Crustal Structures and

The Eastern Extent of the Lower Paleozoic Shelf Strata

Within the Central Appalachians:

A Seismic Reflection Interpretation

by

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(ABSTRACT)

Reprocessing of line PR3 proprietary seismic reflection data (24-fold) has delineated Grenvillian, Paleozoic and Mesozoic structures within the Appalachian foreland, Blue Ridge, and Piedmont of the central Appalachians. The eastern portion of PR3 can be correlated along strike with the western portion of line I-64, reprocessed earlier at Virginia Tech. The I-64 seismic reflection data (12-fold) images the crust from the eastern Valley and Ridge, Blue Ridge, Piedmont and Atlantic Coastal Plain provinces. Automatic line drawing displays were produced from both data sets for the purpose of interpreting and comparing subsurface structures. Within the Piedmont, large reflective structures imaged on both lines PR3 and I-64 are interpreted to be nappes that might be comprised of deformed Catoctin, Evington Group and possibly younger metamorphosed rocks. A concealed extension of the Green Springs mafic mass intrudes a nappe imaged along the PR3 profile.

The Blue Ridge-Piedmont allochthon was transported in a northwest direction along the Blue Ridge thrust, which ramped upward beneath the Piedmont province approximately 12 km east of the surface exposure of the Mountain Run Fault. Along line PR3, the Blue Ridge thrust maintains an undulating geometry, and the maximum thickness of the Blue Ridge allochthon is interpreted to be approximately 4.5 km. The Blue Ridge metamorphic allochthon is generally acoustically

transparent and overlies parautochthonous Lower Paleozoic shelf strata. The maximum thickness of these strata is approximately 8 km. Shelf strata are interpreted to extend as far east as 5 km east of the surface exposure of the Mountain Run Fault, the northeastward extension of the Brevard Fault Zone, where they are truncated by the Blue Ridge thrust at a depth of 10.5 km (3.5 s). Various folds and blind thrusts are imaged beneath the Appalachian foreland; however, the foreland does not appear to have experienced the same degree of deformation as observed in the eastern provinces. A basement uplift approximately 45 km wide is imaged beneath the Valley and Ridge province and is interpreted as having formed prior to Upper Cambrian time. Further west, reflections imaged beneath the Glady Fork anticline in the Appalachian Plateau are interpreted as a positive flower structure associated with wrench fault tectonics. Relatively few deep crustal reflections are imaged along line PR3. The majority of reflections that does exist at these depths is observed beneath the Piedmont and eastern Blue Ridge. The high reflectivity associated with the Grenvillian basement in these areas suggests that this crust was deformed during compression related to the Paleozoic orogenies and extension related to Late Proterozoic and Mesozoic rifting.

Acknowledgements

I would like to express my gratitude to the special people who supported me during my graduate career at Virginia Tech. First and foremost, I would like to thank my co-advisors, Dr. Cahit Çoruh and Dr. John K. Costain for their guidance and assistance throughout my studies. Dr. Çoruh's initial recommendation of this research project and his wealth of knowledge in the field of seismic reflection processing and interpretation formed the cornerstone of my project. Dr. Costain's familiarity of previous and current geophysical and geological studies of the Appalachians has been of tremendous assistance during my research. Most important, however, is the invaluable time and counsel they provided for me during these past few years. Appreciation is also extended to Dr. Edwin S. Robinson for serving on my committee.

Mildred Memitt has been of valuable assistance in the Regional Geophysics Laboratory and I would like to thank her for all of her time and support with regard to seismic processing. She is truly a wonderful person and has provided me with many enjoyable conversations regarding the intricacies of DISCO and various other aspects of life. Thanks is also extended to Bob Montgomery, for maintaining the VAX 11/785 and fixing the technical glitches I sometimes encountered during processing; and to Bill Henika and James F. Conley of the Virginia Division of Mineral Resources, who provided their time and assistance in helping me to gather current geological data pertaining to the central Appalachians study area.

Finally, I would like to thank my family for all of their encouragement and support. My husband, Gregory B. Lampshire, has the patience of a saint and has encouraged me in all my endeavors. Greg, you are truly No Ka Oi (number one, the best)! My parents, Col. Henry M. Dermody Jr. and Mrs. Kathleen T. Dermody, have shown me the true value of a family and to them I will forever be grateful. My sister, Joanna M. Dermody, provided encouragement over the many miles separating us.

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Table of Contents

List of Illustrations

List of Tables

Introduction

Within the past several years, many advances have been made that clarify the subsurface structures of the southern and northern Appalachians; however, relatively few studies have been published that focus primarily on the structural geology beneath the central Appalachians. In particular, the geometry of the Blue Ridge and Piedmont allochthons, the easternmost extent of the parautochthonous Lower Paleozoic shelf strata, and deformational features associated with the Appalachian foreland remain controversial in this region.

Reprocessing of Petty-Ray (now Halliburton Geophysical Services, Inc.) seismic reflection line 3 (PR3) has provided new insight into the internal geometry of the Virginia and West Virginia central Appalachian orogen. Results of an earlier geophysical investigation were reported by Pratt and others (1988) along a 281 km segment of Interstate 64 (I-64) between Staunton, VA, and the Atlantic coast approximately 15 km south of line PR3 (Figure 1). The present study images subsurface geometry west of line I-64, and correlation of images along PR3 and I-64 provides three-dimensional subsurface control when delineating the deformational features beneath the Piedmont and Blue Ridge provinces. The subsurface structures of the Piedmont and Blue Ridge provinces appear to have experienced a more complex series of deformational events than the structures imaged beneath the Appalachian foreland. Subsurface structures beneath the Appalachian Plateau, Valley and Ridge, Blue Ridge and western Piedmont provinces are reevaluated in light of the increased seismic resolution provided by the reprocessed PR3 data. The following is a discussion of subsurface structures that incorporates the seismic reflection data along lines PR3 and I-64, potential field data, well log data and the published geologic data within the central Appalachians of Virginia and West Virginia.

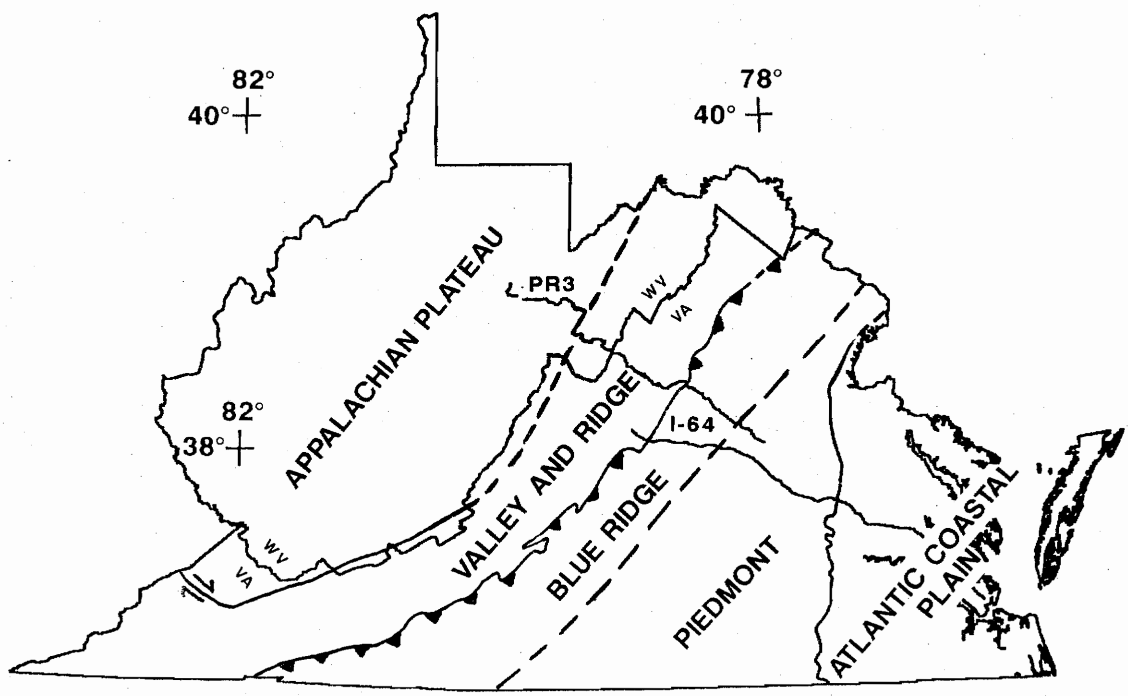


Figure 1. Location of the study area: The PR3 and I-64 seismic reflection data were acquired over the Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont and Atlantic Coastal Plain provinces of the central Appalachians. Figure modified from Rankin (1976) and Rankin and others (1989).

Geologic History of the central Appalachians

The Appalachian mountain system extends from Newfoundland, Canada, southwest to the southeastern United States. This mountain chain is often divided into three geographic regions referred to as the northern, central and southern Appalachians, which are characterized by different structural geometries, stratigraphy or episodes of deformation (Suppe, 1985). In many publications, however, the Appalachian Mountains have been classified into two geographical segments that are separated by the Hudson River, and referred to simply as the southern and northern Appalachians (Rodgers, 1970); the central Appalachians are then considered to be a subset of the southern Appalachians.

The central Appalachians are located between the northern boundary of the Reading Prong (near New York City, NY) and the southern boundary of the northern Blue Ridge (near Roanoke, VA); a distance of about 650 km (Rodgers, 1970; Drake, 1980). Four distinct geologic provinces are located within the central Appalachians. From northwest to southeast, these regions include the Appalachian Plateau, Valley and Ridge, Blue Ridge and Piedmont provinces. These provinces are distinguished on the basis of their varying topography and surface geology.

The topography and stratigraphy of the Appalachian Plateau province are represented by plateaus and wide, open folds composed primarily of Carboniferous strata. In general, these rocks have experienced little deformation and have not been metamorphosed (Wiltschko and Geiser, in Hatcher and others, 1989). The Allegheny structural front defines the eastern boundary of this province.

The Valley and Ridge province, southeast of the Appalachian Plateau, is characterized by a series of narrow, parallel ridges and valleys that strike northeast. The ridges are underlain primarily by sandstones, and the valleys that separate these ridges are underlain by carbonates and shales (Hack, 1989). The Cambrian through Pennsylvanian strata are folded and a few thrust faults are exposed in the PR3 study area; however, these rocks are relatively unmetamorphosed (Glover and others, 1983). Together, the Appalachian Plateau and Valley and Ridge provinces define the Appalachian foreland (Hatcher, 1989a).

The rocks of the Blue Ridge province, east of the Valley and Ridge province, have been interpreted as representing the ancient North American continental margin, which was decapitated and transported westward during Paleozoic orogenies (Brown, 1970; Rankin, 1975; Evans, 1984; Wehr and Glover, 1985; Glover, 1989; Glover and others, 1992). The axis of the Blue Ridge, coincident with the Rockfish Valley (Hayesville-Fries) Fault, might represent the reactivated late Proterozoic hinge zone of this margin (Wehr and Glover, 1985). In the PR3 study area, the Blue Ridge is referred to as the Shenandoah massif, and is considered to be a Middle Proterozoic outlier of the Grenville province (Rankin and others, 1989). The Blue Ridge is characterized by a dominant, asymmetrical allochthonous anticlinorium of Grenville age basement rock, which is approximately 56 km wide in central Virginia (Conley, 1988). Within this area, this northeast plunging anticlinorium was reported as overturned to the northwest (Evans, 1984).

The Piedmont province lies east of the Blue Ridge province and is characterized by rolling hills that slope gently to the southeast. Within the central Virginia Piedmont, mélanges comprised of a phyllite, schist or gneiss matrix containing exotic rocks compose the imbricated thrust sheets of this region (Pavlides, 1989). The majority of exposures in this area is covered by a thick mantle of saprolite derived from the metamorphosed Precambrian and Paleozoic sedimentary and igneous rocks (Rodgers, 1970; Pavlides, 1989).

Relatively little has been published about the geological and tectonic history of the immediate area of seismic line PR3. Work is in progress in central Virginia south of the Potomac Valley, but little of this information has been published (Drake, in Drake and others, 1989). Published data do confirm that the central Appalachian region is the product of several orogenies that occurred during the Proterozoic and Paleozoic eras. Furthermore, in the eastern provinces, the effects of these episodes were complicated and overprinted by extensional events of Mesozoic age. A general discussion of the geologic development of the central Appalachians with regard to the study site has been compiled from various sources and is discussed briefly below.

Proterozoic

Precambrian Laurentian continental basement underlies the Appalachian Plateau and Valley and Ridge provinces, extending eastward beneath the center of the Blue Ridge (Rodgers, 1970). The easternmost extent of this basement in the Appalachian orogen has been the subject of much controversy. This basement was affected by the Grenvillian orogeny and overlain by Late Precambrian and Paleozoic rocks. The allochthonous crystalline rocks of the Blue Ridge (1 b.y.) (Bartholomew, 1984) were deformed during this orogeny, which has been interpreted as a major event that resulted from either Mid-Proterozoic extension within a single continent or by continent-continent collision (Moore, 1986; Woussen and others, 1986). During this event, the basement rocks underwent amphibolite to granulite facies metamorphism (Rankin and others, 1989).

Late Proterozoic - Ordovician

Following the Grenvillian orogeny, a continental margin formed along the eastern Laurentian craton as the result of late Proterozoic extension and rifting of the Grenville basement. Extension began as the metamorphosed basement was uplifted, eroded and intruded by the 690-640 Ma Crossnore Suite plutons (Rankin, 1975; Odom and Fullagar, 1984; Wehr and Glover, 1985; Rankin and others, 1989). The rifting that followed led to the opening of the Iapetus ocean 690-570 Ma (Rankin, 1975; Rankin, 1976; Odom and Fullagar, 1984; Wehr and Glover, 1985).

Wehr and Glover (1985) outlined the formation of the early continental margin, which began with extensional uplift followed by rifting. Subsidence occurred just east of a hinge zone now represented by the transported Blue Ridge axis. Wehr and Glover (1985) proposed that the Rockfish Valley Fault (Hayesville-Fries Fault), which corresponds with this axis, might be the reactivated late Proterozoic hinge zone that separates the foreland basin on the west from the attenuated crust on the east. Rifting was succeeded by rapid subsidence, and during this stage the crust thinned and normal faulting took place. Block-faulted basins that formed on attenuated crust east of the hinge zone were filled with deep-water sediments of the Lynchburg Group, and at the same time, shallower, landward rift basins that formed west of the hinge zone were filled with terrestrial and shallow marine sediments of the Swift Run Formation. These basin deposits were then covered by Catoctin basalts during a volcanic episode around 570 Ma that ended approximately at the beginning of Cambrian time. On the basis of these late Proterozoic and early Paleozoic rocks, Wehr and Glover (1985) divided the Blue Ridge into a western and eastern subprovince, bounded by the anticlinorium axis (Figure 2).

At the beginning of Cambrian time, the seas transgressed and a passive margin formed as the clastic shelf deposits of the Chilhowee Group disconformably overlaid the earlier rift facies sequence (Figure 2). The passive margin sequence of the central Appalachians is comprised of the Late Precambrian to Early Cambrian basal clastic sequence consisting of the Weverton, Harpers and

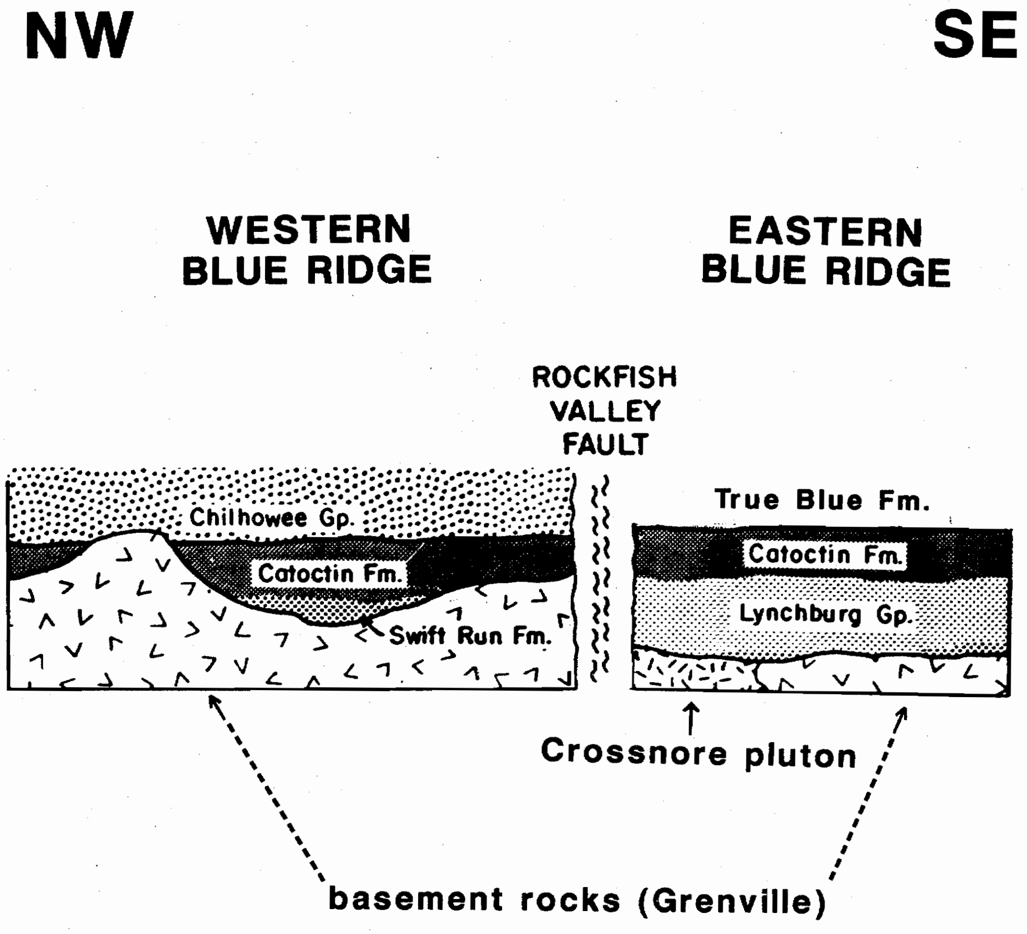


Figure 2. The Late Precambrian-Early Paleozoic stratigraphy of the Blue Ridge: Summary of the stratigraphic units located along the eastern and western limbs of the Blue Ridge anticlinorium in the PR3 study area. Figure modified from Wehr and Glover (1985).

Antietam Formations, the Early Cambrian carbonate sequence (Tomstown/Shady Dolomite), the Early to Middle Cambrian clastics (Waynesboro/Rome Formation), the Middle to Early Late Cambrian sequence (Elbrook Formation), the Late Cambrian cyclic carbonates (Conococheague Formation) and the Ordovician carbonates (Beekmantown Group) (Read, in Rankin and others, 1989). Within the PR3 study area, this passive margin sequence is referred to as the parautochthonous Lower Paleozoic shelf strata (LPSS). These strata are presently overlain by allochthonous crystalline rocks of the Blue Ridge province, but are exposed in the eastern Valley and Ridge province.

Passive margin conditions continued until early Middle Ordovician time, depositing 2-3 km of shallow water carbonates west of the hinge zone (Wehr and Glover, 1985). As the passive margin sequence was deposited, deep marine deposition occurred to the east of the hinge zone, as evidenced by the fine-grained, metasedimentary rocks of the Evington Group (Wehr and Glover, 1985).

Around 550 Ma, the Chopawamsic volcanic rocks originated somewhere east of the passive margin (Pavlides, 1981). These rocks have been interpreted as forming on an island arc or as a segment of a single exotic terrane to the east of Laurentia (Higgins, 1972; Pavlides, 1981; Pavlides and others, 1982a; Glover and others, 1992). From 480 to 435 Ma, the passive margin conditions along the Laurentian margin ended as the exotic terrane collided with Laurentia during the Taconic orogeny (Glover and others, 1983; Wehr and Glover, 1985; Glover and others, 1992). This event resulted in the westward thrusting of attenuated crust and the overlying slope/rise sequence along the Rockfish Valley (Hayesville-Fries) Fault, as illustrated in Figure 3 (Wehr and Glover, 1985; Glover and others, 1992). A slice of the Laurentian hinge zone was decapitated during this collision and this segment represented the proto Blue Ridge (Wehr and Glover, 1985; Glover and others, 1992). Thrusting was followed by erosion of the eastern orogenic uplifts, producing a flood of sediments that was deposited to the west in the foreland basin. These eastward thickening clastic deposits formed the Taconic clastic wedge during the Late Silurian to Middle Devonian (Hatcher and others, 1989).

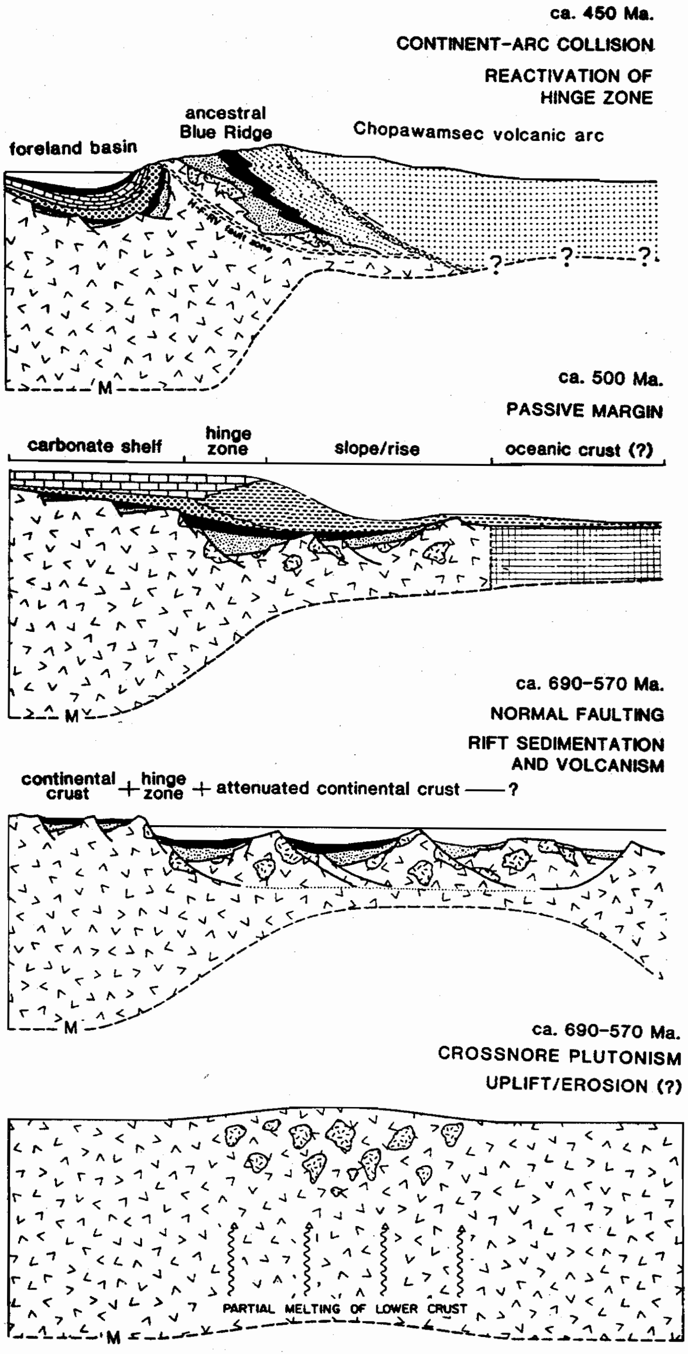


Figure 3. Development of the early Paleozoic continental margin: Summary of the extensional, rifting and drifting episodes that led to the formation of the early Paleozoic passive margin along the eastern Laurentian continent. Development of this margin was discontinued during the initial stages of the Taconic orogeny. Figure from Wehr and Glover (1985).

The 510 to 460 million year old ages of plutons and metamorphic episodes documented in the Piedmont of the central and southern Appalachians suggest that the Penobscottian orogeny might have preceded the Taconic orogeny (Hatcher, 1989b); however, delineating Penobscottian and Taconic orogenic effects in the central Appalachians has been complicated by Acadian and Alleghanian overprinting. According to Drake (Drake and others, 1989), rocks of the Piedmont have been metamorphosed to such an extent that their relationship to the Taconic orogeny is now obscured; however, Glover and others (1983) suggested that Taconic compression caused greenschist to middle amphibolite grade metamorphism in the Blue Ridge and Piedmont, and that these grades of metamorphism extend east to the western edge of the present day Alleghanian deformation front. In light of the available evidence, the Taconic orogeny is often considered to be the most intense Paleozoic deformational event to have effected the central Appalachians.

Silurian - Devonian

During the Silurian and Early Devonian, quartzose sandstones, limestones, dolomites, evaporites and shales were deposited on the passive margin sequence as the Taconic highlands eroded to sea level and were transgressed (Suppe, 1985; de Witt and Milici, 1989). Thus, nonorogenic quartz arenite and carbonate platform strata are now observed overlying the Taconic clastic sedimentary sequence as a result of these marine transgressions (Glover and others, 1983).

The Acadian orogeny played an important role in the northern Appalachians during the Middle Devonian, but the specifics of this episode in the central Appalachians are sketchy. Erosion of most Silurian and Devonian rocks, along with Alleghanian overprinting, has led to uncertainty regarding Acadian events (Osberg and others, 1989). The limited evidence that documents this orogeny has been gleaned from rocks of the Valley and Ridge province. The Middle Devonian black mudstone was overlain by Middle Devonian to Early Mississippian deposits; this sequence comprises the Acadian clastic wedge (Glover and others, 1983; Thomas, in Hatcher and others, 1989).

Early Carboniferous - Permian

During the Alleghanian orogeny, the Blue Ridge-Piedmont composite crystalline thrust sheet was transported westward, ramping into the rift-drift facies and overthrusting the platform sedimentary rocks along a basal detachment that might have originated eastward at the ductile-brittle transition (Hatcher and others, 1989). This event occurred from approximately 330 to 230 Ma as the North American and African plates collided, forming part of the supercontinent Pangaea (Glover and others, 1983). In the Blue Ridge and Appalachian foreland, this detachment is seated in the Lower Cambrian Waynesboro Formation of the Lower Paleozoic shelf strata (Kulander and Dean, 1986). During this time, various other faults propagated upward into shallower detachments within the Ordovician, Silurian and Devonian rocks of the Appalachian foreland (Hatcher and others, 1989).

Westward transport of the basement composite thrust sheet deformed rock units in the Valley and Ridge and Appalachian Plateau. This deformation is preserved as folding and imbricate thrusting within the Valley and Ridge (Wiltschko and Geiser, in Hatcher and others, 1989; Horton and others, 1991). Due to the absence of Permian or Lower to Middle Triassic rocks within the Appalachian orogenic belt, it is difficult to assess when the last stage of Alleghanian deformation occurred (Suppe, 1985).

Post-Paleozoic

The Paleozoic orogenies were followed by the breakup of Pangea and the opening of the Atlantic Ocean during the Mesozoic. Rifting followed the end of compressive deformation, and the subsequent drifting episode led to the formation of the present North American passive margin. As summarized by Manspeizer and others (1989), separation began with late Triassic rifting of the North American and African plates, which was followed by an erosional period. During the Middle

Jurassic, rifting was replaced by drifting as the crust cooled and was transgressed by the sea. This marine transgression was followed by a dominant regression that presently continues (Hatcher, 1989b).

PR3 Research Area

Previous Work

A seismic reflection line across the four provinces of the central Appalachian orogen was acquired along interstate I-64 in Virginia (Figure 1) and interpreted by Harris and others (1982a, 1982b). On the basis of the I-64 seismic reflection data, they interpreted the presence of a "mega-thrust system" consisting of a series of large-scale thrust sheets along the seismic profile. These thrust sheets were transported in a westward direction along a basal décollement(s) that they interpreted as extending from beneath the Valley and Ridge to the Atlantic Coastal Plain. They divided the crust into three basic units consisting of an autochthonous basement overridden by an allochthonous sedimentary rock unit and an allochthonous metamorphic and igneous rock unit.

Following the initial investigation by Harris and others (1982b), Pratt and others (1988) reprocessed the I-64 data and imaged deeper crustal reflections (Figure 4) by applying an extended correlation technique to produce 14 seconds of data from the original 8 seconds of fully correlated data. Gravity modeling was also carried out by Pratt and others (1988) to investigate the Piedmont gravity high. Interpretations of both upper and lower crustal structures were then reevaluated. Their results supported Harris and others (1982b) seismic interpretation of a Blue Ridge allochthon underlain by shelf strata. They suggested that the Evington Group and Chopawamsic rocks between stations 900-1700 (Figure 4) lie within the synformal structure that reaches a maximum depth of approximately 10 km along this profile. Additionally, they interpreted the Goochland terrane in the eastern Piedmont province to be a nappe that was thrust westward over the Chopawamsic metavolcanic rocks. The dipping reflections that define the eastern boundary of this terrane appeared to penetrate the lower crust, and they proposed that these reflections might originate from the edge of the early Paleozoic continental margin. With regard to the lower crust, the reprocessed I-64 data imaged the west dipping Mohorovicic discontinuity at 30-42 km (10-14 s) beneath the Piedmont and Atlantic Coastal Plain provinces. The results from gravity modeling demonstrated a correspondence between the increase in Bouguer gravity values observed traversing eastward over the Piedmont province and the thickness of the crust, and they attributed the cause of the Appalachian gravity gradient to crustal thinning.

The gross crustal framework along the I-64 seismic profile was also interpreted by Çoruh and others (1988). They suggested that the 100 km wide antiform between stations 1300-2600 (Figure 4 and Figure 5), which is defined by the westward and eastward dipping reflections (B and E on Figure 5), represents a compressional-extensional feature that formed as the result of westward thrusting, crustal thinning and westward tilting during the Mesozoic era. The Moho (M) is imaged best within this compressed and extended region of the crust. Other features that they interpreted on this section include the brittle-ductile transition zone (C) and a dike swarm (D) that might have been intruded during Mesozoic extension. Later comparison of this data set with other seismic data in South Carolina and Georgia (Hubbard and others, 1991) suggests that (D) might be an older intrusion (Çoruh, personal communication). With regard to potential field data, Çoruh and others (1988) correlated this dike swarm with a positive Bouguer gravity anomaly. They attributed the absence of a distinct aeromagnetic anomaly to a greater depth to the top of the dike swarm (F). They also interpreted the westward dipping flank of the antiform to be the locus of the "transported Taconic suture" (TS in Figure 5).

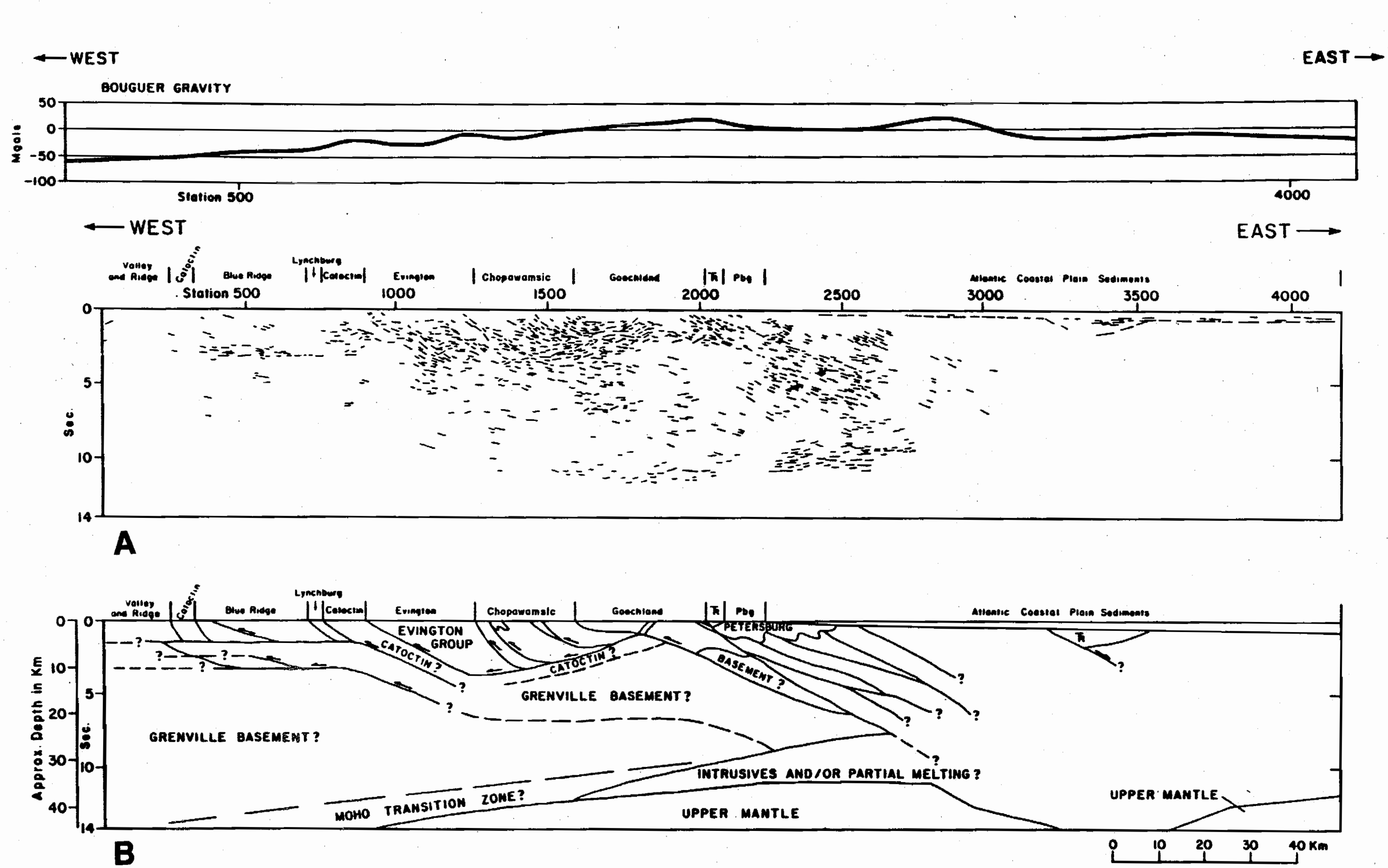


Figure 4. Crustal model along seismic line I-64 by Pratt and others (1988): Interpreted line drawing of post stack time migrated I-64 seismic data (A) and the subsurface interpretation (B).

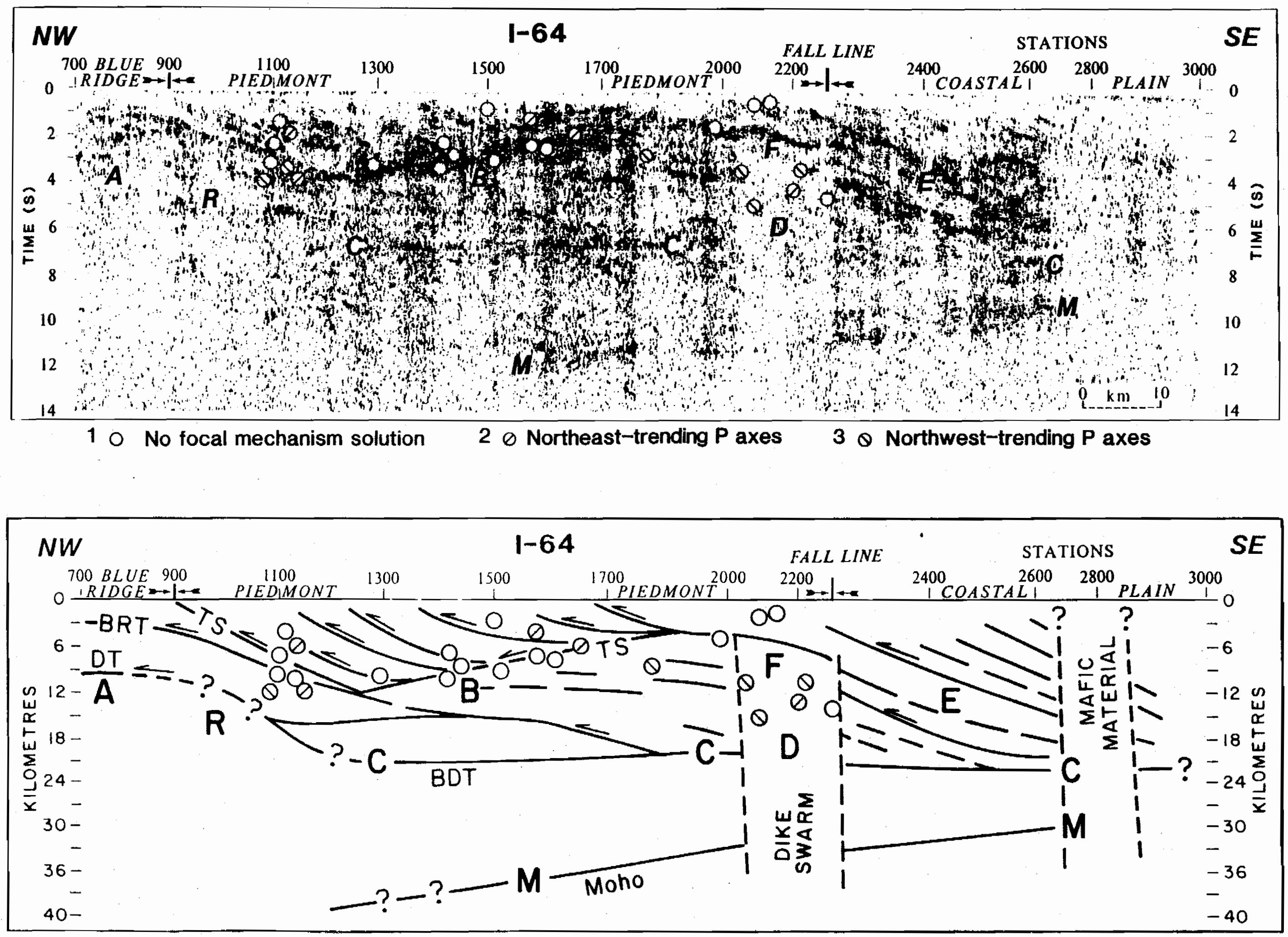


Figure 5. Crustal model along seismic line I-64 by Çoruh and others (1988): Automatic line drawing (top) and gross structural interpretation (bottom). A = parautochthonous Lower Paleozoic shelf strata, B = westward dipping reflections, BDT = brittle-ductile transition zone, BRT = Blue Ridge master décollement C = brittle-ductile transition, D = dike swarm, DT = deeper detachment, E = eastward dipping reflections, F = top of dike swarm, M = Moho, R = ramp, TS = transported Taconic suture.

Further west, the structure and tectonics of the Valley and Ridge and Appalachian Plateau provinces of the Virginia central Appalachians were examined by Kulander and Dean (1986). Their study employed surface geologic data, potential field data, deep-well data, and regional and local reflection seismic data. This information was used to investigate structures within this region and to compile structural cross sections of the crust between the surface and basement. Their cross section 4 (Figure 6) represents the subsurface structures parallel to and just north of line PR3. They proposed that the main structural elements of the Appalachian foreland are the Blue Ridge, Martinsburg and Waynesboro sheets. As shown in Figure 6, the Lower Cambrian Waynesboro shale is the glide unit that forms the sole detachment above the basement; all overlying strata have been displaced westward along this detachment. They noted that Middle Devonian, Silurian, and Mississippian shales within the Martinsburg sheet also served as detachment zones, and shortening within this upper sheet always exceeds shortening within the underlying Waynesboro sheet. With regard to shallower detachments in the eastern segment of their study area, they interpreted the Blue Ridge and Piedmont allochthons as being transported along the North Mountain-Pulaski fault system, which is seated in the Upper Ordovician Martinsburg shale.

Evans (1989) published a detailed study of the structural geometry of the rock units within the Great Valley subprovince and Blue Ridge province of Virginia. In this study, Line 5 corresponds to a segment of line PR3. The Great Valley comprises the eastern region of the Valley and Ridge province, and is bounded on the east and west by the Blue Ridge thrust and the North Mountain thrust (also referred to as the Little North Mountain thrust), respectively. For the purposes of this discussion, the Great Valley is contained within the eastern portion of the Valley and Ridge province and is not considered as a separate subprovince in the PR3 study area. The data of ten separate seismic reflection lines were published in the form of tracings of reflectors interpreted from seismic sections, structural cross sections and restored sections. Since Line 5 is an actual segment of line PR3 processed earlier from the same uncorrelated data, this line will be examined in greater detail. Evans (1989) separated the allochthonous and parautochthonous rocks of the Blue Ridge and eastern Valley and Ridge in this area into three units; the Blue Ridge thrust sheet of Precambrian-Late Cambrian rocks, the North Mountain thrust sheet of Cambrian-Ordovician

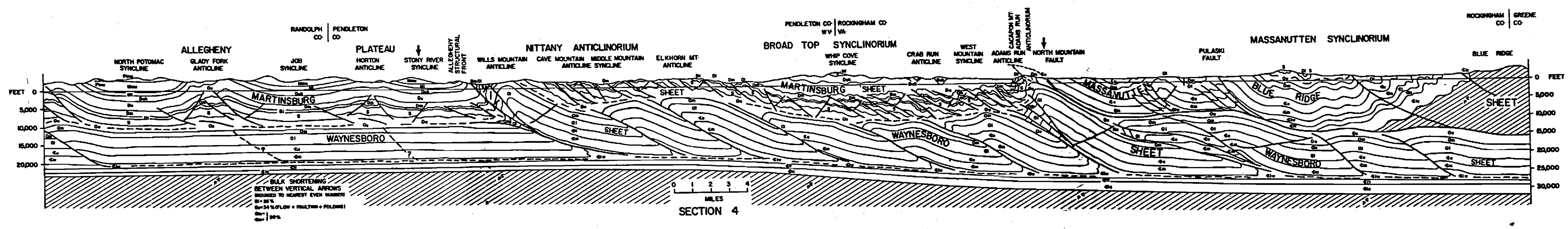


Figure 6. Structural cross section through the central Appalachian Plateau and Valley and Ridge provinces by Kulander and Dean (1986): This section is parallel to seismic line PR3, approximately 10 mi (17 km) to the north. Corresponding stratigraphic units are described in Figure 7.

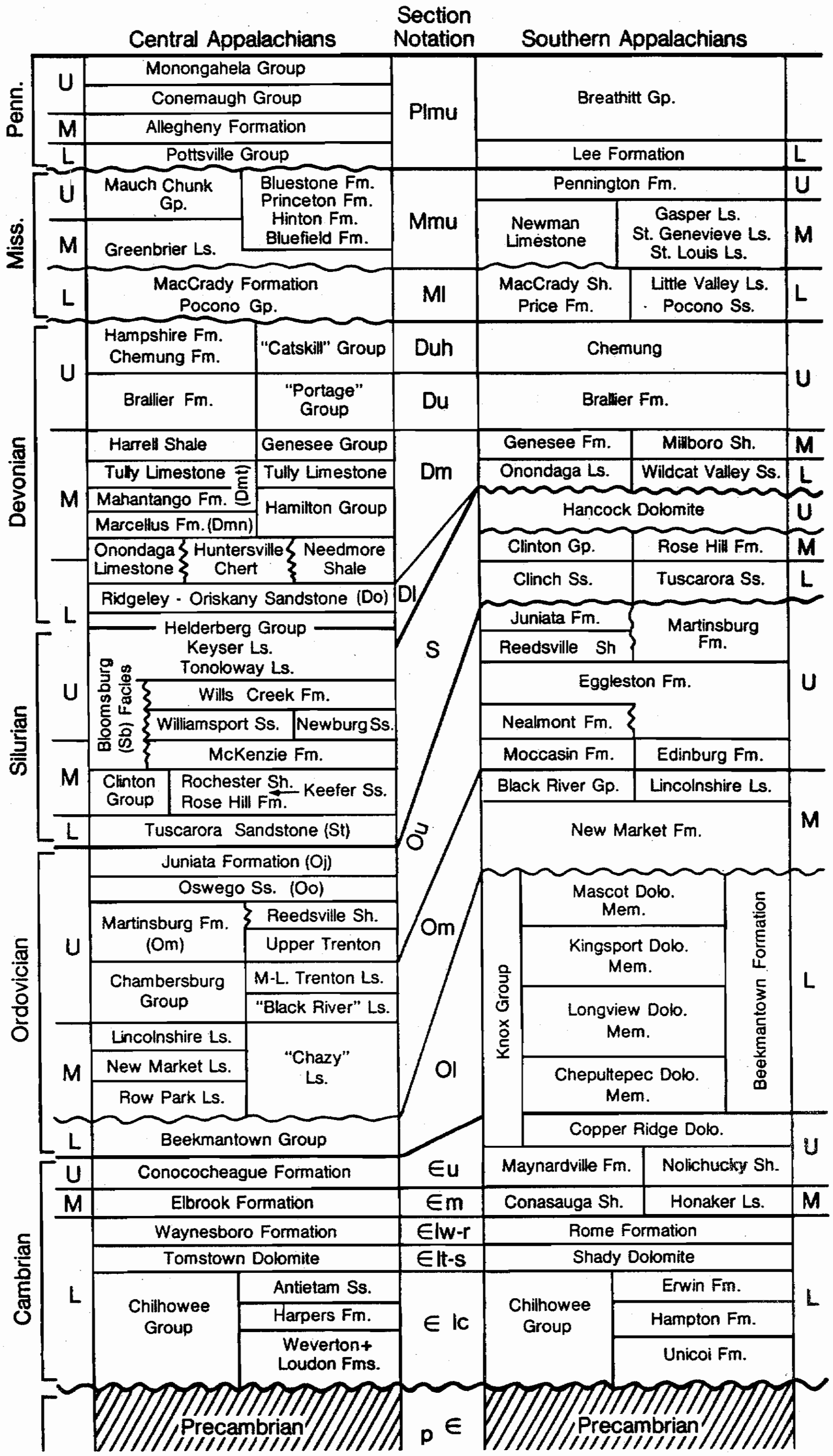


Figure 7. **Central Appalachian stratigraphic chart compiled by Kulander and Dean (1986):** Generalized stratigraphic correlation chart of lithological units found in the central and southern Appalachians.

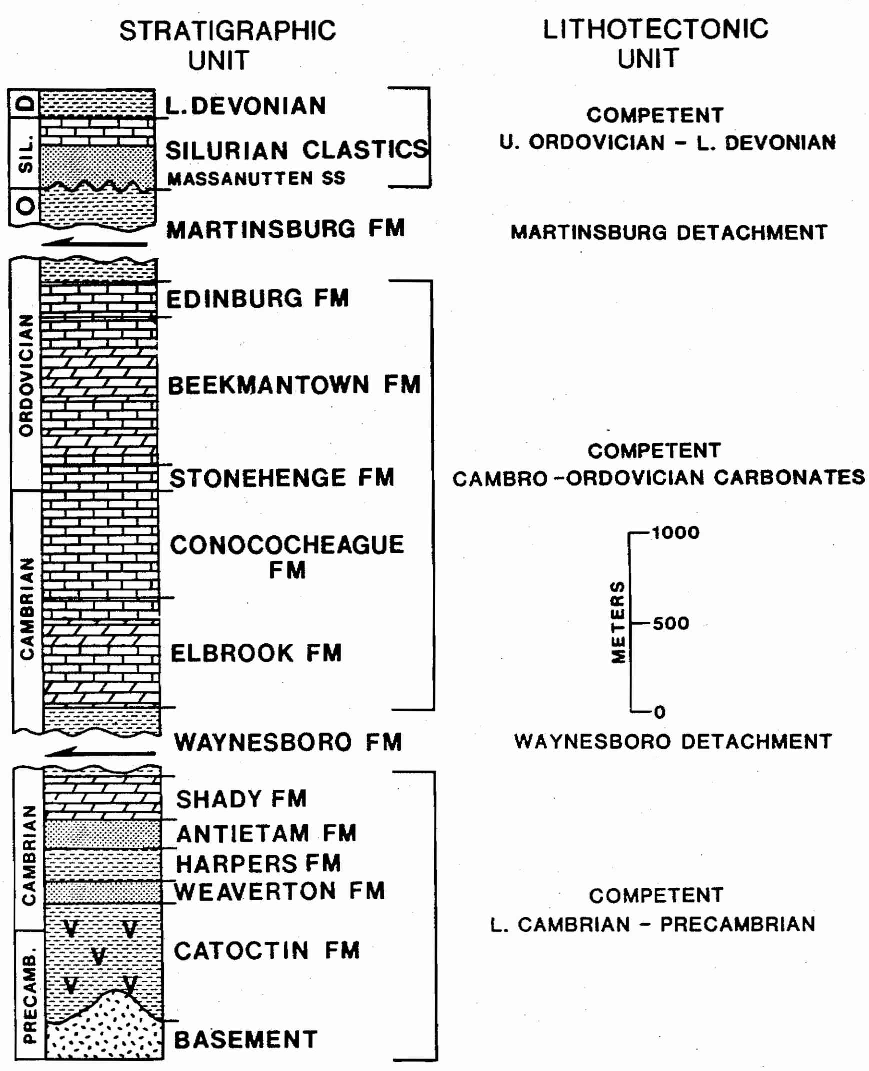


Figure 8. Competent lithotectonic units of the central Appalachians by Evans (1989): The principle competent lithotectonic units which compose the allochthonous, parautochthonous and autochthonous crust of the central Appalachians.

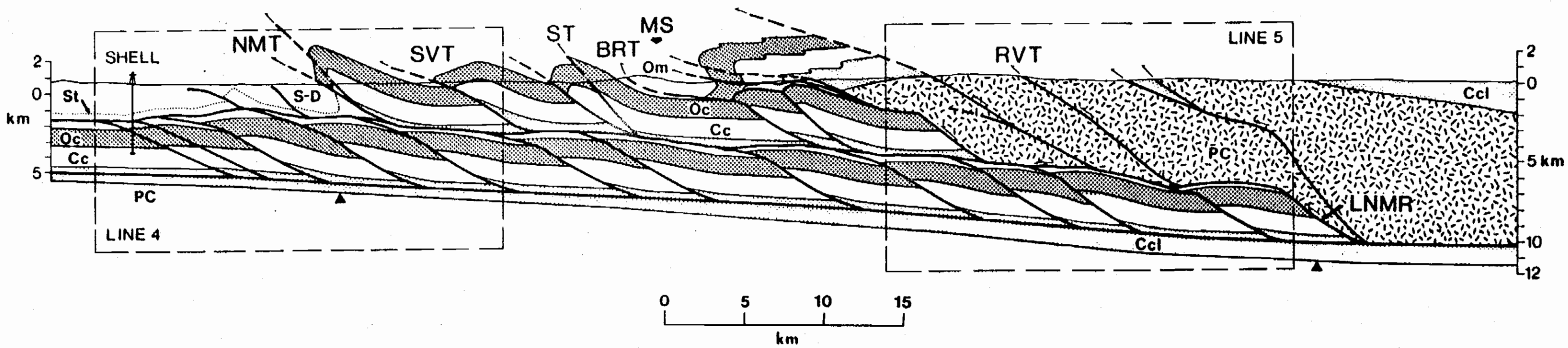


Figure 9. Cross section of subsurface geometry of the Blue Ridge and Great Valley provinces by Evans (1989): Cross section is based on the line 5 seismic reflection data. BRT = Blue Ridge thrust, Cc = Cambrian carbonates, Ccl = Cambrian-Precambrian clastics and metavolcanics, LNMR = lower North Mountain ramp, MS = Massanutten synclinorium, NMT = North Mountain thrust, Oc = Ordovician carbonates, Om = Martinsburg Formation, PC = Precambrian crystalline rocks, RVT = Rockfish Valley thrust, S-D = Silurian through Devonian rocks, St = Tuscarora Formation, ST = Staunton thrust, SVT = Saumsville thrust.

carbonates, and the Upper Ordovician-Late Devonian clastic rocks (Figure 8). He suggested that both the Blue Ridge and North Mountain sheets are seated in the Ordovician Martinsburg shale. Evans interpreted the Blue Ridge thrust sheet as being thrusted over the North Mountain thrust sheet along the Blue Ridge thrust (Figure 9). Additionally, the lower North Mountain ramp (LNMR in Figure 9) represents the footwall cutoff of the North Mountain thrust sheet. In Figure 9, this ramp defines the present eastern extent of the parautochthonous Paleozoic shelf strata.

Seismic Data

Line PR3 is approximately 278 km in length and extends from just west of Elkins, West Virginia, to Louisa, Virginia, across the Appalachian Plateau, Valley and Ridge, Blue Ridge and western Piedmont provinces (Figure 1). The PR3 seismic data were collected by Petty-Ray in 1980 moving from east to west using four Y-600 B vibrators, which were spaced 30.5 m apart and coupled together as a source array. A split spread array of 48 channels was used to record the data. Since both the group interval and source spacing were 91.4 m, this resulted in 24-fold stacked data. A 7 second, 14-56 Hz up-sweep was used to record the data for 12 seconds, producing a total listening time of 5 seconds. Additional parameters pertaining to the acquisition of line PR3 are listed in Appendix A.

The I-64 seismic reflection data were acquired in 1981 by Geophysical Services Incorporated (GSI) for the U. S. Geological Survey and reprocessed at Virginia Tech. The acquisition and recording parameters of this line, along with the processing sequence, are listed in Appendix A. These parameters are mentioned because the I-64 data are herein compared with the PR3 seismic images, and used to verify their extension along strike.

PR3 Seismic Data Processing

An interpretive processing method was conducted on the PR3 seismic data at the Regional Geophysics Laboratory of Virginia Tech. Interpretive processing means that the interpretation of the seismic data was carried out while the processing parameters were chosen, thereby allowing one to make logical inferences about what is signal and what is noise. The processing sequence used on these data varied from the conventional sequence because of the application of vibroseis whitening before correlation (Çoruh and Costain, 1983), the application of extended correlation using the self-truncating method (Pratt, 1982; Pratt, 1986; Okaya, 1989), and the omission of a geometrical spreading correction because of whitening.

Vibroseis whitening was applied to improve the signal-to-noise ratio (S/N) and increase seismic resolution. This process involves the application of an automatic gain control (AGC) before crosscorrelation to compensate for amplitude changes due to frequency and time-varying attenuation. AGCs of 500, 1000 and 2000 ms were applied to various shot records before the vibroseis correlation. From these tests, an AGC of 1000 ms was chosen to whiten the spectral content and partially correct for the effects of geometrical spreading and intrinsic dampening.

The original PR3 data were fully correlated to a listening time of 5 seconds while the deeper reflections were recovered by extended correlation down to 10 seconds. After this correlation, the frequency bandwidth between 0-5 seconds is 14-56 Hz, and tapers out linearly to converge to 14-26 Hz at 10 seconds. The bandwidth at 10 seconds is approximately one octave (14-28 Hz). Extended correlation was not applied beyond 10 seconds due to expected ringing associated with a bandwidth of less than one octave.

Finally, a geometrical spreading correction is often used to compensate for the amplitude loss created by the expanding spherical wavefront. When imaging shallow data, application of this correction enhances the signal. This correction should also be applied if the signal amplitude decays rapidly with respect to depth or offset. In the case of line PR3, reprocessing focused on imaging the large scale subsurface structures observed between the surface and a depth of approximately 30 km; the imaging of shallow features was not the primary target. Additionally, the recoverable frequencies were limited to 14-56 Hz. Since this survey was not designed to yield high resolution data, the decay of the higher frequency signal amplitudes was not a crucial factor. Considering these issues and taking into account the application of vibroseis whitening before crosscorrelation, the increase in resolution resulting from the application of a spherical divergence correction after correlation was deemed negligible and was therefore not applied.

Additional processing parameters applied to the PR3 seismic data are included in Appendix A. Both the unmigrated and migrated sections are displayed as automatic line drawings. The automatic line drawing (ALD) displays were created using a technique related to coherency estimations (Çoruh, and others, 1988). As such, original waveforms are preserved while presenting the relative reflection amplitudes. ALD displays tend to enhance the subsurface images observed in conventional (wiggly-line) sections and lessen background noise (Figure 10). For the purposes of displaying seismic sections for interpretation along PR3, these automatic line drawings are less biased in their presentation than manual line drawings created by the interpreter. Therefore, due to their less subjective nature and excellent resolution during reproduction, the automatic line drawing displays are favored for the purpose of interpretation instead of conventional seismic displays. With regard to the migrated displays, the data were completely migrated down to 6 seconds. Between 6-10 seconds, the data were only partially migrated.

In the PR3 ALD displays, the zero time corresponds to the 600 m reference datum. The time axes represent two-way travel time. Time-to-depth conversions were calculated using a constant velocity of 6 km/s. For conversion of two-way travel times on these displays, a velocity of 3 km/s, equal to one-half the constant velocity of 6 km/s, can be used. All PR3 seismic data displays are scaled one-to-one unless otherwise noted.

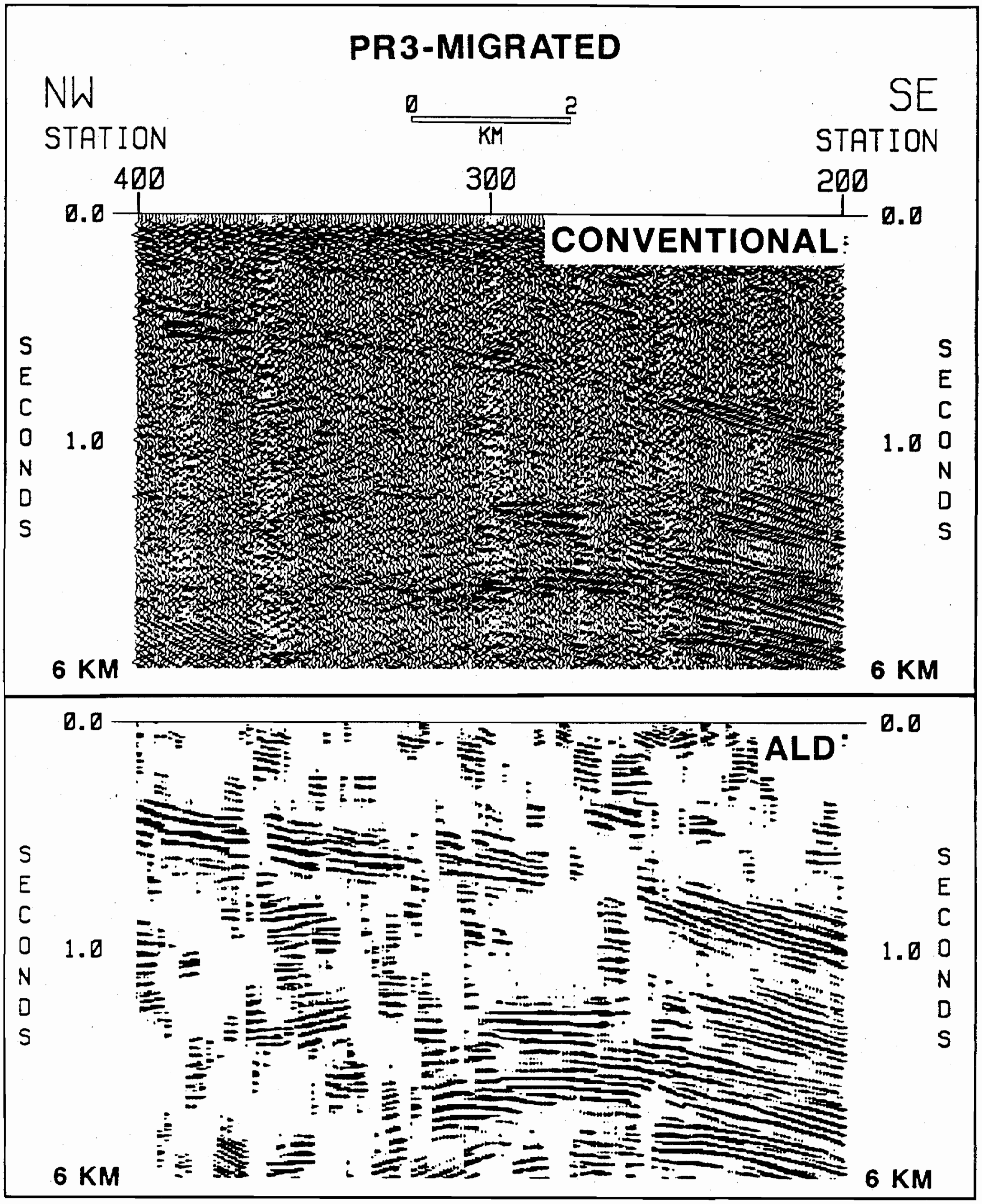


Figure 10. A comparison of ALD and conventional seismic displays: The advantage of the automatic line drawing (ALD) (bottom) over the conventional seismic section (top) lies in the ability to enhance subsurface images, offer a more objective presentation of the data than is possible from hand-tracings of reflectors, and allow greater resolution during reproduction.

Interpretation and Discussion

The interpretation presented herein is based on the compilation of geophysical and geological data, with a primary emphasis on the seismic reflection data obtained from the reprocessed line PR3. The discussion will focus on the seismic images of crustal structure along the western Piedmont, Blue Ridge, Valley and Ridge and Appalachian Plateau provinces and will incorporate potential field data anomalies that are related to the interpretation.

Allochthonous and Parautochthonous Crust

The concept of thin-skinned deformation proposed by Rich (1934) has been confirmed many times by seismic reflection profiling and drilling within the central and southern Appalachians (Harris and Milici, 1977; Cook and others, 1979; Harris and Bayer, 1979; Ando and others, 1983; Cook and others, 1983; Harris and others, 1982b; Pratt and others, 1988). As described by Harris and others (1981), deformation resulted from the westward stacking of thrust sheets along low-angle faults. Specifically, these sheets were displaced above uninvolved crystalline basement and are presently observed as allochthonous and parautochthonous rock units overlying an autochthonous basement unit.

Harris and Bayer (1979) proposed that the southern Appalachian orogen, from the Appalachian Plateau to the Atlantic Coastal Plain, is underlain by a basal décollement that dips gently to the southeast. Through the use of surface geology and seismic reflection data, it was suggested that the lower Paleozoic shelf strata, consisting of Cambrian and Lower Ordovician clastic and carbonate rocks, overlie the basal décollement and are presently concealed beneath Precambrian crystalline and Paleozoic rocks of the Blue Ridge and Piedmont allochthons that were thrust westward. Movement along the basal décollement most likely occurred during several Late Proterozoic and Paleozoic tectonic events (Harris and Bayer, 1979); however, the eastern extent of this décollement in the southern Appalachians remains controversial (Cook and others, 1979; Harris and Bayer, 1979; Hatcher and Zietz, 1980; Iverson and Smithson, 1982; Cook and others, 1983; Secor and others, 1986). Seismic profiles within parts of the central and southern Appalachians have imaged a package of relatively continuous reflectors, usually between 6-12 km (2-4 s) that resembles the basal décollement that underlies the southern Appalachians (Cook and others, 1979; Harris and others, 1982b; Çoruh and others, 1987; Pratt and others, 1988; Evans, 1989; Hubbard and others, 1991).

The Piedmont Province

The PR3 seismic profile begins in the western Piedmont. Within the PR3 study area, no deep wells have penetrated the autochthonous basement beneath the Blue Ridge or Piedmont allochthons. The allochthonous crust overlying the Blue Ridge thrust represents the Blue Ridge-Piedmont composite thrust sheet, which is considered to be the largest (greatest horizontal transport) overthrust sheet in the central Appalachians (Hatcher and others, 1989). During the Alleghanian orogeny, this composite crystalline unit was transported westward, deforming the thrust sheet and initiating the westward propagation of the Paleozoic shelf strata within the Appalachian foreland (Hatcher and others, 1989).

Along the PR3 seismic reflection profile (Figure 11), the western Piedmont is highly reflective and is bounded below by southeast dipping reflectors that are imaged to a depth of 15 km (3 s), and might extend deeper further east. The event BRT is interpreted to overlie these dipping reflectors and reflections imaged above this event attest to the complex deformational episodes that affected the Piedmont. A highly reflective zone (A in Figure 11) between 4.5-9 km (1.5-3 s), whose reflector geometry is interpreted here as a nappe, overlies the event labeled BRT. Individual reflectors within this zone appear relatively continuous. This reflective zone (A) is separated from an acoustically transparent region (NRZ) above by a package of high amplitude, southeast dipping reflectors (F1).

After migration, the Blue Ridge thrust (BRT in Figure 12) beneath the Piedmont allochthon is interpreted at 10.5 km (3.5 s) along the eastern edge of the profile, where it turns upward toward the west after reaching a maximum depth of 13.5 km (4.5 s). Along seismic line I-64, this thrust also turns upward beneath the western Piedmont (Figure 4). In restoring the reflectors to their true subsurface positions, the arcuate reflection package (A) appears narrower on the migrated data. The reflections representing the western limb of the nappe (WA in Figure 12) appear to terminate just east of the surface exposure of the Mountain Run Fault (MRF). This fault is the northeastern extension of the Bowens Creek Fault, which coincides with the Brevard Fault Zone further south (Horton and others, 1991; Hubbard and others, 1991).

In the PR3 unmigrated and migrated sections, subhorizontal, discontinuous reflectors (SRP) are imaged between the Blue Ridge thrust (BRT) and reflection package A (Figure 11 and Figure 12). It would appear likely that a detachment zone (Z) separates the two structural styles, and that an overlying sheet was thrust westward above this boundary. Another significant result of migration is the presence of an acoustically transparent region (GS) along the easternmost segment of the profile that extends to 9 km (3 s) (Figure 12).

Although line PR3 extends far enough to the east to image only one of these arcuate reflection packages (A), line I-64 clearly images two additional packages (B and C in Figure 14) of similar

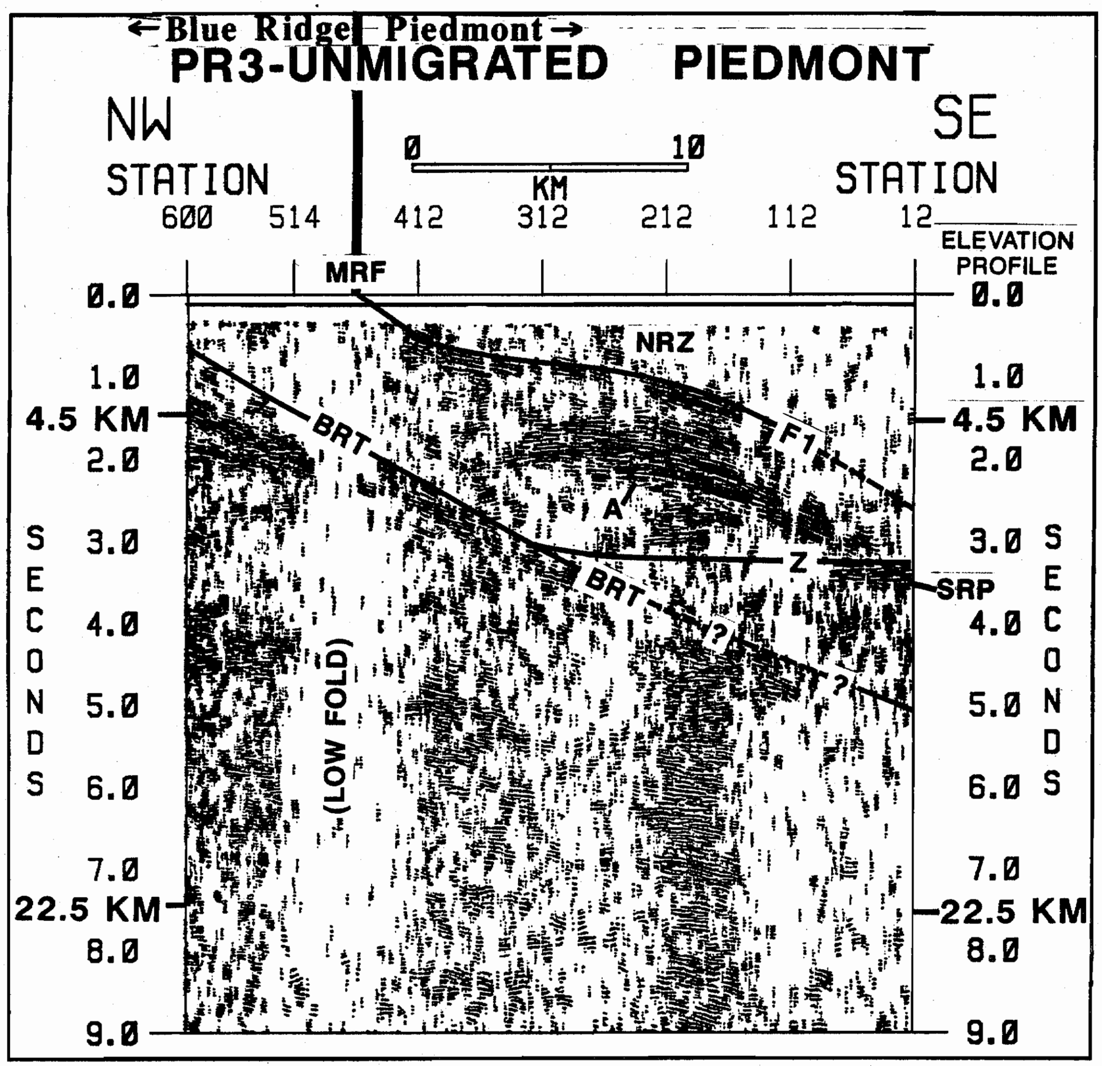


Figure 11. ALD display of unmigrated PR3 seismic reflection data from the western Piedmont crust: Compare with Figure 12. A = nappe, BRT = Blue Ridge thrust, F1 = thrust fault, MRF = surface exposure of the Mountain Run Fault (Bowens Creek Fault-Brevard Fault Zone), NRZ = non-reflective zone, SRP = subhorizontal reflection package, Z = detachment zone. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

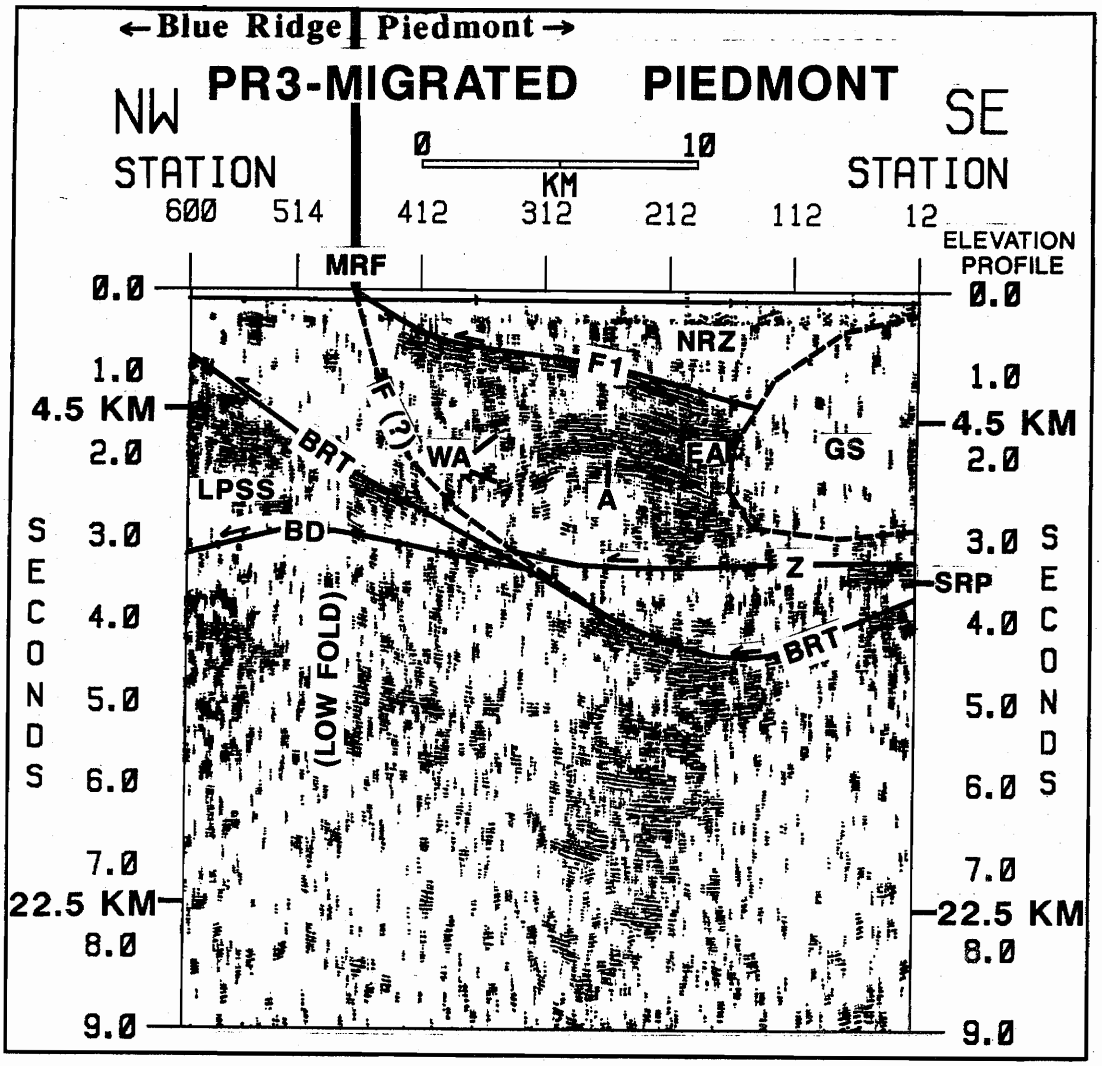


Figure 12. Interpreted ALD display of migrated PR3 seismic reflection data from the western Piedmont crust: A = nappe, BD = basal décollement BRT = Blue Ridge thrust, EA = reflections from eastern limb of the nappe, F (?) = fault (?), F1 = thrust fault, GS= extension of Green Springs mafic mass, MRF = surface exposure of Mountain Run Fault (Bowens Creek Fault-Brevard Fault Zone), NRZ = non-reflective zone, SRP = subhorizontal reflection package, WA = reflections from the western limb of the nappe, Z = detachment zone. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

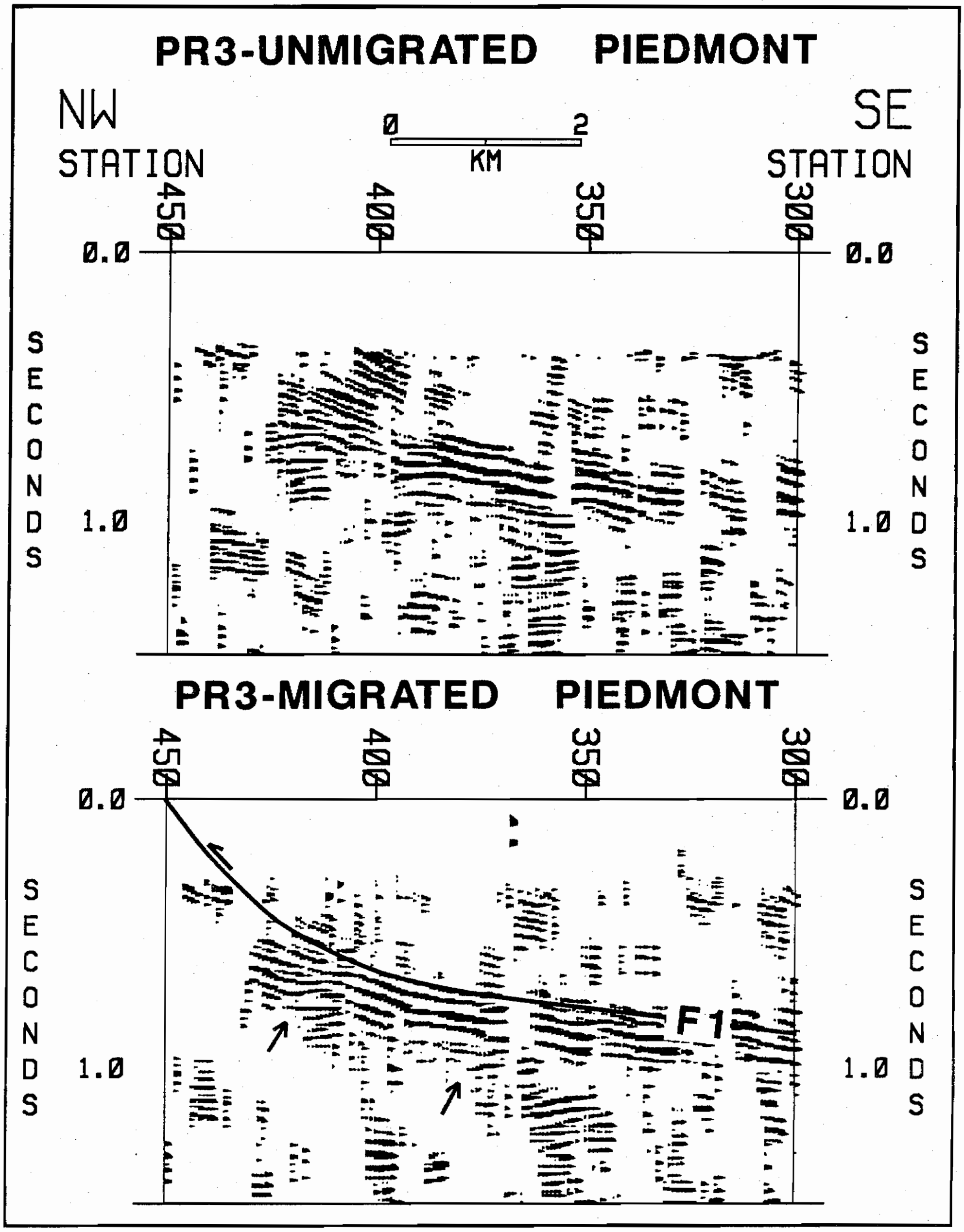
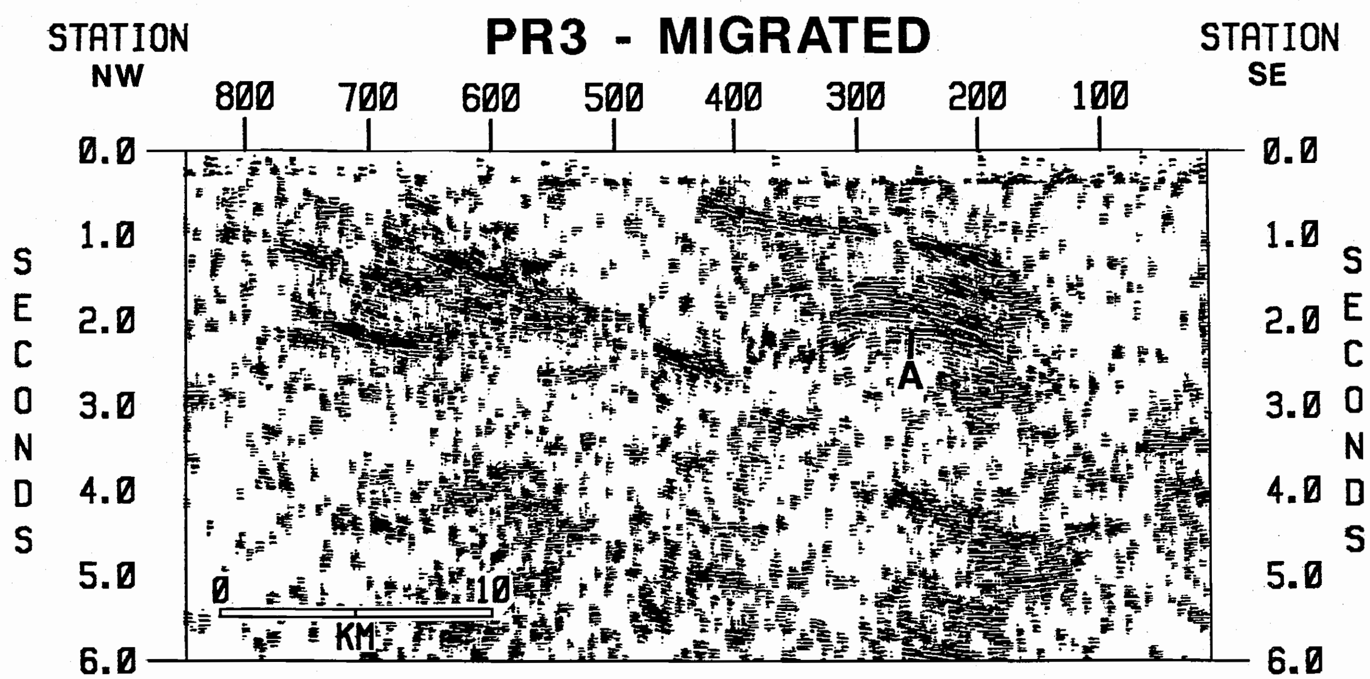


Figure 13. Detailed examination of a thrust fault beneath the western Piedmont: As imaged by the unmigrated (top) and migrated (bottom) PR3 seismic reflection data, the southeast dipping reflectors truncate a series of horizontal reflectors (indicated by the arrows) to the west. This dipping event is interpreted as a thrust fault (F1). (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)



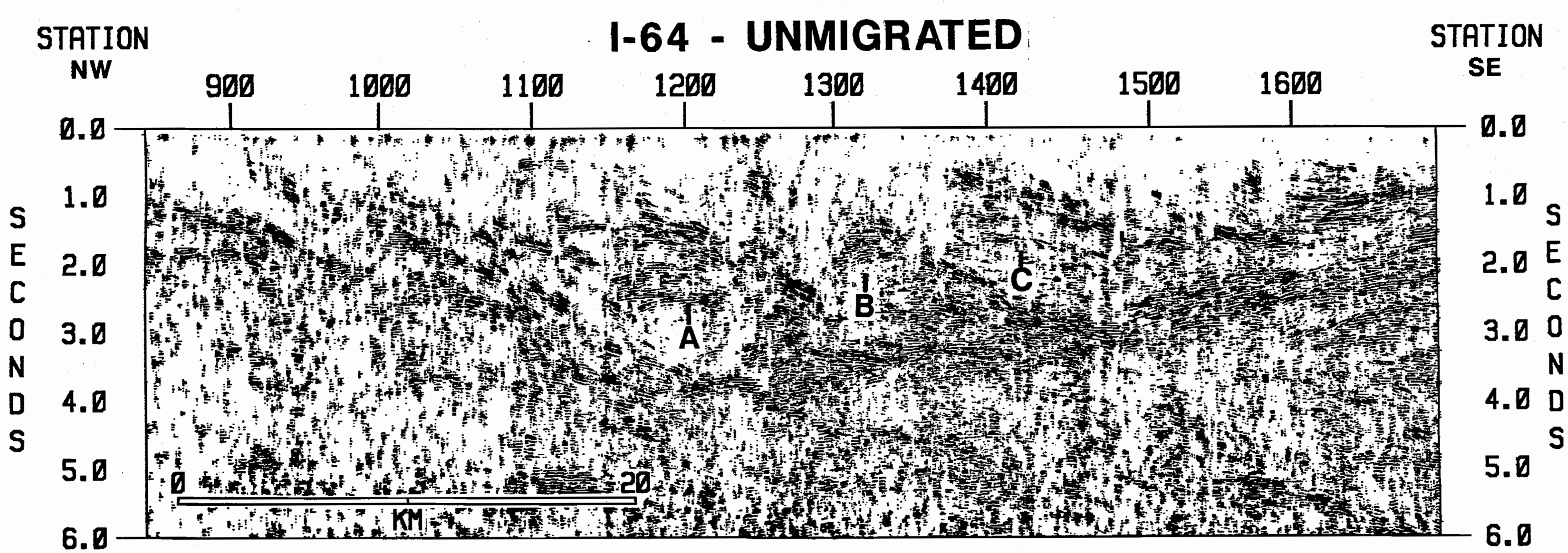


Figure 14. **Comparison of PR3 and I-64 seismic reflections:** Automatic line drawings of subsurface structures within the Piedmont allochthon along lines PR3 (top) and I-64 (bottom). A = B = C = nappe. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

geometry and reflectivity. Reflection packages A, B and C imaged by the PR3 and I-64 data are herein interpreted to be nappes, and each of these structures might represent an imbricate thrust nappe of a thrust complex that continued along strike in this region of the central Appalachians. Reflector packages A, B and C in Figure 14 lie above prominent westward-dipping reflectors that might originate from the Catoctin and younger formations (Pratt and others, 1988). Pratt and others (1988) interpreted reflector packages B and C to originate from rocks of the Evington Group and Chopawamsic Formation, which were extended from the surface down to the bottom of the basin-shaped synform (Figure 4). An alternative interpretation was proposed by Phinney and Roy-Chowdhury (1989). They suggested that the clastic and volcanic deposits in this synform might be in place and represent a failed rift. On the basis of the PR3 and I-64 seismic reflection data, the reflections comprising these packages might originate from the Catoctin Formation, Evington Group strata, and possibly younger metamorphosed rocks that were transported westward during Paleozoic orogenies.

Along the surface of the western Piedmont in the PR3 study area, the Mountain Run Fault is the boundary between the Piedmont and Blue Ridge, and separates the mélanges of the Mine Run Complex on the east from the continental deposits of the True Blue Formation on the west (Pavlides and others, 1983; Pavlides, 1989). Faulting along this zone was initiated in the early Paleozoic, reactivated during the early Mesozoic, and now this fault represents the eastern boundary of the Culpepper Basin (Pavlides and others, 1983). The ductile to brittle deformation observed by Conley (1987) at an exposure of the Mountain Run Fault confirmed Pavlides and others (1983) interpretation of early Paleozoic faulting along this zone. Phyllonite, mylonite and breccias are found along the surface of this fault zone, and a fault-line scarp can be traced along most of its length, from the Culpepper basin southwest toward the Scottsville basin (Pavlides, 1989). Exposures of mélange zones III and IV of the Mine Run Complex lie along the surface of the western Piedmont that is crossed by line PR3 (Figure 15 and Figure 16). These rocks appear to correspond, respectively, to the Shores mélange and Hardware metagraywacke of Evans (1984) and Glover and others (1992). The mélanges of the Mine Run Complex are interpreted as having formed in a Cambrian-Ordovician back-arc or marginal basin that lay between the Laurentian continent and the Chopawamsic island arc (Pavlides, 1989). Melange zone III is characterized by rocks composed of a deformed phyllite and schist matrix, which contains abundant exotic blocks of euhedral magnetite. On the other hand, rocks of mélange zone IV consist of an intercalated metavolcanic phyllite matrix that contains few exotic blocks, and euhedral magnetite is noticeably less abundant (Pavlides, 1989).

Various intrusive bodies are located near line PR3 in the western Piedmont. The surface exposure of the Ellisville granodiorite pluton lies to the east of line PR3 (Oe in Figure 15 and Figure 16). At the surface, this 440 Ma pluton intrudes the lower grade metamorphic rocks of the Chopawamsic Formation and the higher grade metamorphic rocks of the Hatcher Complex (Columbia pluton) further south (Pavlides and others, 1982b; Sinha and Guy, in Drake and others, 1989). Emplacement of this granitoid is believed to mark the end of Penobscottian-Taconian deformation and metamorphism within this area of the Piedmont province (Pavlides, 1989). To the southwest of line PR3 lies the Green Springs mafic mass. This pluton, like the Ellisville, was probably emplaced during Ordovician time (Conley and others, unpublished). The Green Springs pluton was later intruded by the Green Springs granitoid, also referred to as the Pore Creek pluton, during the Ordovician-Silurian time (Pavlides, 1989; Conley and others, unpublished).

Examination of Bouguer gravity data within the central Appalachians reveals a transition from the gravity low over the Valley and Ridge to the Piedmont gravity high to the east. This transition is conventionally called the Appalachian gravity gradient. Within the PR3 study area, negative Bouguer gravity values less than -65 mgals are observed over the Valley and Ridge. These values increase to the southeast where they reach maxima greater than -8 mgals over the Piedmont (Figure 17).

An inspection of the Bouguer gravity variations along the Piedmont and Blue Ridge segment of PR3 (Figure 17 and Figure 18) reveals a positive Bouguer gravity anomaly associated with the acoustically transparent region along the eastern edge of the PR3 profile (GS in Figure 12). Just west of Louisa, Virginia, is a closed positive gravity anomaly that is herein associated with the

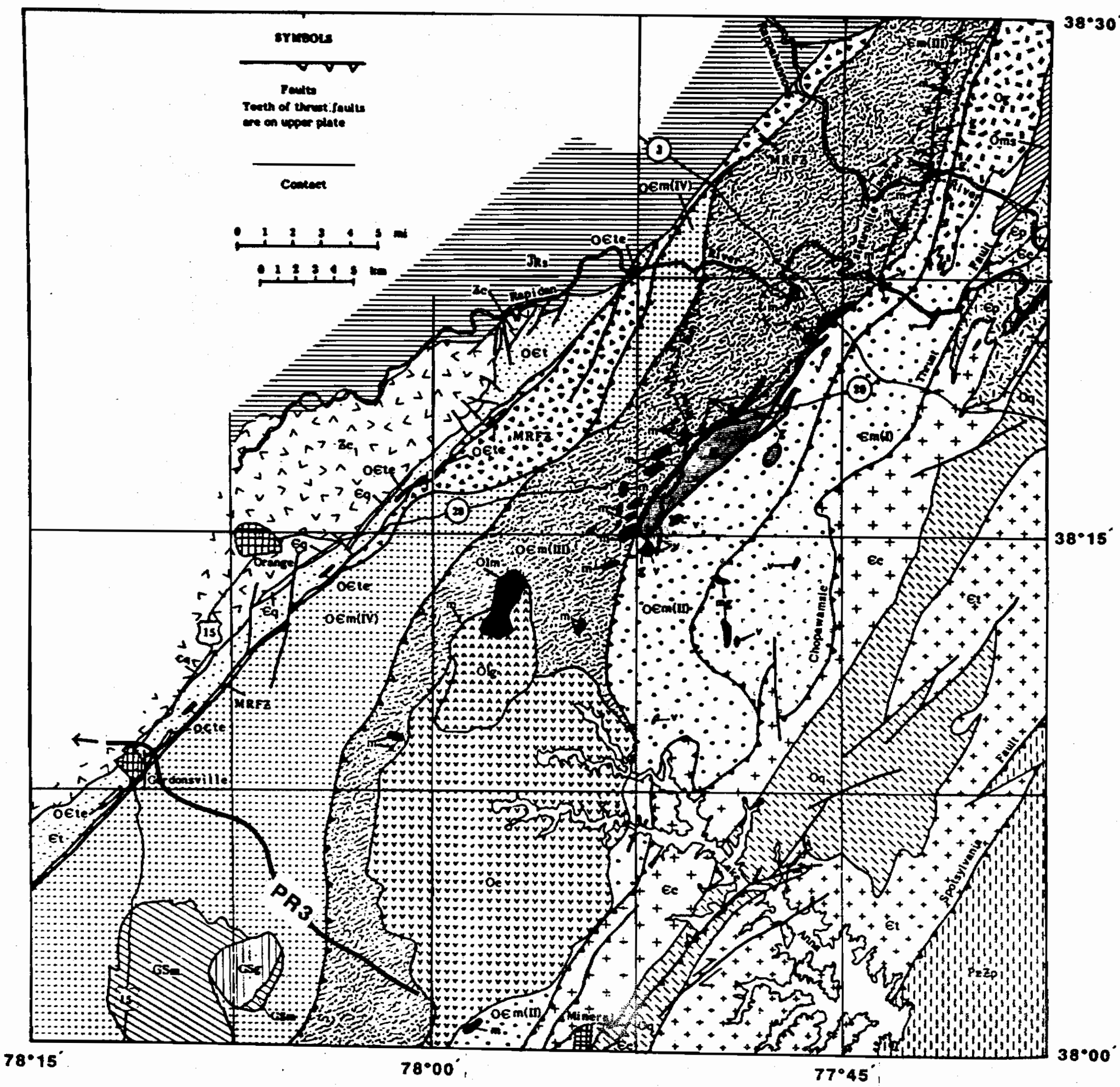


Figure 15. Detailed surface geology of the western Piedmont and easternmost Blue Ridge as mapped by Pavlides (1989): The Mountain Run Fault zone defines the boundary between the Blue Ridge and Piedmont provinces. The acoustically transparent region (GS in Figure 12) along the eastern edge of the PR3 profile is interpreted to originate from an extension of the Green Springs mafic mass just south of this line (GSm on this map). Explanation provided in Figure 16.

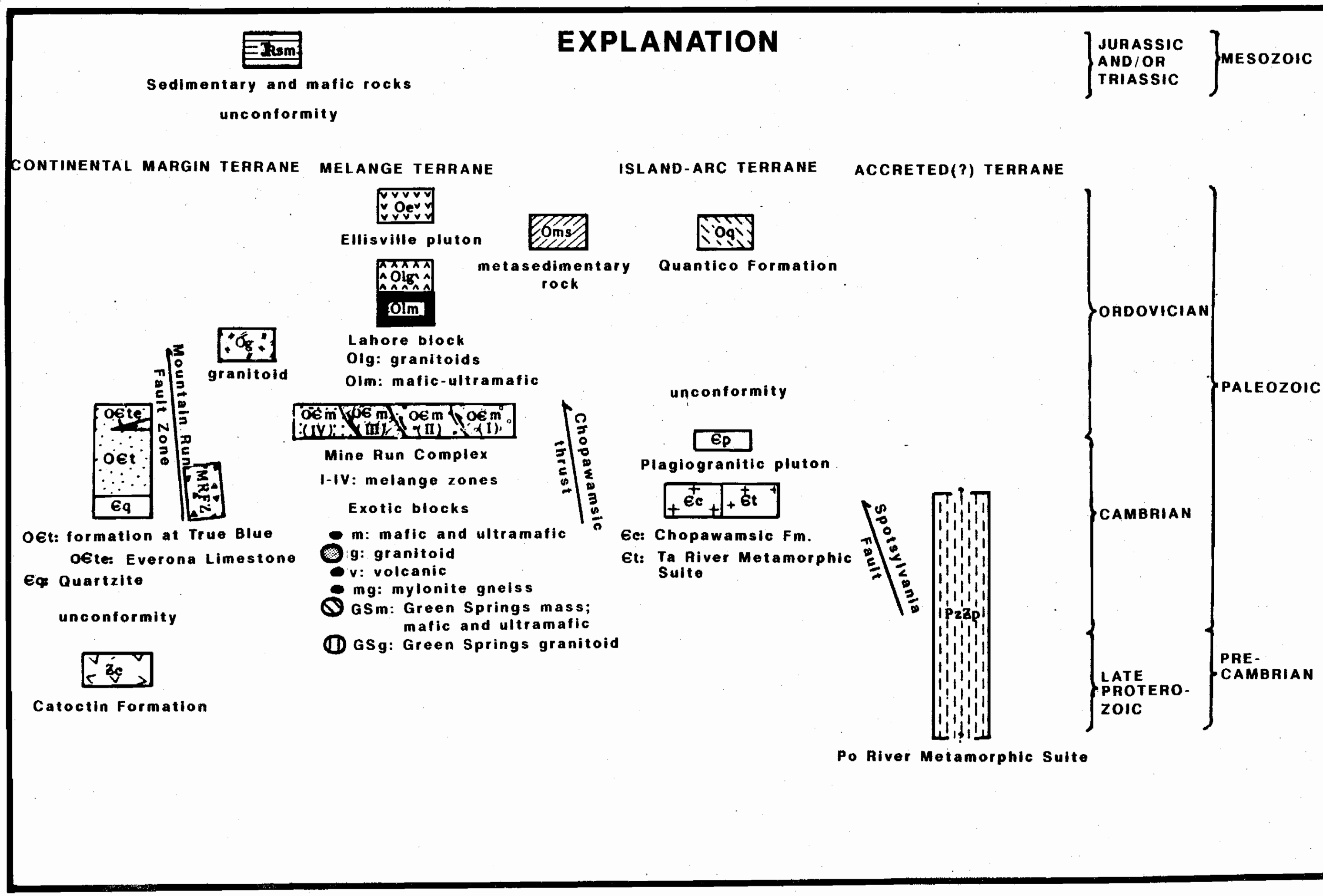


Figure 16. Explanation of the western Piedmont/eastern Blue Ridge geologic map by Pavlides (1989): Explanation provided for Figure 15.

Green Springs mafic and ultramafic pluton (GSA in Figure 17 and Figure 18). On the basis of the low reflectivity in the ALD displays often associated with intrusive bodies (Çoruh and others, 1988; Hubbard and others, 1991), the high Bouguer gravity anomaly observed along this eastern segment of the profile, and the abrupt southeastern termination of the reflection package F1 in Figure 12 at approximately 3 km (1 s), this non-reflective region is attributed to a buried extension of the Green Springs pluton.

Variations of the magnetic field anomaly of the central Appalachians are generally attributed to changes in the percent of magnetite in the rocks (Robinson and Çoruh, 1988). A linear magnetic high is located over the western Piedmont province of the study area (WPM in Figure 19). This anomaly might correlate with a poorly reflective zone on the PR3 seismic profile and suggests that this feature might represent a deep seated, vertical intrusion that extends along strike; however, the I-64 seismic data does not support such an event in the western Piedmont. Therefore, this anomaly is interpreted to correspond with the surface exposure of mélange zone III of the Mine Run Complex. The abundant euhedral magnetite within this mélange has been correlated with narrow, linear magnetic anomalies on aeromagnetic maps (Pavlides, 1989).

The PR3 and I-64 seismic reflection data, available surface geology and potential field data have been combined to present an integrated interpretation of the central Piedmont. The nappe (A) on Figure 11 and Figure 12 is overlain by a southeast dipping reflection package (F1). A detailed examination of this event (Figure 13) shows that this dipping reflection package truncates a series of subhorizontal reflectors to the west. On the basis of this observation, this package in interpreted as a thrust fault zone. This nappe is also interpreted to be bounded on the west by a steeply dipping fault that is not imaged on line PR3 because of its slope. The trace of the Mountain Run Fault in the PR3 study area was mapped by Pavlides (1989) as a linear feature (Figure 15), suggesting that this mapped surface fault has a steep dip. On the basis of the linear trace defined by the surface exposure of the Mountain Run Fault, and the termination of the reflections originating from the western limb (WA) of the nappe (A), a steeply dipping fault (F (?) in Figure 12) is interpreted to merge with the Blue Ridge thrust at about 10.5 km (3.5 s). Its projected surface

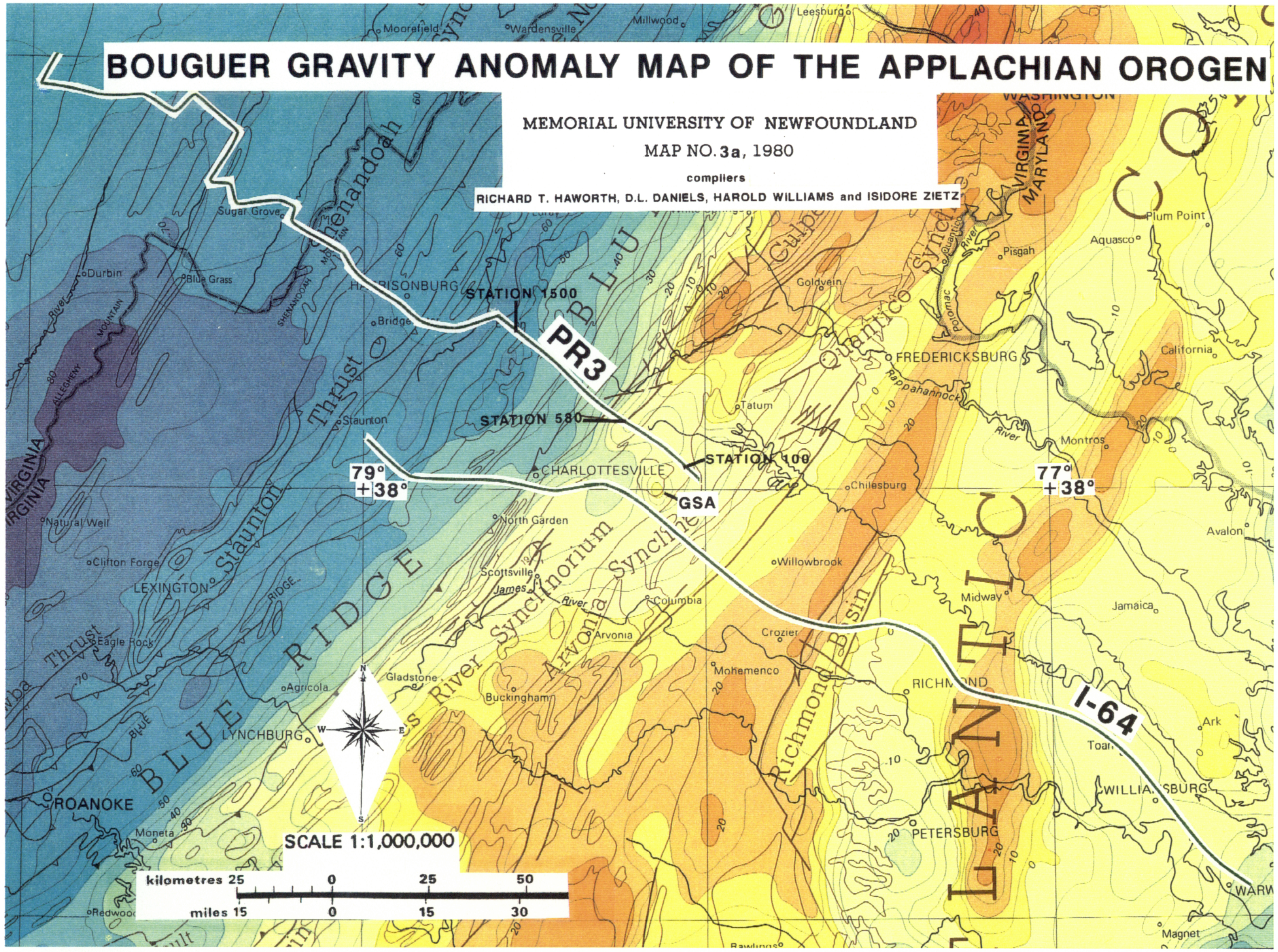


Figure 17. Bouguer gravity anomaly map along line PR3: GSA = Green Springs Bouguer gravity anomaly. Figure from Haworth, Daniels, Williams and Zietz (1980).

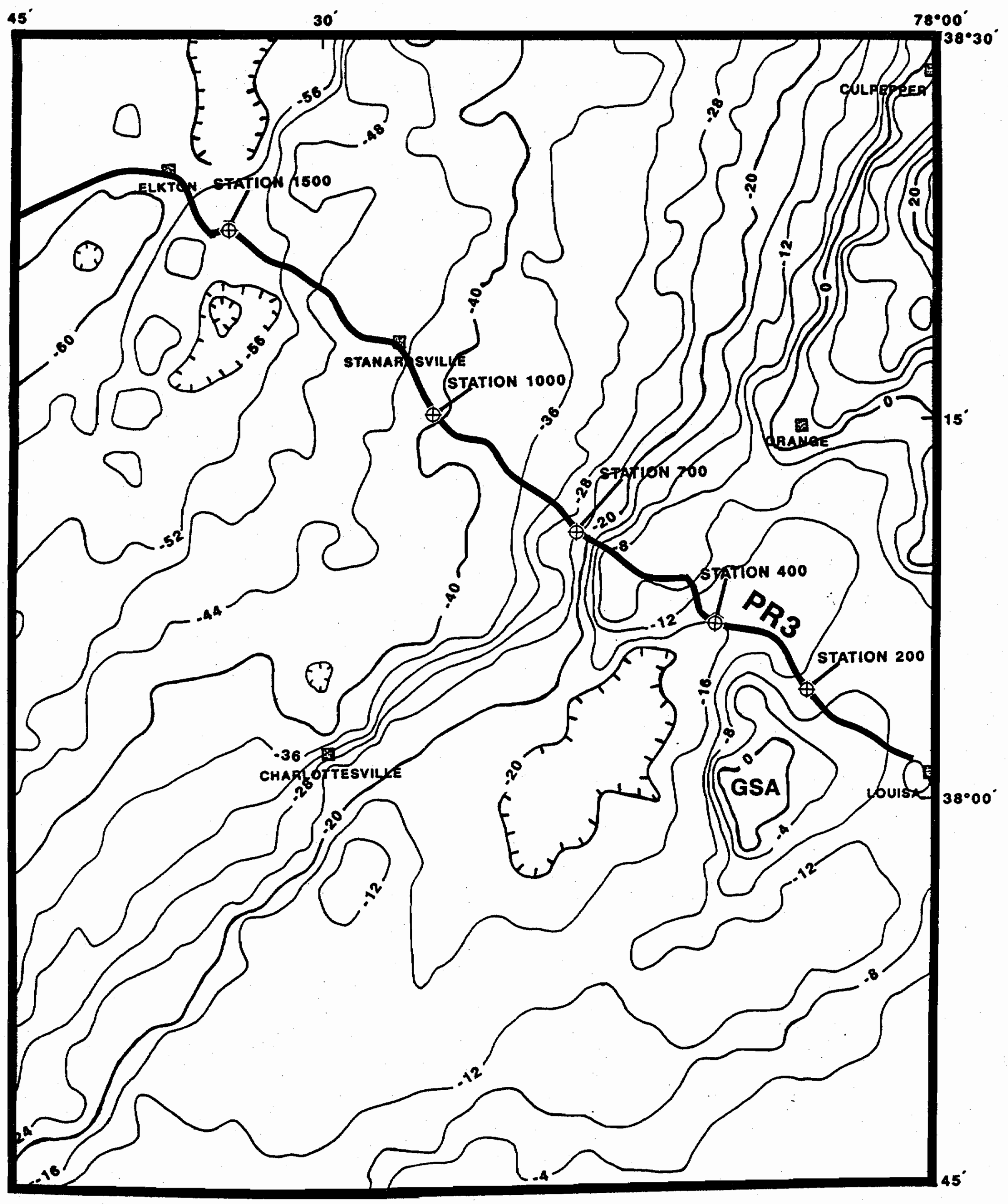


Figure 18. **Detailed Bouguer gravity anomaly map along line PR3:** GSA = Green Springs Bouguer gravity anomaly. Figure from the gravity map by Johnson (1971).

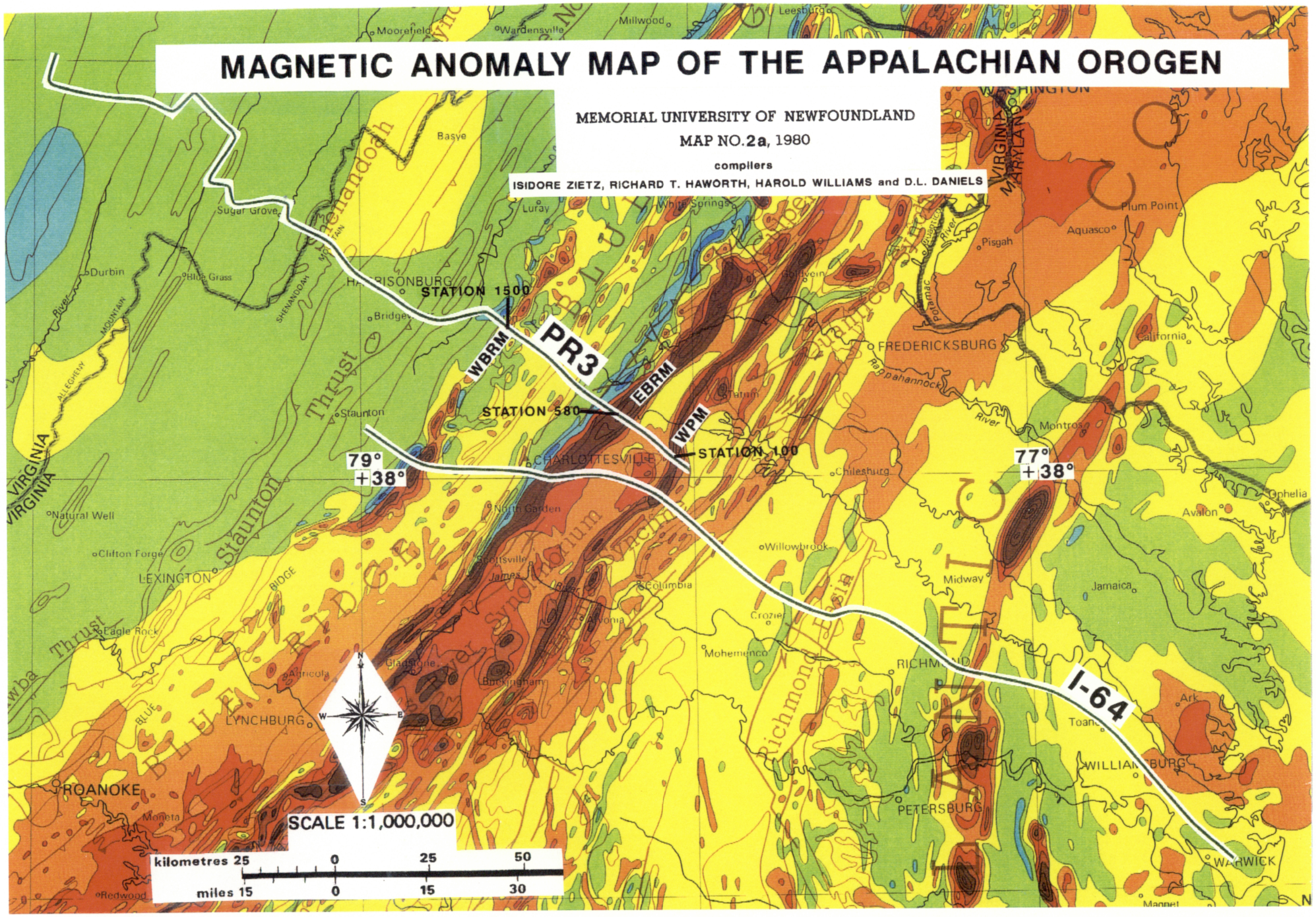


Figure 19. **Magnetic anomaly map along line PR3:** WPM = western Piedmont magnetic linear anomaly (anomaly attributed to mélange zone III of the Mine Run Complex), EBRM = eastern Blue Ridge magnetic linear anomaly (anomaly attributed to the Catoctin Formation), WBRM = western Blue Ridge magnetic linear anomaly (anomaly attributed to the Catoctin Formation). Figure from Zietz, Haworth, Williams and Daniels (1980).

location coincides approximately with the exposure of the Mountain Run Fault as mapped by Pavlides (1989). The reflections originating from the shallow thrust fault (F1) in Figure 11 and Figure 12 also project to the surface exposure of the Mountain Run Fault. Since the surface projections of these faults converges to the mapped location of the Mountain Run fault, it is not possible to determine whether the thrust fault (F1) or the steeply dipping fault (F (?)) represents the Mountain Run fault.

The Blue Ridge Province

The Blue Ridge province lies to the west of the Piedmont and is bounded on the east and west, respectively, by the Mountain Run Fault (Bowens Creek Fault-Brevard Fault Zone) and Blue Ridge thrust. Along the surface of this region, from east to west, are exposures of the True Blue continental margin deposits, Catoctin metabasalts, Lynchburg metasediments, Blue Ridge crystalline rocks and Chilhowee clastics (Figure 2 and Figure 15)(Williams, 1978; Wehr and Glover, 1985; Pavlides, 1989). These rocks were carried westward with the Blue Ridge allochthon during the Alleghanian orogeny. The Blue Ridge thrust is the frontal thrust of the Blue Ridge-Piedmont thrust sheet (Pratt and others, 1988; Hatcher, in Hatcher and others, 1989).

Various seismic reflection profiles across the central and southern Appalachians have shown that the Blue Ridge thrust is underlain by a thick sequence of Cambrian and Ordovician carbonates, which in turn, overlie a basal décollement (Clark and others, 1978; Cook and others, 1979; Harris and Bayer, 1979; Harris and others, 1982a; Harris and others, 1982b; Cook and others, 1983; Çoruh and others, 1987; Pratt and others, 1988; Evans, 1989; Hubbard, and others, 1991). The relatively continuous reflections from shelf strata that have been imaged above a basal "décollement" (Hubbard and others, 1991) suggest that horizontal transport along a basal décollement is less than that along the Blue Ridge thrust. Therefore, the Lower Paleozoic shelf strata are designated as "parautochthonous". Analysis of earlier seismic data within the central Appalachians suggests that this décollement is seated in the shales of the Lower Cambrian Rome-Waynesboro Formation, and extends westward beneath the Valley and Ridge and Appalachian Plateau (Kulander and Dean, 1986; Evans, 1989; Geiser, in Hatcher and others, 1989).

Within the PR3 study area (Figure 8), the Lower Paleozoic shelf sequence of Cambrian-Ordovician limestones and dolomites overlies autochthonous Grenvillian basement and is bounded above by shales of the Martinsburg Formation (Evans, 1989). In a study of crustal reflectivity, Christensen and Szymanski (1991) carried out a series of experiments using measured compressional wave velocities and densities of the sedimentary rocks within the Valley and Ridge of the southern Appalachians. These physical properties were used to determine the seismic properties and the origin of reflectivity from the parautochthonous shelf strata that overlie the basal décollement. By generating a synthetic seismogram and comparing it with an actual reflection profile, they determined that the reflections originating from the Cambrian-Ordovician shelf strata were often attributed to vertical facies changes within the formations, instead of the formation boundaries. The compressional wave velocities of the shelf strata ranged from 3.6 km/s for shales to 7.2 km/s for dolomites. In southwest Virginia, interval velocities calculated from the sonic log of Gulf's W. R. Price #1 well are 6.4 km/s and 4.4 km/s for the Maynardville dolomite and Nolichucky shale, respectively (Figure 20). These formations correspond to the Conococheague Formation in the central Appalachians (Figure 7), and the Conococheague Formation is located within the Lower Paleozoic shelf sequence (Figure 8). Supported by the results from the reflectivity study conducted by Christensen and Szymanski (1991) and data from the W. R. Price #1 well, the reflections originating from the Lower Paleozoic shelf strata in the PR3 study area are attributed to velocity variations within this parautochthonous sequence. The reflectivity observed within the shelf strata along line PR3 might also be associated with tectonic imbrication. Costain and others (1986) identified imbricate structures, referred to as "duplex tuning wedges", within the Paleozoic shelf strata along seismic profiles across the southern Appalachians. They proposed that reflections associated with the duplex tuning wedges originate from wavelet tuning in tectonically imbricated thin beds within the structures, and are important because they mark locations in the crust where thrust faults ramp upward.

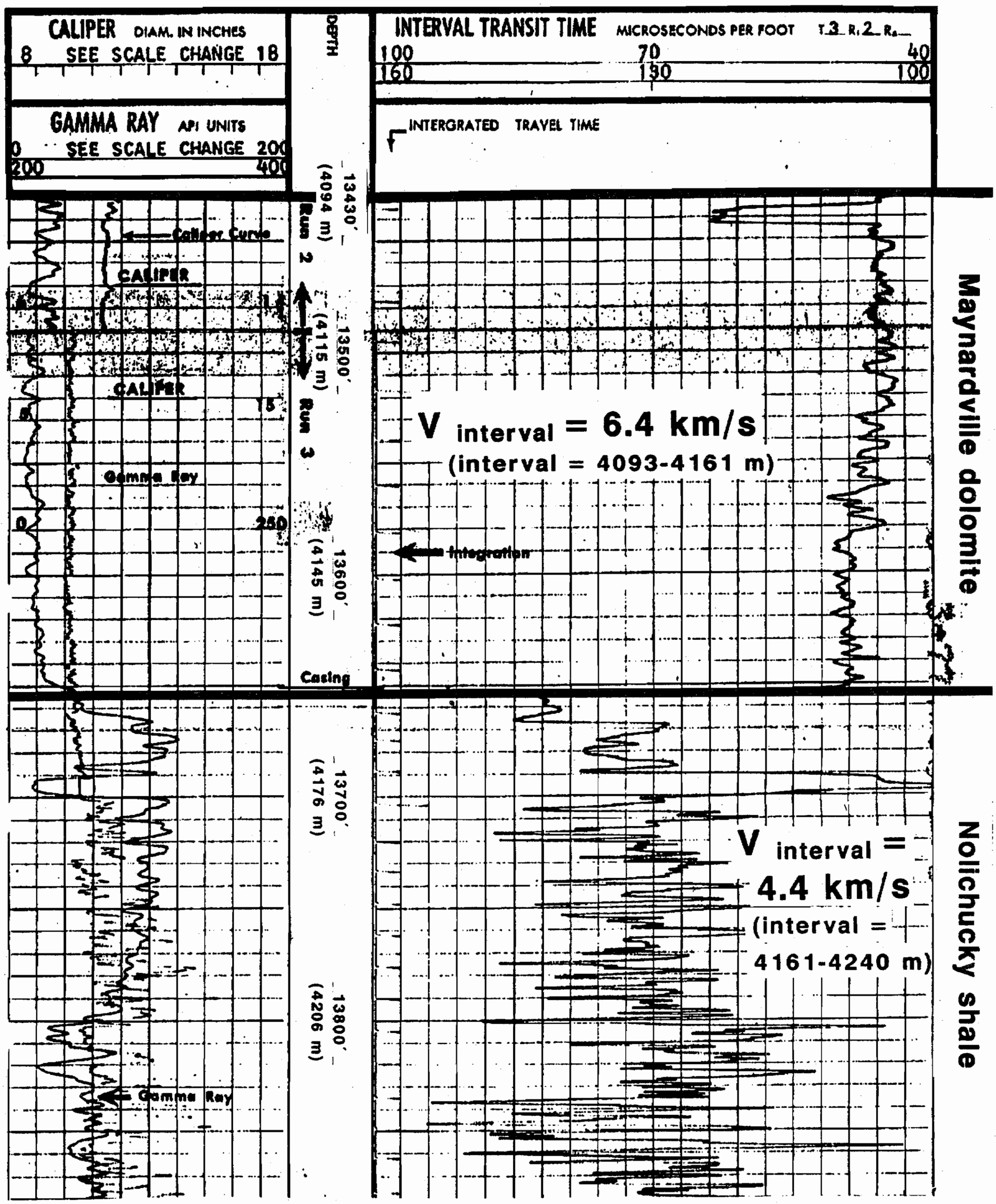


Figure 20. **W. R. Price #1 well gamma ray log and borehole compensated sonic log data (4094-4230 m):** Note the variations in these logs at the Maynardville dolomite/Nolichucky shale interface.

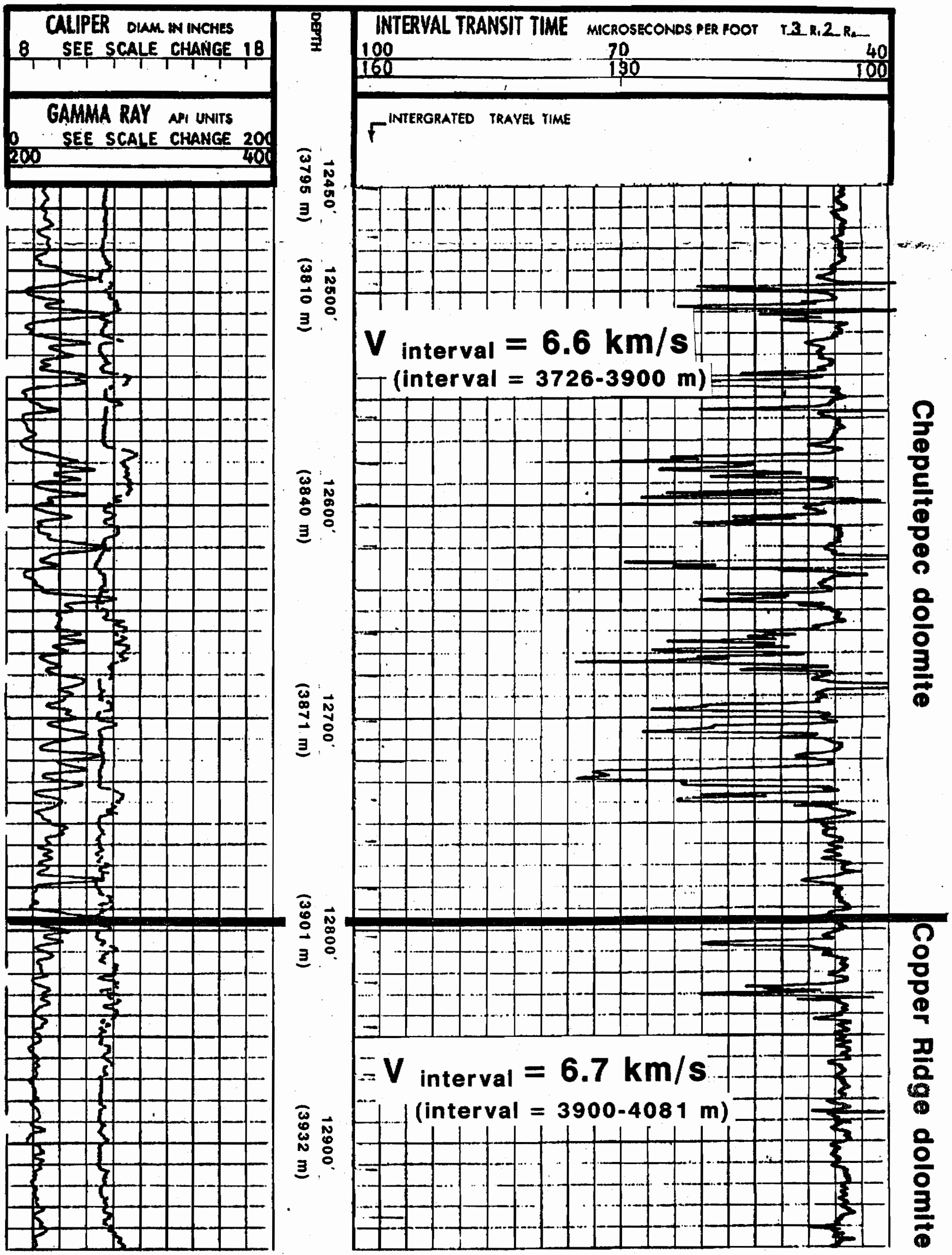


Figure 21. **W. R. Price #1 well gamma ray log and borehole compensated sonic log data (3795-3947 m):** Note the lack of variations in these logs at the Chepultepec dolomite/Copper Ridge dolomite interface.

Reflections that originate from the Blue Ridge crystalline rocks are relatively sparse when compared to the strong reflections from the underlying shelf sequence (Costain and others, 1986; Çoruh and others, 1988). The majority of thick carbonate sequences within the shelf strata are also acoustically transparent (Christensen and Szymanski, 1991; Hubbard and others, 1991). As measured from the sonic log of the W. R. Price #1 well, the average interval velocity of the Chepultepec dolomite is 6.6 km/s, and the interval velocity of the Copper Ridge dolomite is approximately 6.7 km/s (Figure 21). These two formations are correlated with the Beekmantown Group and Conococheague Formation of the Paleozoic shelf strata (Figure 7 and Figure 8). The low reflectivity originating from these carbonates within the PR3 study area is associated with the lack of velocity variations between these two formations as indicated by the sonic log (Figure 21). With regard to the crustal reflectivity of the central Appalachians Blue Ridge, the automatic line drawing generated from the reprocessed seismic line PR3 has shed new light on the structural geometry of the Blue Ridge allochthon and the parautochthonous shelf strata.

In an attempt to delineate the Blue Ridge thrust along the PR3 profile, and therefore define the upper boundary of the Paleozoic shelf strata, the following observations were taken into account:

- The Blue Ridge allochthon is cored by Grenville basement rocks, which have relatively low reflectivity (Çoruh and others, 1988).

- Since the core of the Blue Ridge is characterized by a low reflectivity, the shallowest reflection packages probably originate from the interface between the Blue Ridge basement rocks and the Paleozoic shelf strata, and not from within the crystalline unit.

- The average depth of the Blue Ridge thrust within the central and southern Appalachians has been estimated as 3 km (1 s) (Çoruh and others, 1987; Pratt and others, 1988; Hubbard and others, 1991).

- The presence of duplex tuning wedges can be used to identify locations in the parautochthonous shelf strata where thrusts ramp upward (Costain and others, 1986).

In addition to the above points, an attempt was made to use interval velocities to distinguish high and low velocity zones that could possibly represent rocks of basement and shelf strata. Difficulties were encountered in attempting to relate the interval velocities with lithologies. The interval velocities computed from various velocity spectra were useful in establishing the presence of velocity inversions within the subsurface, but could not be used to identify the lithologic units. Specifically, the interval velocities calculated between similar reflection packages on the conventional PR3 seismic display did not correlate, and it was not possible to identify velocities associated with the shelf strata from velocities associated with the crystalline basement. Therefore, supported primarily by the discontinuous reflection packages imaged beneath the region of low reflectivity on the PR3 seismic data, the Blue Ridge thrust is interpreted ramp upward beneath the Piedmont at approximately 13.5 km (4.5 s) (BRT in Figure 23). This ramp has also been imaged on seismic lines in Virginia and South Carolina, and was interpreted to be the same ramp that extends along strike at least 600 km (Costain and others, 1987). From the PR3 seismic data (Figure 23), the Blue Ridge thrust is interpreted to truncate the eastward extent of the Lower Paleozoic shelf strata. The thrust continues westward until it surfaces at station 1600 where this thrust fault was mapped by Williams (1978) and Conley and others (unpublished). The Blue Ridge allochthon is interpreted as an acoustically transparent unit above the Blue Ridge thrust; the various formations exposed at the surface cannot be delineated by seismic data in the subsurface due to the lack of reflectivity contrasts (Figure 23).

The Blue Ridge province was interpreted as the crest of the early Paleozoic hinge zone of Laurentia that was decapitated by a thrust fault during the Taconic orogeny (Rankin, 1975; Glover and others, 1983; Wehr and Glover, 1985; Glover, 1989). As such, this crest represents the eastern edge of the early Paleozoic North American continent (Brown, 1970; Hatcher, 1972; Rankin, 1975; Hatcher, 1978; Wehr and Glover, 1985). Of all the formations that were deposited on Grenvillian basement, only the True Blue, Catoctin and Lynchburg Formations (Figure 2 and Figure 15) are presently preserved along the eastern limb of the Blue Ridge anticlinorium (Wehr and Glover, 1985; Pavlides, 1989). According to Pavlides (1989), the protoliths of the True Blue continental margin deposits of slate and argillite accumulated during the Middle Cambrian through Early Ordovician times. This formation overlies basal quartzites and Catoctin metabasalts. The late Proterozoic-Cambrian Catoctin basalts erupted during the Iapetus rifting and overlie the metasediments of the Lynchburg Group along the eastern limb (Wehr and Glover,1985). The protolith of the Lynchburg Group consists of deep-water sediments that were deposited nonconformably on the Blue Ridge crystalline basement during the early phase of Iapetus rifting (Wehr and Glover, 1985). These formations are not imaged in the PR3 seismic data.

In the past several years, a particular emphasis has been placed on analyzing the middle Proterozoic crystalline basement rocks, which compose the core of the anticlinorium. On the basis of varying assemblages of igneous and metamorphic rocks mapped at the surface, Bartholomew and others (1981) divided these crystalline rocks into two terranes that are separated by the Rockfish Valley Fault. To the west of this fault lies the Pedlar massif, and to the east, the Lovingston massif. Both of these terranes contain different assemblages of charnokites and gneisses that experienced high pressure metamorphism during the Grenville event (Bartholomew and others, 1991). The Lovingston massif also contains late Proterozoic Crossnore plutons that are associated with the initial rifting of the Iapetus (Rankin, 1975; Rankin, 1976; Wehr and Glover, 1985; Bartholomew and others, 1991). Although PR3 crosses the surface exposure of the Rockfish Valley Fault, neither this fault nor the intrusive bodies associated with the Lovingston massif were imaged in the PR3 data. On the western limb of the Blue Ridge anticlinorium in the PR3 study area, the Pedlar massif is noncomformably overlain by the Catoctin metabasalts, which are overlain by the metasandstones and metasiltstones of the Chilhowee Group (Wehr and Glover, 1985). These rocks were not imaged in the PR3 seismic data.

With regard to the potential field data, two linear magnetic anomalies are located within the Blue Ridge province (EBRM and WBRM in Figure 19). These anomalies, which are composed of adjacent positive and negative parts, are interpreted to correlate with the Catoctin metabasalts.

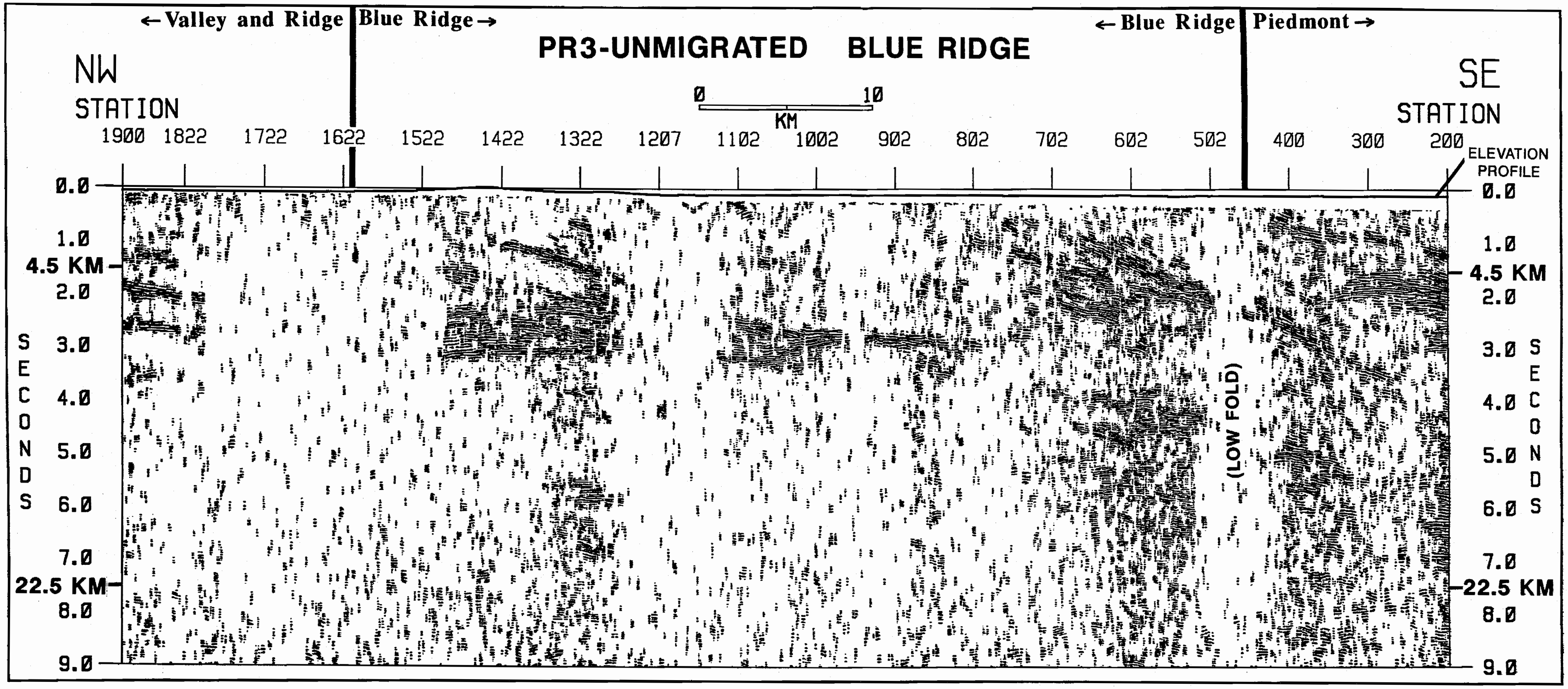


Figure 22. **ALD display of unmigrated PR3 seismic reflection data from the Blue Ridge crust:** Compare with Figure 23. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

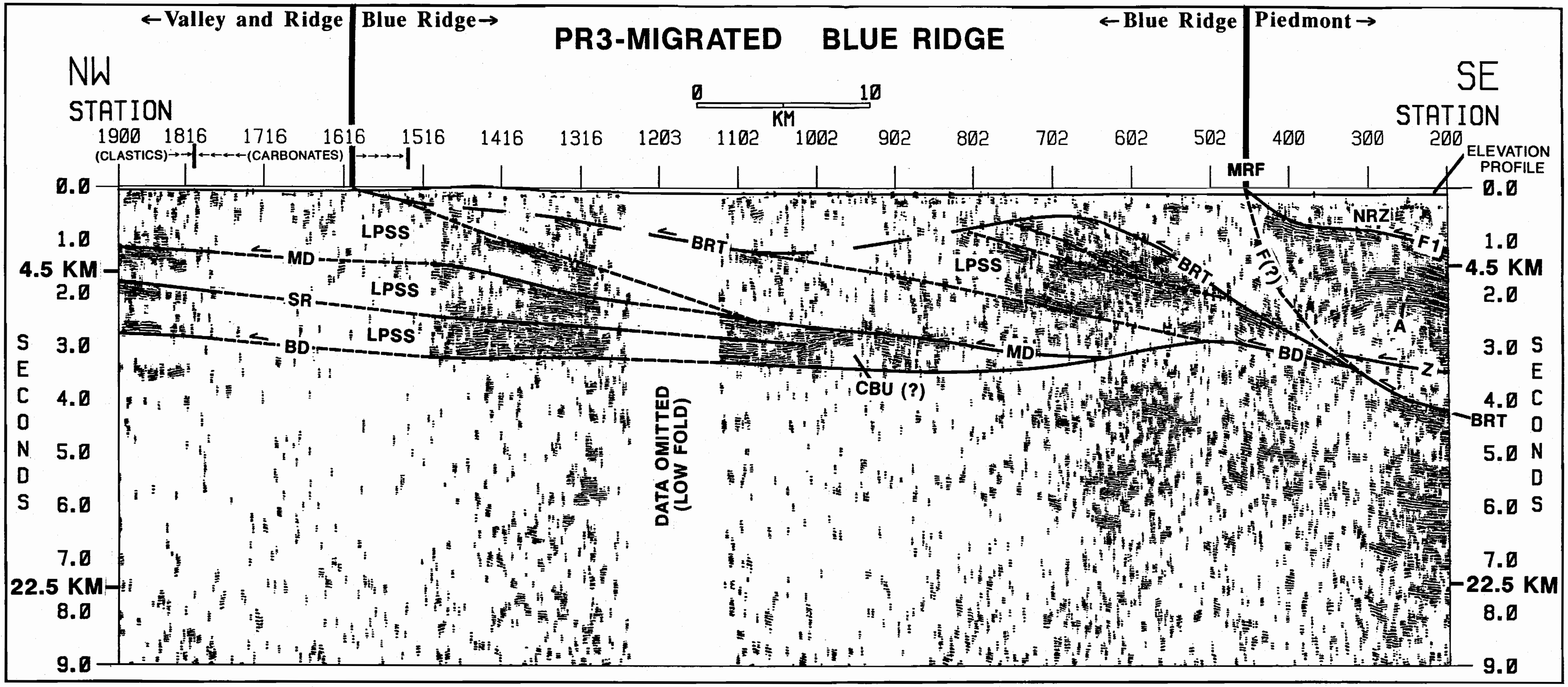


Figure 23. **Interpreted ALD display of migrated PR3 seismic reflection data from the Blue Ridge crust:** A = nappe BD = basal décollement underlying the central Appalachians, BRT = Blue Ridge thrust, CBU (?) = carbonate buildup (?), F (?) = fault (?), F1 = thrust fault, LPSS = Lower Paleozoic shelf strata, MD = Martinsburg detachment, NRZ = non-reflective zone, SR = subhorizontal reflections, Z = detachment zone. Small dashed lines beneath the Blue Ridge thrust (BRT) are interpreted as imbricate thrusts within the Lower Paleozoic shelf strata. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

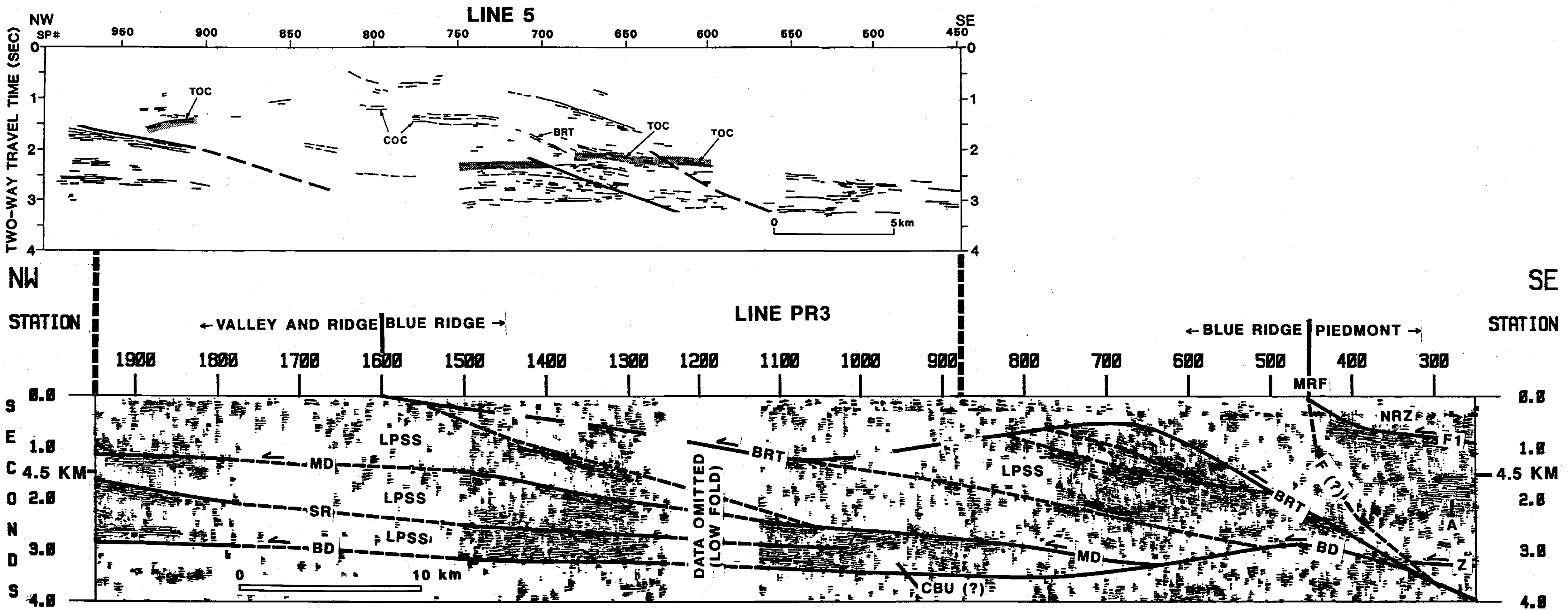


Figure 24. **Subsurface models of the Blue Ridge crust interpreted from the same seismic data:** Line 5 was interpreted by Evans (1989) and represents a segment of line PR3 within the Blue Ridge province. The PR3 display is an automatic line drawing generated from the reprocessed PR3 seismic data using a technique related to coherency estimations. A = nappe, BD = basal décollement, BRT = Blue Ridge thrust, CBU (?) = carbonate buildup (?), COC = undifferentiated Cambrian-Ordovician carbonate reflectors, F (?) = fault (?), F1 = thrust fault, LPSS = Lower Paleozoic shelf strata, MD = Martinsburg detachment, NRZ = non-reflective zone, SR = subhorizontal reflections, TOC = top of Cambrian-Ordovician carbonates, Z = detachment zone. Small dashed lines beneath the Blue Ridge thrust (BRT) on line PR3 are interpreted as imbricate thrusts within the Lower Paleozoic shelf strata. Line drawing displays are not scaled one-to-one. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

As shown in Figure 19, the eastern Blue Ridge magnetic anomaly (EBRM) is more prominent and continuous than the western Blue Ridge anomaly (WBRM). The differences between these magnetic anomalies might be explained by the greater number of Catoctin feeder dikes that have been identified in the eastern Blue Ridge; fewer dikes have been located in the western Blue Ridge (Reed and Morgan, 1971; Evans, 1984).

The eastern extent of the Lower Paleozoic shelf strata: During the Alleghanian orogeny, the Blue Ridge-Piedmont composite unit was thrust over the relatively unmetamorphosed Lower Paleozoic shelf strata (Hatcher and others, 1989). In the southern Appalachians, the thickness of these strata was reported to be approximately 6100 m (20,000 ft) beneath the Tennessee Blue Ridge (Milici and others, 1979). Along the PR3 profile, the strata are identified by the presence of duplexes and duplex tuning wedges that are bounded by the overlying Blue Ridge thrust and underlying basal décollement. Within these parautochthonous strata, duplexes are delineated by the images of "duplex tuning wedges". The various reflections contained within the duplexes are often discontinuous and are interpreted to originate from duplex tuning wedges. A particular region at about 9 km (3 s) is imaged as an acoustically transparent lens-shaped feature (CBU on Figure 23). Judging from the high reflectivity associated with the reflections near the top of this structure, and the onlapping nature of these events, this structure might represent a carbonate buildup (Bubb and Hatlelid, 1977).

The reflector geometry of the Paleozoic shelf sequence along the PR3 profile suggests that the strata extend to approximately 5 km east of the surface exposure of the Mountain Run Fault, where they are truncated by the Blue Ridge thrust at about 10.5 km (3.5 s). The maximum apparent thickness of this shelf sequence is approximately 8 km (2.6 s). The strata have been duplicated by tectonic imbrication. Further west, beneath the Appalachian foreland, the average thickness of the Paleozoic shelf strata is approximately 5 km, and is comparable to the thickness of the shelf strata observed in the southern Appalachians. The presence of multiple, small scale duplexes within the shelf strata along the eastern Blue Ridge attests to the greater degree of compressional deformation experienced in this region when compared to the subhorizontal reflections originating from the strata beneath the western Blue Ridge.

The interpretation of the Blue Ridge allochthon and underlying shelf strata construed from the seismic images in the PR3 data is shown in Figure 24 along with the interpretation by Evans (1989) of the same data (Line 5). On the basis of the higher resolution provided by the reprocessed PR3 seismic data (Figure 23, bottom), the average thickness of the Blue Ridge allochthon is interpreted to be 3 km (1 s), with a maximum thickness of approximately 4.5 km (1.5 s). Along the PR3 profile, the Martinsburg detachment is interpreted to splay from the basal décollement that transported the Lower Paleozoic shelf strata westward. Transport along the Martinsburg detachment doubled the thickness of the strata beneath the eastern Valley and Ridge province. The most significant aspect of the reprocessed PR3 is that Lower Paleozoic shelf strata extend eastward beneath the Piedmont province approximately 5 km east of the surface exposure of the Mountain Run Fault and are truncated on the east by the Blue Ridge thrust. This model differs from the cross section compiled by Evans (1989), which shows the lower North Mountain ramp (LNMR in Figure 8) as marking the westernmost extent of the shelf strata approximately 14 km west of the surface exposure of the surface location of the Mountain Run Fault.

The Valley and Ridge Province

The Valley and Ridge province is bounded on the east by the Blue Ridge thrust, and on the west by the Allegheny structural front (Figure 26 and Figure 28). According to Weaver (1970), in the central Appalachians, this front represents the change from the intensely deformed rocks of the Valley and Ridge to the gently folded rocks of the Appalachian Plateau further west. Carbonates of the Lower Paleozoic shelf strata dominate the surface of the eastern Valley and Ridge and are bounded on the west by the Little North Mountain Fault. The scattering of seismic energy throughout the near-surface region is a common occurrence in regions with karst topography. The carbonates exposed at the surface in the eastern Valley and Ridge traversed by seismic line PR3 cause scattering and prevent the imaging of subsurface structures. The acoustically transparent character observed beneath stations 1500-1800 and 1975-2700 along the PR3 profile (Figure 26) is attributed to the presence of carbonates at the surface. These subsurface structures are masked and cannot be observed because of limitations related to the conventional (P-wave) seismic data acquisition. It might be possible to image these structures in SH-wave data acquired over these carbonate regions if the karst topography is minimal (Gresko and Costain, 1985). In the regions where reflections do exist, clastic rocks such as shales or siltstones are exposed on the surface.

The subsurface interpretation of this eastern region is constrained by the few reflections imaged beneath the clastic rocks, and therefore is open to a large degree of subjectivity. As shown by the PR3 reflector geometry, the eastern Valley and Ridge is comprised of two dominant structural units (Figure 26). The lower unit consists of parautochthonous Paleozoic shelf strata bounded below by the basal décollement in the Waynesboro Formation (BD), and bounded above by the Martinsburg detachment (MD)(Kulander and Dean, 1986). Kulander and Dean (1986) refer to this structural unit as the Waynesboro sheet, which appears to be relatively continuous beneath the Appalachian foreland along the PR3 profile (Figure 26, Figure 28, and Figure 31). A zone of subhorizontal reflections (SR in Figure 26 and Figure 28) is imaged within the Waynesboro sheet at a depth of approximately 4.5 km (1.5 s) and can be traced westward beneath the Appalachian Plateau (Figure 31). The lack of deep well data within this area precludes identifying the lithologic unit(s) from which this reflection package (SR) originates. On the basis of the PR3 seismic data, the Lower Paleozoic shelf strata exposed at the surface in the eastern Valley and Ridge are interpreted to be thrust westward over the Waynesboro sheet along the Martinsburg detachment. As mentioned earlier, the Martinsburg detachment appears to splay from the basal décollement beneath station 650, and it is possible that the proposed carbonate buildup (CBU (?) in Figure 23), which is approximately 2 km (0.6 s) thick, controlled the location of related ramping. Kulander and Dean (1986) interpreted the Little North Mountain Fault (LNMT in Figure 26) as the frontal thrust of the Massanutten-Blue Ridge thrust sheet. Furthermore, they proposed that both the Little North Mountain Fault and the Pulaski-Staunton Fault are seated in the Martinsburg shales, and the Pulaski-Staunton Fault splays from the Little North Mountain Fault, separating the Blue Ridge from the Massanutten unit (Figure 6). The present interpretation of the PR3 reflector geometry does not include Lower Paleozoic shelf strata as part of the Blue Ridge-Piedmont composite unit. The Cambrian-Ordovician strata carried westward along the Martinsburg detachment are considered as a separate entity. Additionally, both the Little North Mountain and Pulaski-Staunton faults (LNMT and PST in Figure 26) are interpreted to splay from the Martinsburg detachment, and are considered to be imbricate thrusts seated in the shales of the Martinsburg Formation as observed by Kulander and Dean (1986). Large scale imbricate thrusts represented by the various detachment zones segment the shelf strata and appear to root in the basal décollement beneath the Blue Ridge allochthon. Previously, the Waynesboro sheet and overlying Paleozoic shelf strata (Figure 6 and Figure 9) were divided into many segments by imbricate thrusts (Kulander and Dean, 1986; Evans, 1989); however, the limited reflectivity within this region along the PR3 profile suggests the presence of fewer thrusts than previously reported.

West of the Little North Mountain Fault, the Martinsburg detachment carried the overlying Upper Ordovician-Late Devonian clastics and carbonates westward through the Appalachian foreland (Kulander and Dean, 1986; Evans, 1989). Kulander and Dean (1986) suggested that the subsurface structures of the foreland are controlled primarily by the Waynesboro, Martinsburg and Massanutten-Blue Ridge thrust sheets. They defined the Martinsburg thrust sheet as containing the Upper Ordovician through Pennsylvanian strata that lie above the Martinsburg detachment west of the Little North Mountain Fault. The topography of the foreland is characterized by anticlinoria and synclinoria of the Martinsburg sheet, and they proposed that the structural relief of the basal décollement is responsible for these structures. Specifically, lower sheet ramping from the Waynesboro Formation results in antiformal structures and the relative absence of imbrications within this formation results in synformal structures. Furthermore, they demonstrated that in every cross section they compiled across the Appalachian foreland, shortening within the upper sheet exceeds that of the lower sheet.

Upward ramping from the basal décollement is apparent in the PR3 reflector geometry (Figure 28). Upward thrusting of the lower sheet has carried the overlying units westward where they

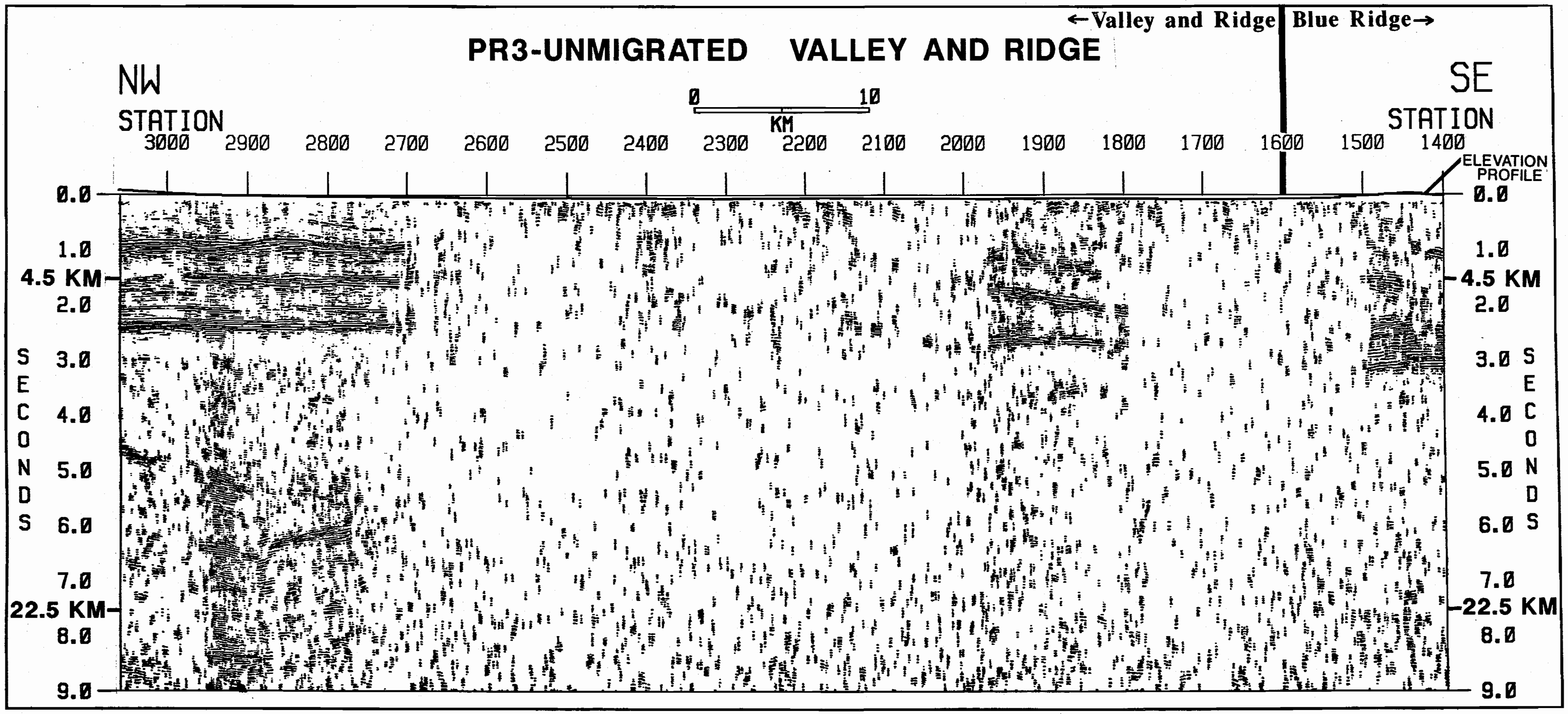


Figure 25. ALD display of unmigrated PR3 seismic reflection data from the eastern Valley and Ridge crust: Compare with Figure 26. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

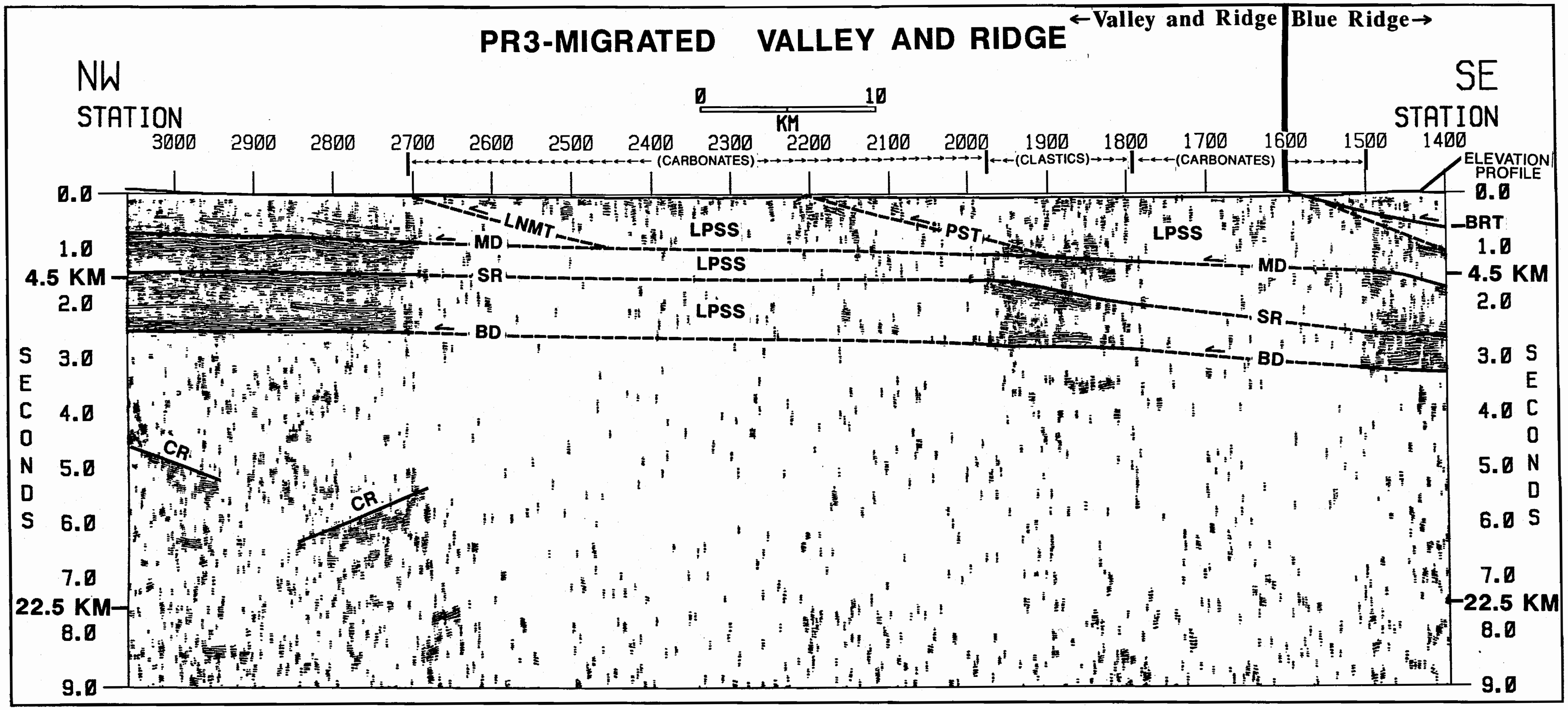


Figure 26. Interpreted ALD display of migrated PR3 seismic reflection data from the eastern Valley and Ridge crust: BD = basal décollement, BRT = Blue Ridge thrust, CR = coherent midcrustal reflections, LNMT = Little North Mountain thrust, LPSS = Lower Paleozoic shelf strata, MD = Martinsburg detachment, PST = Pulaski-Staunton thrust, SR = subhorizontal reflection package. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

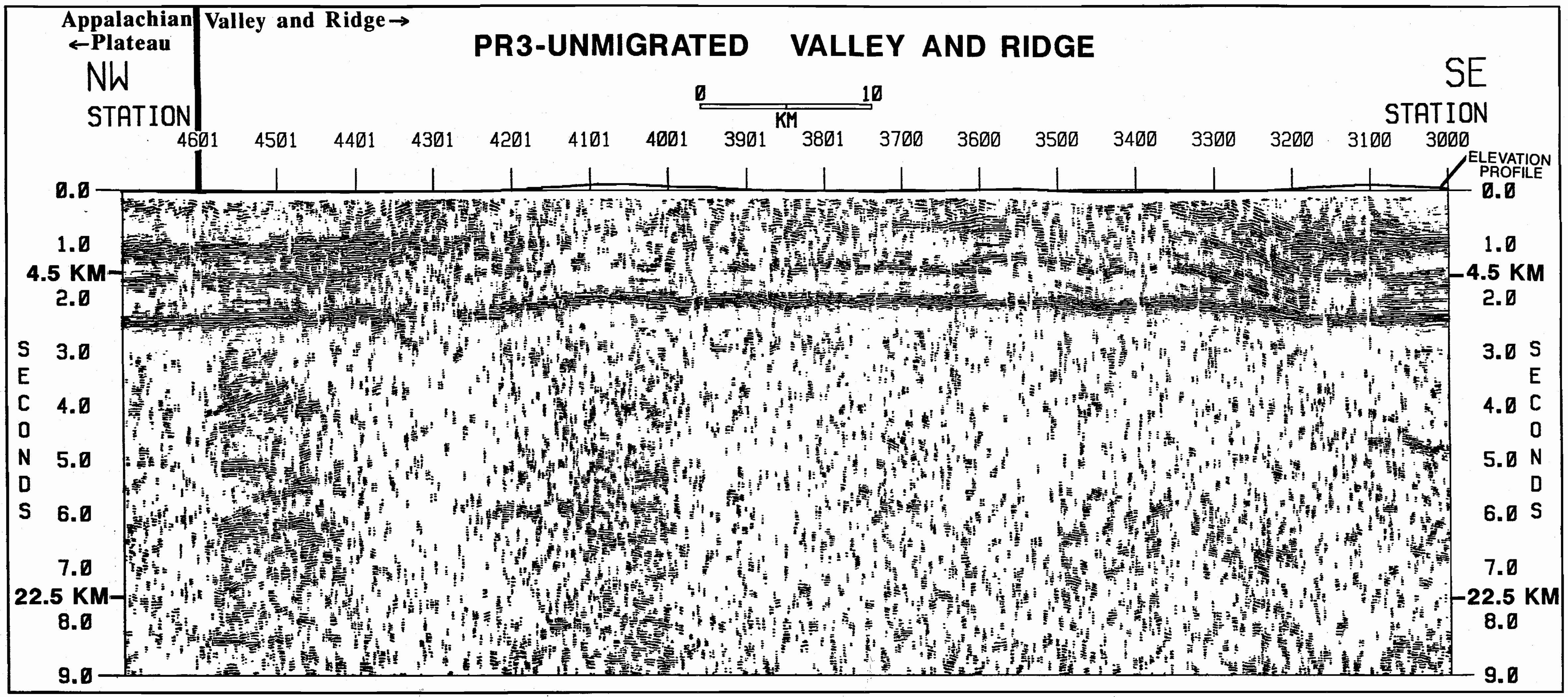


Figure 27. ALD display of unmigrated PR3 seismic reflection data from the western Valley and Ridge crust: Compare with Figure 28. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

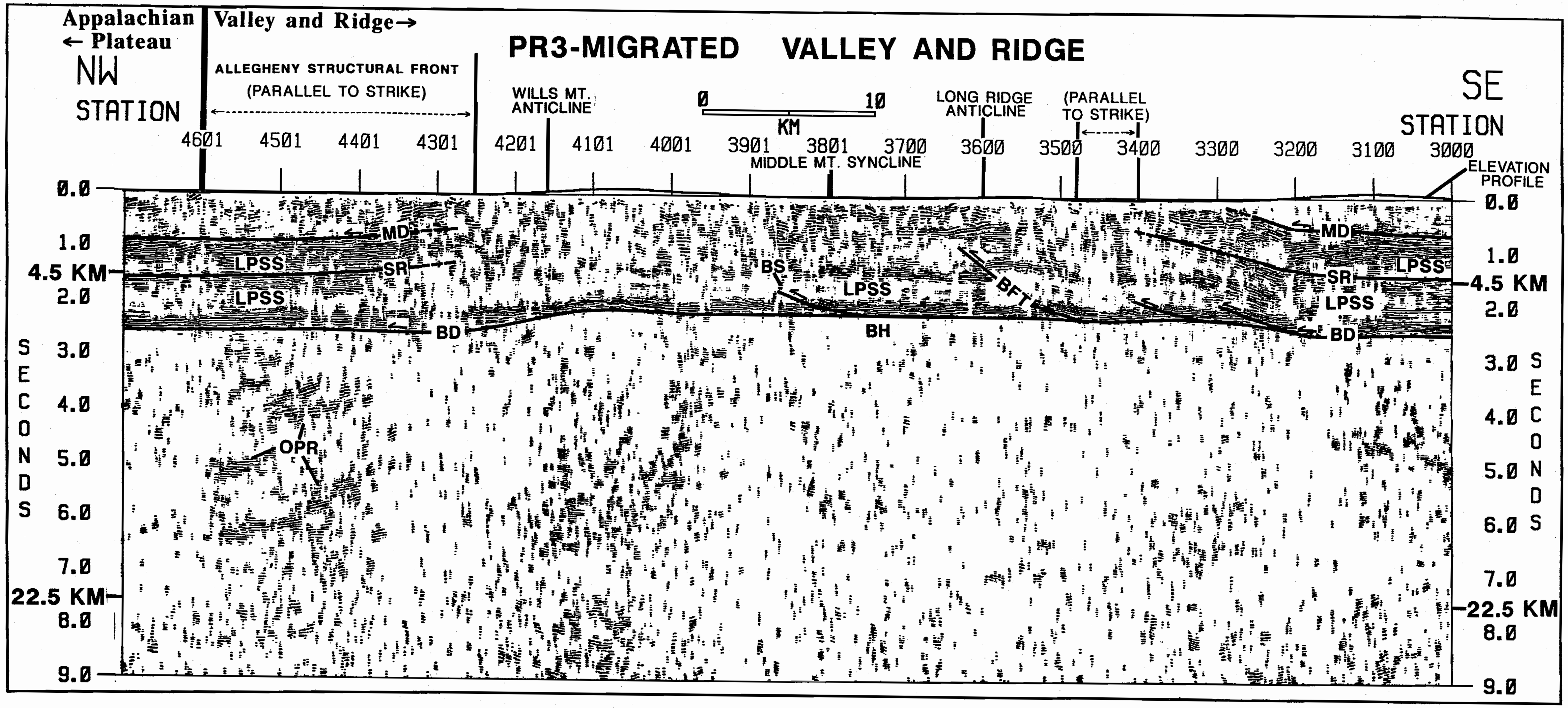


Figure 28. Interpreted ALD display of migrated PR3 seismic reflection data from the western Valley and Ridge crust: BD = basal décollement, BFT = blind frontal thrust, BH = basement high, BS = basal décollement splay, LPSS = Lower Paleozoic shelf strata, MD = Martinsburg detachment, OPR = out-of-plane reflections, SR = subhorizontal reflection package. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

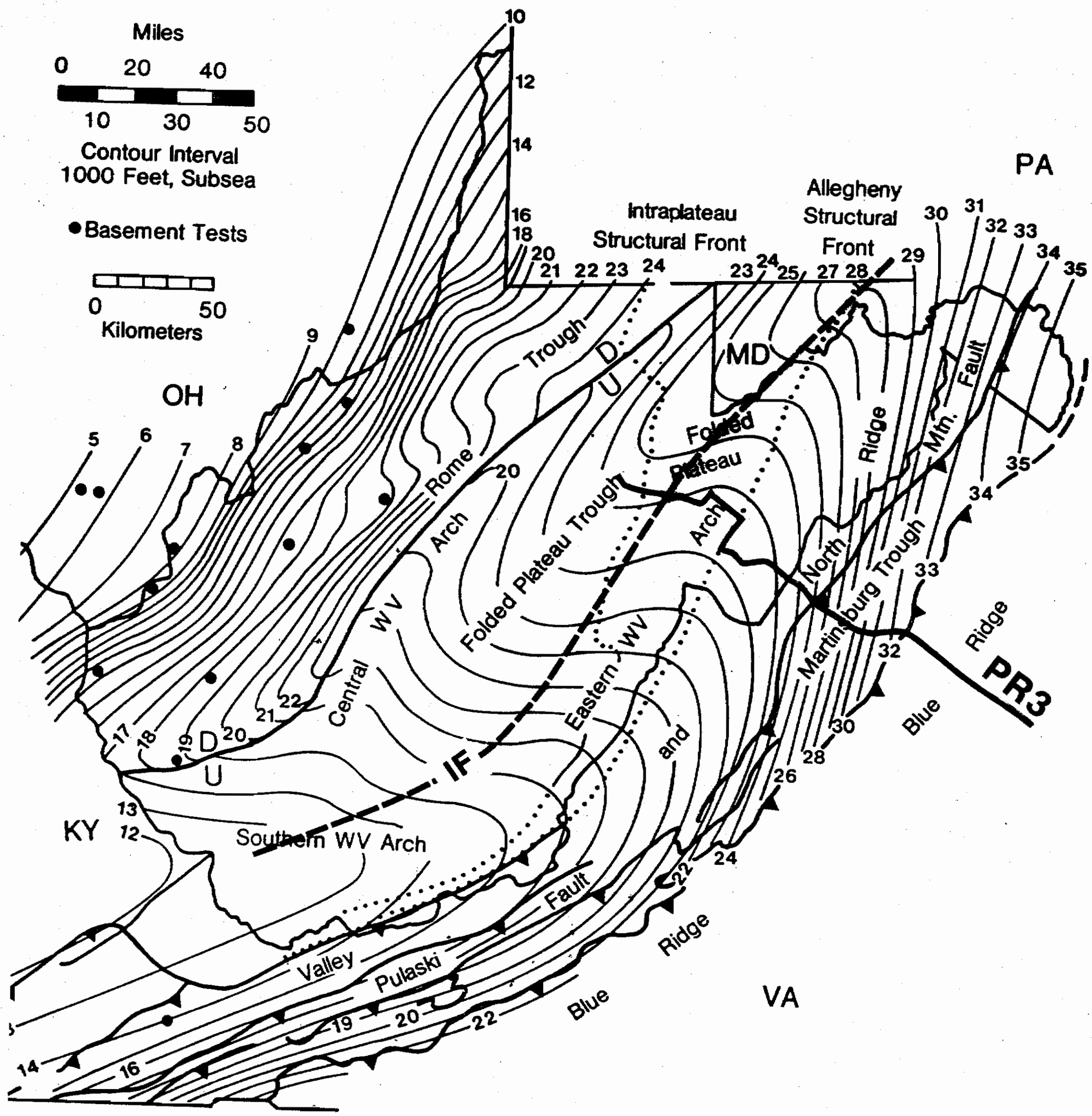


Figure 29. Basement structure contour map of the western Valley and Ridge and Appalachian Plateau from Kulander and Dean (1986): IF = inflection line separating the eastern West Virginia arch and the folded Plateau trough.

are folded against a blind, frontal thrust (BFT). On the surface, this thrusting is manifested in the Long Ridge anticline. This ramping of the lower sheet might have been controlled by the basement high in the western Valley and Ridge, which is imaged in the PR3 seismic data (BH in Figure 28). The seismic stacking velocities exhibit small lateral variations across this region, thereby suggesting that this structure is not a "velocity pull-up". Furthermore, this basement high corresponds with the eastern West Virginia arch (Kulander and Dean, 1986) shown in the basement structure contour map (Figure 29). The basement high (BH) is approximately 45 km wide along the PR3 profile. The observed thinning of the Conococheague Formation, Chazy Group and Chambersburg Group carbonates over the eastern West Virginia arch (Chen, 1977; Kulander and Dean, 1986) suggests that this structure was formed prior to deposition of the Conococheague Formation during the Upper Cambrian (Kulander and Dean, 1986), and might represent a horst.

West of the Long Ridge anticline, the Middle Mountain syncline structure is attributed to the minor displacement along the basal décollement splay (BS). Moving westward from the Long Ridge anticline, it is also apparent that the subhorizontal reflection package (SR) at 4.5 km (1.5 s) becomes discontinuous and cannot be delineated. The Wills Mountain anticline is adjacent to the Allegheny structural front, and line PR3 traverses this front along strike in a northeast direction. The eastern West Virginia arch is roughly coincident with the structural front, and the PR3 reflector geometry and basement structure contour map reveal that the depth to the basement surface increases moving northeast along this arch (Figure 28 and Figure 29).

The Appalachian Plateau Province

The westernmost province of the central Appalachians is the Appalachian Plateau, which is bounded on the east by the Allegheny structural front. Relatively unmetamorphosed exposures of Silurian-Pennsylvanian sedimentary rocks are exposed at the surface, and these rocks exhibit little deformation (Kulander and Dean, 1986; Wiltschko and Geiser, in Hatcher and others, 1989). The topography of this province is characterized by a series of broad open folds (Wiltschko and Geiser, in Hatcher and others, 1989), and no faults have been reported at the surface in the PR3 study area. Furthermore, along the PR3 profile, only one imbricate thrust (BT in Figure 31) is imaged in the Appalachian Plateau province that appears to splay from the basal décollement (BD in Figure 31). This observation confirms the diminished lower sheet ramping and folding noted by Kulander and Dean (1986) west of the eastern West Virginia arch, which roughly coincides with the Allegheny structural front in Figure 29.

Many of the synclines and anticlines mapped at the surface of this province are mimicked by the shallow reflection packages observed within the upper 2 km (0.6 s). These shallow reflection packages reveal the synformal structure of the Stony River, Job and North Potomac synclines (SRS, JS and NPS in Figure 31). Due to low fold coverage between stations 4925-5025 in Figure 31, the Horton anticline, which lies between these two synclines, is not readily apparent; however, the geometry of this structure can be inferred from the turned-up reflections characterizing the western and eastern boundaries of the Stony River and Job synclines beneath stations 4925 and 5025, respectively. The Stony River and Job synclines are interpreted to result from the absence of displacement along the Martinsburg and Waynesboro detachments. The axis of the Stony River syncline, as mapped on the surface (Cardwell and others, 1968) is labeled by a solid vertical line in Figure 31; however, the PR3 seismic data suggest that the axis of this syncline is located to the east of this mapped location, as indicated by the arrow. Further west, a change in the basement topography (CBT) appears to have controlled the development of the Glady Fork anticline and the North Potomac syncline. The Glady Fork anticline is located above the "inflection line" (IF) that separates the eastern West Virginia arch and folded plateau trough (Figure 29). Given a seismic line traversing westward along the dip direction, it would be reasonable to image an increase in basement depth upon crossing this topographic transition. The PR3 reflector geometry displays a northwest dip (CBT) along the basal décollement reflection package that is interpreted to be associated with the basement surface transition between the eastern West Virginia arch and the folded plateau trough. The Glady Fork anticline is underlain by a series of concealed faults. As noted by Bally (1983), strike-slip fault zones resulting from convergent systems "are often associated with foreland deformation". The images observed in the PR3 seismic data appear to satisfy some of the

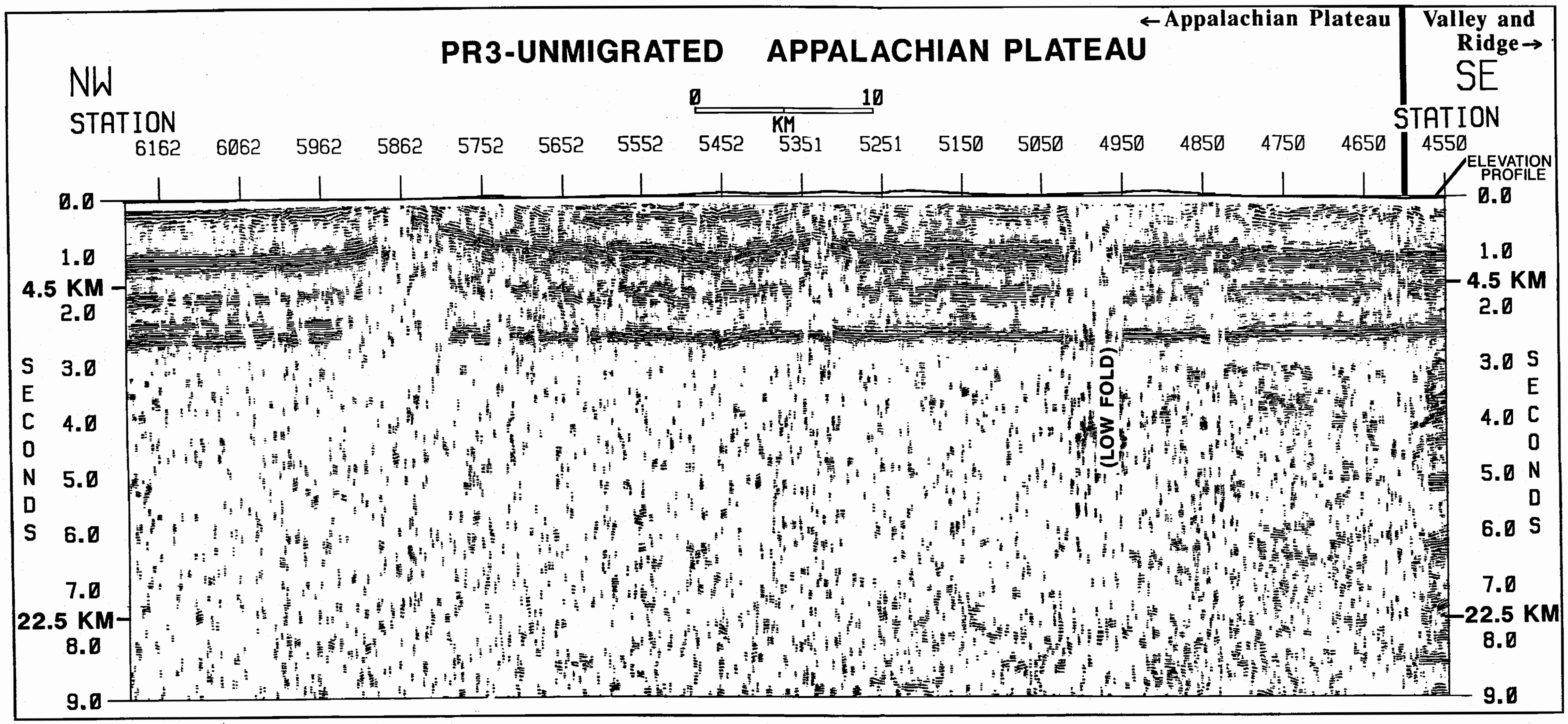


Figure 30. ALD display of unmigrated PR3 seismic reflection data from the Appalachian Plateau crust: Compare with Figure 31. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

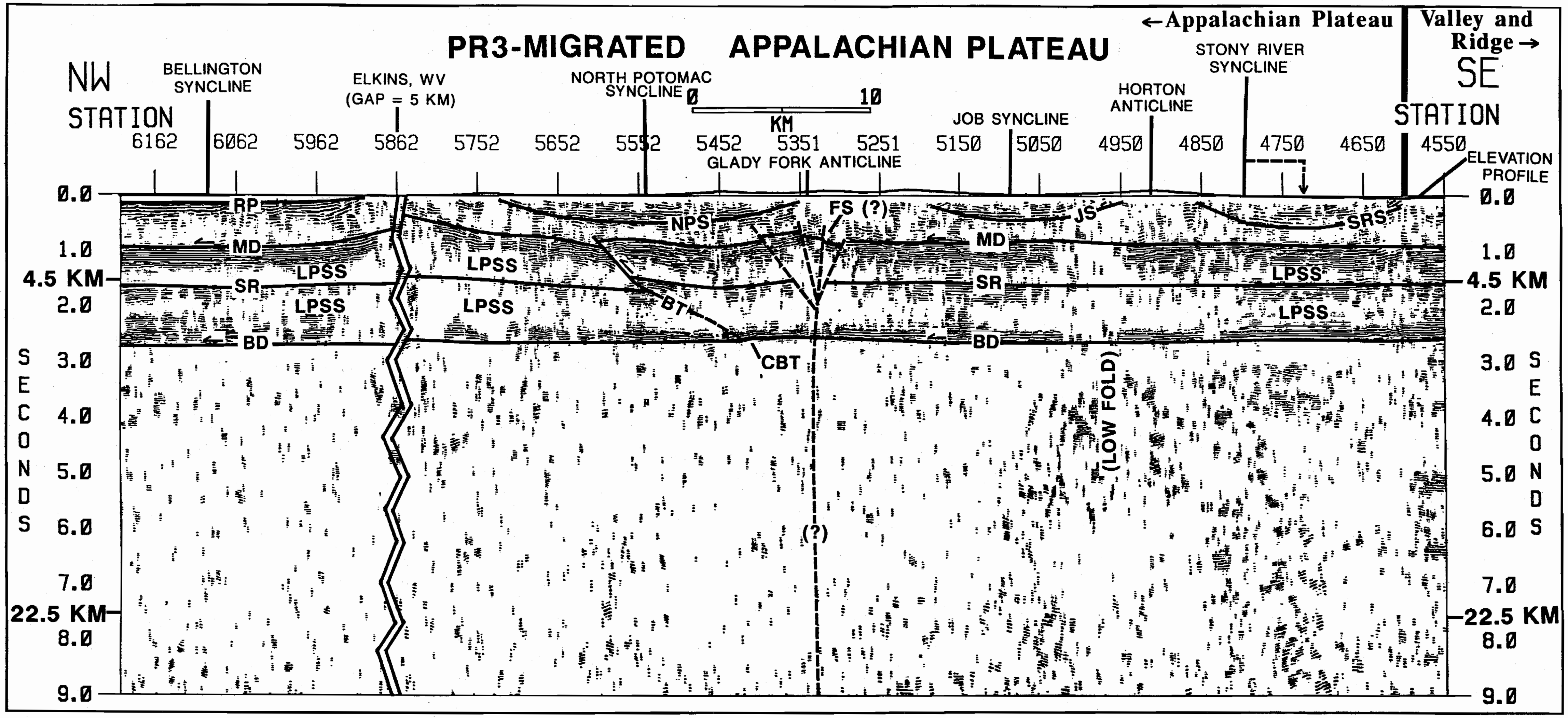


Figure 31. **Interpreted ALD display of migrated PR3 seismic reflection data from the Appalachian Plateau crust:** BD = basal décollement underlying the central Appalachians, BT = blind thrust, CBT = change in basement topography, FS (?) = positive flower structure (?), JS = Job syncline, LPSS = Lower Paleozoic shelf strata, MD = Martinsburg detachment, NPS = North Potomac syncline, RP = reflection package, SR = subhorizontal reflection package, SRS = Stony River syncline. (Uncorrelated PR3 seismic data provided by Halliburton Geophysical Services, Inc.)

criteria listed by D'Onfro and Glagola (1983) for identifying a wrench fault. The images in Figure 31 are herein interpreted as a positive flower structure (FS (?)) with changes in dip across the faults comprising this structure, and changes in the fault throw with depth. Harding and others (1983) state that

> Structural relief on the upturned beds (associated with these flower structures) commonly decreases downward and in many examples is replaced at depth by a simple, vertical step (separation) of a subhorizontal basement surface.

As such, the "basement step" (CBT) in Figure 31 might also be the associated with convergent wrench faulting within the Appalachian foreland. In general, geologic maps do not document transpressional stress west of the Brevard Fault Zone; however, the interpretation of this positive flower structure implies that transcurrent movement has occurred within this region. On the basis of the PR3 seismic data, no evidence exists for the presence of strike-slip faults at the surface because this structure is presently concealed by Paleozoic strata.

Adjacent to the North Potomac syncline, the reflection package (MD) observed at approximately 3 km (1 s) turns upward and duplicates the eastern limb of an anticline. The axis of this anticline runs through the town of Elkins, WV; however, seismic data were not acquired through this residential area and a gap of approximately 5 km resulted between stations 5852 and 5854 in Figure 31. West of Elkins, beneath station 5900, these reflections gradually turn down again, imaging the western limb of the aforementioned anticline. Low fold coverage within this region prevents the continuous imaging of the basal décollement. The westernmost edge of the PR3 profile displays fairly continuous, subhorizontal reflections at approximately 1 km (0.3 s), 3 km (1 s), 5 km (1.6 s) and 8 km (2.6 s) (RP, MD, SR and BD on Figure 31).

The Autochthonous Crust

Basement rock is interpreted to lie beneath the Piedmont allochthon and the basal décollement along the entire PR3 seismic line to a depth of 30 km. Along the I-64 seismic profile, the Moho is imaged at a depth of approximately 30 km (10 s) beneath the eastern Piedmont, and continues to a westward depth of approximately 42 km (14 s) before it is no longer imaged beneath the Blue Ridge province (Figure 4). Along line PR3, the data does not extend far enough into the subsurface to reach the Moho, and this crustal transition zone is not imaged. On the unmigrated and migrated profiles (Figure 11 and Figure 12), the crust beneath the basal detachment (BD) east of station 650 is more reflective than the crust located further west. Because of poor reflectivity (Çoruh and others, 1988), the autochthonous crust west of station 650 is interpreted to be relatively undeformed Grenvillian basement.

In the attempt to delineate the top of autochthonous basement along the PR3 profile, the borehole compensated sonic log of the W. R. Price #1 well was analyzed. This well was drilled in the Valley and Ridge of southwest Virginia, and penetrated the top of the basement at a depth of 5074 m (16,646 ft). The sonic log (Figure 32) shows little change in interval velocity between the Shady dolomite, Basal Sand and underlying Basement Complex at this location. Furthermore, the variations in density between these formations are minor. It was concluded that the acoustic impedance contrast between the basement rock and its overlying cover is relatively weak, and therefore the top of the Grenville basement cannot be clearly delineated from the seismic reflection data. Herein, the Grenville basement and the overlying sequence comprised of the Swift Run, Catoctin, Chilhowee Group and Tomstown/Shady dolomite (Figure 8) is interpreted as the autochthonous crust below a basal decollement (BD).

The upper boundary of the autochthonous crust that underlies the parautochthonous shelf strata is distinguished by a high velocity contrast between these different lithologies on well logs. As reported by Christensen and Szymanski (1991), the reflection coefficient of shales in contact with carbonates in the Valley and Ridge of the southern Appalachians usually ranges between ± 0.33 to ± 0.41. In the central Appalachians (Figure 8), the basal décollement, seated in the Waynesboro shale, overlies the Shady dolomite at the top of the autochthonous unit (Evans, 1989). On the basis of density and velocity values compiled by Edsall (1974), Kolich (1974) and Gresko (1985), the calculated reflection coefficient at the Rome (Waynesboro) shale and Shady (Tomstown) dolomite interface is ± 0.32. The high amplitude reflections associated with this reflection coefficient are correlated with this interface on the PR3 seismic data and are interpreted as the boundary between the parautochthonous and autochthonous crust.

Various Paleozoic compressional events and Mesozoic extension affected the crust of the central Appalachians. The cause of middle and lower crustal reflectivity presently remains one of the most elusive aspects of reflection seismology. In particular, it is not known if middle and lower crust reflections are the result of collisional deformation, or whether they represent preexisting structures that were unaffected by collisional forces (Lillie and Yousuf, 1986). Smithson and others (1986) proposed that these crustal reflections originate from mylonites in a sheared crust. They attributed the reflectivity of the shear zones to the compositional layering, fabric, planar and continuous geometry, and chemical alterations within these rocks. They also correlated reflective mylonites with crustal regions where extensional deformation has been most recent. Middle and lower crustal reflectivity may also be affected by magmatic intrusions and the presence of water (Phinney and Roy-Chowdhury, 1989).

Crustal reflections and diffractions are often associated with gneissic terrane, such as the Grenville basement (Gibbs, 1986). In this case, reflection groups generally appear between 9-24 km (3-8 s) and sometimes correspond in size and style with folds mapped at the surface (Gibbs, 1986). A few reflective zones are imaged in the Grenville crust in the Valley and Ridge province along line PR3. The northwest dipping package at 10.5 km (3.5 s) and midcrustal reflections (OPR in Figure 28) displayed beneath the Allegheny structural front are interpreted to originate from out of the plane of this section because the data in this region were acquired along the direction of strike. On the other hand, coherent reflections were imaged that dip to the southeast and northwest from 12-25 km (4-8.3 s) (CR in Figure 26). These reflections were imaged in a dip direction and are approximately 8 km in length. The origin of these midcrustal reflections is open for elaborations.

The midcrustal reflections at approximately 9-30 km (3-10 s) beneath stations 12-650 (Figure 12 and Figure 23) are highly reflective when compared to the crustal reflectivity west of this

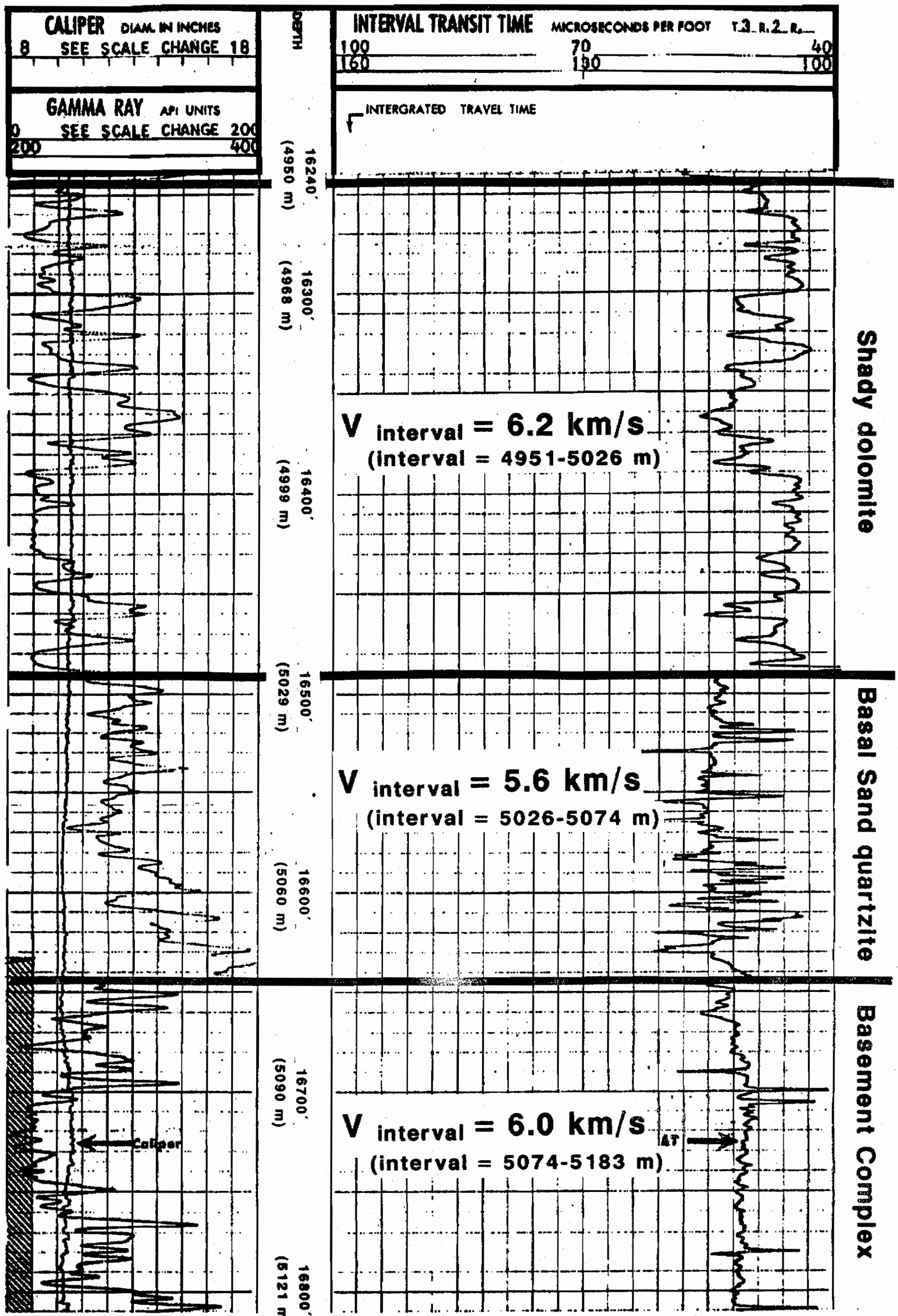


Figure 32. **W. R. Price #1 well gamma ray log and borehole compensated sonic log data (4950-5124 m):** Note the lack of variations exhibited in these logs at the Shady dolomite, Basal Sand quartzite and Basement Complex contacts.

segment of the PR3 traverse. A similar highly reflective region within the autochthonous crust was also imaged on seismic lines that crossed the boundary between the Piedmont and Blue Ridge boundary further south in Virginia and South Carolina, and was interpreted to originate from extended crust (Li and others, 1990). Seismic reflection data acquired in southeastern Arizona, Death Valley, California, and the Rio Grande rift, New Mexico, have also imaged midcrustal reflections (De Voogd and others, 1988; Goodwin and Thompson, 1988). Many of these events appear as laterally continuous reflections. These events have been attributed to fracture zones, compositional layering, regions of velocity anisotropy and magmatic intrusions associated with crustal extension (De Voogd and others, 1988; Goodwin and Thompson, 1988). Within the southeastern U. S., Çoruh and others (1992) attributed the midcrustal reflectivity to compressional and extensional deformation, and the reflections were interpreted to originate from imbricated crust that was injected by mafic material.

The midcrustal reflections beneath the western Piedmont and the Blue Ridge thrust ramp are interpreted to originate from crust that was deformed during multiple extensional and compressional episodes. The extensional episodes are associated with the initial rifting of the ancient continental margin and Mesozoic rifting; the compressional episodes occurred during the Paleozoic orogenies.

Conclusions

Integration of the reprocessed PR3 seismic data along with additional published seismic reflection, geological and potential field data is used to clarify the subsurface structures beneath the central Appalachians in Virginia and West Virginia. The allochthonous western Piedmont and Blue Ridge crust is bounded below by the Blue Ridge thrust, which is interpreted as an undulating reflector beneath the Piedmont and Blue Ridge provinces. The highly reflective nappes within the Piedmont allochthon might be composed of Catoctin, Evington Group strata and possibly younger metamorphosed rocks. Along the eastern edge of the PR3 seismic profile, the nappe closest to the western boundary of the Piedmont is most likely intruded by a concealed nose of the Green Springs mafic mass, which is associated with an acoustically transparent region. A steeply dipping fault is interpreted to separate the subsurface structures of the Piedmont and Blue Ridge within the Blue Ridge-Piedmont composite terrane. The surface projections of this fault and the shallow thrust that overlies the nappe are coincident with the mapped exposure of the Mountain Run Fault.

The Blue Ridge thrust ramps upward beneath the Piedmont and underlies the acoustically transparent Blue Ridge allochthon. The average thickness of this allochthon is 3 km (1 s), and the maximum thickness is interpreted to be 4.5 km (1.5 s). The Lower Paleozoic shelf strata beneath the Blue Ridge allochthon are characterized by the presence of duplex tuning wedges. These strata are interpreted to extend approximately 5 km east of the surface exposure of the Mountain Run

Fault, where they are truncated at a depth of 10.5 km (3.5 s) by the Blue Ridge thrust. The Paleozoic shelf strata are located above a basal décollement that is seated in the Waynesboro formation. The relatively continuous reflection package originating from this décollement is imaged at approximately 9 km (3 s) beneath the Blue Ridge, Valley and Ridge and Appalachian Plateau provinces on the PR3 seismic data. This décollement represents the boundary between the parautochthonous crust and underlying autochthonous crust.

A basement high is imaged beneath the Valley and Ridge province and extends laterally approximately 45 km along the PR3 seismic profile. This structure is interpreted to have formed prior to the Upper Cambrian. The basal décollement within the Waynesboro formation has ramped upward along the eastern boundary of the basement high and displaced the overlying shelf strata. Further west, in the Appalachian Plateau province, reflections beneath the Glady Fork anticline are interpreted as representing a concealed positive flower structure associated with transpressional deformation.

The poorly reflective autochthonous crust west of the eastern Blue Ridge is interpreted to be relatively undeformed Grenvillian basement. The midcrustal reflections beneath the western Piedmont and vicinity of the Blue Ridge thrust ramp in the PR3 seismic data are attributed to compression during the Paleozoic orogenies and to extension during the early Laurentian and Mesozoic stages of rifting.

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Appendix A. Seismic Reflection Data Parameters

Field Parameters

The source and recording parameters used during acquisition of lines PR3 and I-64 are listed Table 1.

Processing Parameters

Seismic processing was conducted using the CogniSeis Development DISCO seismic processing package. The processing sequence applied to line PR3 is as follows:

Demultiplex

Amplitude balancing (AGC 1000 ms)

Vibroseis correlation (data extended to 10 s)

from 0-5 s, the frequency bandwidth ranged from 14-56 Hz

from > 5-10 s, the frequency bandwidth tapered out linearly and converged to 14-26 Hz at 10 s

Definition of line and CDP geometry

Datum statics

datum elevation = 600 m (minimum surface elevation = 145 m, maximum surface elevation = 1094 m)

replacement velocities ranged from 4000 m/s to 6400 m/s and were determined from the shot records at 32 stations along line PR3

Edit

CDP sort

Trace balancing (AGC 500 ms)

Deconvolution

(Piedmont to Valley and Ridge)

gap = 16 ms

filter length = 1200 ms

design window length = 500-2500 ms

application window = 0-10000 ms

(Valley and Ridge to Appalachian Plateau)

gap = 24 ms

filter length = 2400 ms

design window length = 300-3300 ms

application window = 0-10000 ms

NMO correction

Bandpass filter (Hanning tapering)

frequency at low end of tapered zone = 10-14 Hz

frequency at high end of tapered zone = 50-56 Hz

Velocity analysis

iterations with alternating residual statics corrections

Residual statics corrections

iterations with alternating velocity analyses

Velocity spectra analyses

Mute

Stack

Migration

post-stack finite difference method

velocity = linear, 95 percent of stacking velocity

layer thickness = 96 ms (TWTT)

panel width = 48 traces

data fully migrated down to 6000 ms; between 6000-10000 ms, data was partially migrated

This sequence varies from the conventional sequence by the application of vibroseis whitening, extended correlation and the omission of a geometrical spreading correction. These three processes were discussed in an earlier section of this paper.

Velocity spectra analyses

Velocity spectra analyses were conducted in order to distinguish the various lithologies associated with the allochthonous Piedmont and Blue Ridge units from the parautochthonous Paleozoic shelf strata. Earlier studies at the Regional Geophysics Laboratory at Virginia Polytechnic Institute and State University have shown that the allochthonous Blue Ridge crystalline rock has an average compressional wave velocity around 6000 m/s; the compressional wave velocity of the shelf strata is around 5500 m/s (Gresko, 1985).

Velocity coherency estimates were computed using 7 consecutive CDPs at nine locations within the western Piedmont, Blue Ridge, and eastern Valley and Ridge province. Computation of these coherency estimates began by collecting the first three consecutive CDPs at each study location and combining them into one CDP. The previous datum statics applied using the datum elevation of 600 m were removed, and for each velocity study location, datum statics were reapplied using a datum elevation equal to the average elevation of the location. The velocity spectra at each location was then computed using three of these combined CDPs.

After plotting the spectra, the interval velocities were computed from the spectra using the Dix equation. Since the Dix equation considers the case of horizontally layered strata, the dip effects were removed from the stacking velocities using the following equations: $\tan\beta = \frac{\Delta z}{\Delta x} = \sin\alpha$, and $\Delta z = V_1(\Delta t)$, where α is the true dip and β is the apparent dip. By measuring β, Δx and Δt from the stacked seismic section, $\alpha = \sin^{-1}(V_1 \frac{\Delta t}{\Delta x})$ is computed using V_1 = 5.5 km/s. Once α is known, then the stacking velocity, V_{rms}, is corrected using the equation $V_{rms} = \cos\alpha(V_{\text{apparent rms}})$, where $V_{\text{apparent rms}}$ is obtained from the velocity spectra. The corrected stacking velocities (V_{rms}) were then used in the Dix equation to calculate the interval velocities.

Table 1. Field information

Source Parameters	PR3	I-64
year acquired	1980	1981
vibrator model	Y-600B	(model unknown)
vibrators	4	2-3
sweep length	7 sec	10 sec
sweep frequencies	14-56 Hz	14-56 Hz
taper length	N/A	1 sec
source interval	300′ (91.4 m)	440′ (134 m)
Recording Parameters	**PR3**	**I-64**
geophones	Mark L-25L	GSC-20D
natural frequency	8 Hz	10 Hz
instruments	MDS-10	DFS V
receiver group spacing	300′ (91.4 m)	220′ (67 m)
spread (feet)	8100-1200-1200-8100	5500-660-660-5500
spread (meters)	2469-366-366-2469	1676-201-201-1676
number of channels	48	48
configuration	split spread	split spread
sample interval	4 sec	4 sec
record length	12 sec	24 sec
recording filter	N/A	12-18-90-72 Hz
data length	5 sec	14 sec
fold	24	12

Vita

Laura Dermody was born on November 18, 1966, at Fort Carson, Colorado, to Kathleen T. and Henry M. Dermody Jr. Her family moved various times before she graduated in 1985 from Iolani School in Honolulu, Hawaii. In 1985, she entered Wellesley College and graduated with a Bachelor of Arts Degree in geology and mathematics in 1989. In August, 1989, she married her eight grade science partner, Gregory B. Lampshire, and enrolled in the graduate program in the Department of Geological Sciences at Virginia Polytechnic Institute and State University. Upon completion of her Master of Science degree in geophysics, she will begin employment with Shell Offshore Inc. in New Orleans, Louisiana.

Laura D. Lampshire