift necessary to eliminate the deleterious effects engendered by the lateral variations. Small remaining offsets due to travel paths through different portions of the near surface may remain, and may be compensated for through residual static corrections. The elevations of the topography traversed by the seismic lines ranged from 250 to 1100 m. The average elevations were chosen for each line as the datum elevation for that particular line to yield an optimal (minimal) static corrections. The automatic line drawing sections were ultimately manually shifted to a common datum of 500 m after processing for line tying and mapping.

Gain

The application of the gain functions such as vibroseis whitening, spherical divergence corrections, and AGC partially corrects for amplitude losses due to geometrical spreading and intrinsic dampening. The corrections result in well-balanced sections with high signal-to-noise ratios and reveal smaller reflectors that would have been otherwise masked. These corrections were applied to the conventionally processed data.

Other processes, such the amplitude decay correction, correct for geometrical spreading, absorption, and other amplitude decay losses, and yet still retain relative amplitude information. Although the signal-to-noise ratio is not increased, the relative amplitude sections enable a discrimination between reflection packages based on the reflection strength and character. An amplitude decay correction was applied to all relative amplitude data.

Spherical Divergence

The application of a spherical divergence correction after correlation also helps to boost amplitudes which have been attenuated by geometrical spreading. The DISCO method invokes a user-defined velocity function to determine the necessary gain function. The user-defined spherical divergence velocity function can be designed to boost decayed amplitudes or to reduce large amplitudes, such as those characteristic of ground roll. The velocities were thus chosen to yield the optimal amplitude correction prior to sorting. Shot 112 of ADCOH Line 6 is shown (Figure 36 to Figure 39) without vibroseis whitening or spherical divergence corrections, without vibroseis whitening but with spherical divergence corrections, with vibroseis whitening but without spherical divergence corrections, and lastly with vibroseis whitening and with spherical divergence corrections. Several shot record gain tests revealed that the most balanced records were those to which both vibroseis whitening and spherical divergence corrections had been applied. Vibroseis whitening and spherical divergence corrections were thus applied to all conventionally processed data.

Amplitude Decay Correction

To correct for geometrical spreading, absorption and amplitude decay losses due to coupling problems, while retaining relative amplitude information, an automatic amplitude decay correction was designed (Çoruh, 1989 unpub.) and applied to the relative amplitude data in the CDP domain. The correction is determined by the amplitude decay curve (Figure 40) of each pre-stack trace and is subsequently applied to the related trace. The correction involves the determination of the amplitude decay curve from the partial energy computed from within a moving, user-defined time gate. The inverse of the amplitude decay curve is subsequently invoked to correct the amplitude of the trace. All sample points proceeding the first time gate midpoint are multiplied by the scalar of the first midpoint; all sample points following the last midpoint in the last time gate are multiplied by the scalar determined for the last midpoint. A resulting side effect of this correction is that the beginning and end of a trace are affected by the length of the user-defined moving window. A shorter

Figure 36. ADCOH Line 6, Shot 112: Displayed without vibroseis whitening or without spherical divergence corrections.

Figure 37. ADCOH Line 6, Shot 112: Displayed with vibroseis whitening but without spherical divergence corrections.

Figure 38. ADCOII Line 6, Shot 112: Displayed without vibroseis whitening but with spherical divergence corrections.

Figure 39. ADCOH Line 6, Shot 112: Displayed with vibroseis whitening and with spherical divergence corrections.

Figure 40. Amplitude Decay Curve: Time gate of 100 (left) and 2000 (right) ms.

Figure 41. Amplitude Decay correction: Time gate of 0, 100 and 2000 ms.

time gate results in a more balanced trace (Figure 41) at the expense of lost relative amplitude information. A longer time gate results in higher amplitudes near the surface due to the fact that all sample points proceeding the half-window length were multiplied by the scalar determined for the center of the first time gate, thereby enhancing the large, near surface amplitudes. However, the use of a larger time gate retains the relative amplitude information. After amplitude decay correction tests, a time gate of 2000 ms was chosen as the optimal length to balance the trace and yet still preserve relative amplitude information. Such a time gate helped to reduce coupling effects and was utilized during the application of the amplitude decay correction on all relative amplitude processed data.

Residual Static Corrections

Irregularities in the surface elevation, thickness of the weathered layer, the velocity of the weathered layer, and the presence of a water table, alluvial or glacial fill, all contribute to small but significant deviations in seismic arrival times. Since the velocity and the thickness distribution of the weathered layer are unknown, the determination of the appropriate static corrections is problematic. The trace-to-trace coherency must be improved prior to stack to obtain an optimal stack. The method invoked to compensate for arrivals due to a varying weathered layer is a residual statics correction. The residual statics correction employed herein is a surface-consistent process; the near surface conditions are the same regardless if the station is occupied by a receiver or by a shot. Thus, the static corrections depend upon the geometry of the shot and the receivers, not upon the raypaths. To determine the corrections, a time gate containing a good signal-to-noise ratio is extracted from the normal moved-out CDP data. A pilot trace is constructed by stacking together a specified number of gathers. The pilot trace is subsequently cross-correlated with the traces, and the time shifts between the original trace and the reference trace are recorded. The traces are then shifted according to the determined shift value, and stacked again to yield an updated reference trace. The

new reference pilot trace is in turn cross-correlated with the adjusted traces to yield updated residual static shifts. This process continues in an iterative fashion; when the process is complete, the static shift values are stored in the data base for application at a later time. A maximum allowable time shift is usually imposed to avoid unrealistic corrections. After application of the static corrections, a velocity analysis is performed, and the velocities are updated. The process of extracting a time gate of normal moved-out data, determining the static shifts in an iterative fashion, applying the determined shifts to the whole CDP data set, and updating the velocities continues until the resulting improvement is negligible.

During the processing of the ADCOH data set, a maximum time shift of 20 ms was imposed. Statics were computed 3-9 times per line and were occasionally computed over more than one window on a given line. The residual statics application was followed by a detailed velocity analysis which resulted in greatly improved signal-to-noise ratio on all sections.

Velocity Analysis

Stacking velocities were manually determined using constant velocity panels roughly every 50th CDP (approximately every 2 km) on all ADCOH data and on SEISDATA Line 6. Due to the complex nature of the recorded waveform engendered by the convoluted geology, the stacking velocities obtained from the data were laterally variable and often contained inversions. The stacking velocities were thus chosen to obtain the best signal-to-noise ratio which would in turn maximize the stacking of the events considered to be primaries rather than to give realistic Dix's formula interval velocities.

Reprocessing included an increased number of multi-pass, multi-iteration statics followed by careful and more detailed (i.e. interval between analyzed CDPs smaller) velocity analysis. Due to rough terrain encountered in the ADCOH site region, highly variable near surface velocities (from 4.2

km/s to 7.0 km/s), and unknown lateral variations in the weathered layer, the application of the residual static corrections followed by a detailed velocity analysis were the most critical processing steps for the SEISDATA and ADCOH data.

Frequency - Wavenumber Filtering

Using two-dimensional Fourier transformations, traces can be transformed from the (x,t) domain into the (f,k) domain. A constant velocity function in the x,t domain will map into the f-k domain as a single, radial line ($v = \frac{\omega}{k}$). By defining a reject or pass fan in the frequency-wavenumber domain, it is possible to attenuate undesirable wave trains with pre-determined velocities, such as those characteristic of ground roll or of evanescent energy.

To attenuate the unwanted low velocity noise and spurious dipping events (i.e., sideswipe), an appropriate dip-pass filter was chosen for each line. The unmigrated ADCOH data sets were filtered with a gentle f-k filter prior to stack (4.5-14.5 ms/trace). The filtering resulted in decreased noise and rendered the reflections more continuous. To avoid removing steeply dipping real diffractions and steeply dipping reflections, f-k filtering was not performed on the sections that were to be migrated, although a gentle post stack f-k filter (15 ms/trace) was sometimes applied to the sections after migration.

Deconvolution

Predictive filters can be designed to selectively attenuate repetitive events having specified periodicities. If multiple energy is apparent on autocorrelations of the recorded trace, predictive deconvolution with a prediction lag that is equal to the second zero crossing of the autocorrelation

is commonly used to eliminate the noise. Although multiple energy was not apparent on the autocorrelations of the SEISDATA or ADCOH data, predictive deconvolution tests with a gap time of 20 ms and with a varying filter point of length 20-150 sample points (by 10) were run. As the tests did not improve the data, and even degraded the data in places, deconvolution was not applied to the SEISDATA or ADCOH data during processing. One obvious reason that predictive deconvolution did not improve the conventionally processed data is that spectral whitening was accomplished during vibroseis correlation.

Migration.

All ADCOH and Seisdata were conventionally time-migrated using a finite differencing technique following Claerbout (1985). The migration was performed on stacked data using a velocity function which was proportional to the stacking velocity function for that line. Using a finite difference algorithm to solve an equation which contains a parabolic approximation theoretically should result in undermigration (Yilmaz, 1987). However, the discontinuous nature of many of the reflectors acts as a series of spikes which introduce noise patterns on the migrated sections. These patterns, which are generally in the form of upturned smiles, can be attenuated by using a migration velocity lower than the stacking velocities. The migration velocities employed herein were obtained empirically by running several migration tests prior to the full migration. In addition, gain was applied to the stacked data prior to migration to reduce the noise patterns generated from reflection terminations.

Many shortcomings contribute to an inaccurate migration. The velocity function that was used to stack the data was determined using the normal move-out equation, which is based on an invalid horizontal reflector assumption. Our lack of knowledge of the true velocity function limits the accuracy of the migration. Additionally, the finite aperture size restricts the range of reflector dips that can be adequately migrated by the algorithm. The presence of extreme lateral velocity variations

in the site area suggests that a time migration will not result in the true positioning of the reflector, yet a depth migration cannot be invoked because of the inaccurate velocity structure specification. In addition, system limitations (i.e., array processor memory) permitted only up to about 8 s of data to be migrated, depending on the line length. Because of the limitations associated with the system and with the migration algorithm, both the migrated and unmigrated sections were used for the interpretation.

Automatic Line Drawing

The accuracy and quality of hand line drawings are directly related to the ability of the interpreter to abstain from bias and to be able to filter out incoherent noise. Herein, an Automatic Line Drawing technique (ALD; Çoruh et al, 1987) was employed to produce line drawings of all final conventional and relative amplitude migrated and unmigrated sections. The technique estimates the coherency between the traces within a moving, user-defined time-distance gate. The coherencies are then subject to further selection by taking their power with a pre-defined exponent. The resultant coherent reflections are subsequently displayed as a variable-area shaded plot. The ALD display retains the original waveform and exhibits relative seismic reflectivity. This allows the interpreter to observe coherent reflections that were previously too weak or obscured by noise to be recognized and thus permits an unbiased and detailed interpretation. Often the noise patterns (i.e., smiles) created by the migration process are coherent enough that they are picked up by the line drawings. The conventional display sections and the automatic line drawings of all migrated and unmigrated data were thus used in conjunction for the interpretation.

Vita

Susan Sharpless was born on May 2, 1962 to Leslie and Barbara Sharpless. Susan graduated from University of California at Santa Barbara with a Bachelor of Arts Degree in geology in 1985. From 1985 to 1987, Susan worked at the U.S. Geological Survey in Menlo Park, California. In 1987, Susan married Alan Hubbard, and they both enrolled in the graduate program in the Department of Geology at Virginia Polytechnic Institute and State University. After completing her Masters of Science Degree in geophysics, Susan will work for ARCO Oil and Gas Company in Lafayette, Louisiana.

Susan Sharpless Hubbard