GEOLOGY OF THE TERMINUS OF THE ST. CLAIR FAULT: A STUDY ACROSS THE CENTRAL AND SOUTHERN APPALACHIAN JUNCTURE, VIRGINIA-WEST VIRGINIA

by

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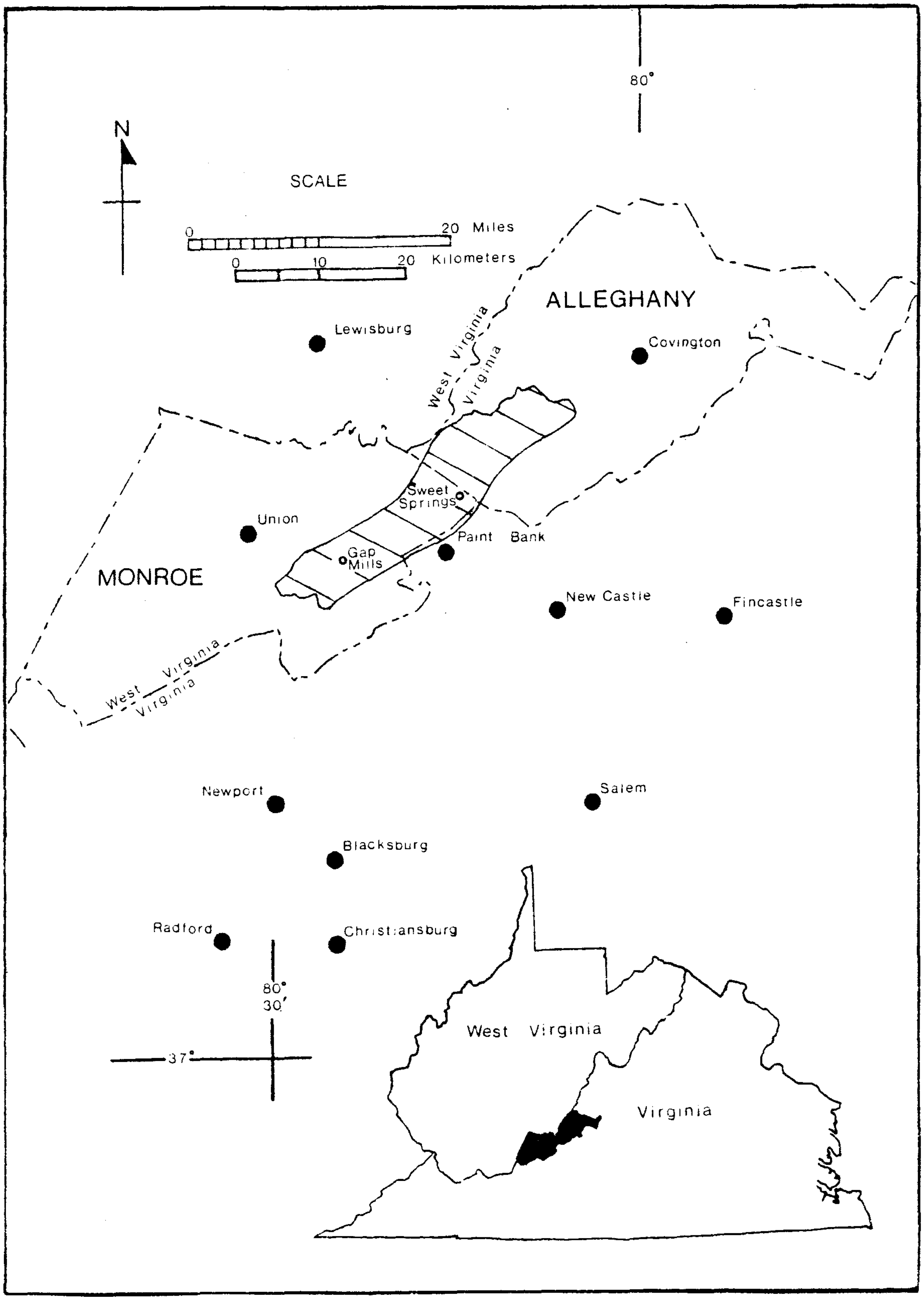
INTRODUCTION

This study of the terminus of the St. Clair fault and its attendant structural setting involved primarily geologic mapping (Plate 1). Additional observations on warm springs, structure, stratigraphy, and brecciation were made in order that light might be shed on the development of the junction of the Central and Southern Appalachians.

The study area lies along the northwestern edge of the Valley and Ridge Province in Monroe County, West Virginia and Alleghany County, Virginia (Figure 1 and Plate 2). The map area is bounded on the southeast by the crest of Peters Mountain and on the northwest by Middle Mountain-Big Ridge. The area extends from Crimson Springs Road in Monroe County, on the southwest, to just north of Morning Knob in Alleghany County, on the northeast, and includes parts of the Gap Mills, Glace, Paint Bank, Alleghany, Potts Creek, and Jordan Mines 7.5-minute quadrangles.

This area is tectonically significant because within it is the junction zone between the Central and Southern Appalachians. The St. Clair fault, of the Southern Appalachians, penetrates approximately 13 miles into the Central Appalachian segment before it loses stratigraphic displacement and dies out near Covington, Virginia down the plunge of an anticline that is overturned and brecciated at its nose. In this northwesterly belt, the topographic change in strike from N.60-65° E. in the Southern Appalachians to N.30-35° E. in the Central Appalachians is more noticeable than in areas to the southeast. This is clearly evident on the satellite photograph (Plate 2, arrow) in the recess between Gap and Moss Mountains. This recess is one of the sharpest bends occurring at the junction.

Figure 1. Location map of the study area with the region mapped shown outlined and cross hatched. Location of Alleghany County, Virginia and Monroe County, West Virginia are shown on the index map.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Virginia
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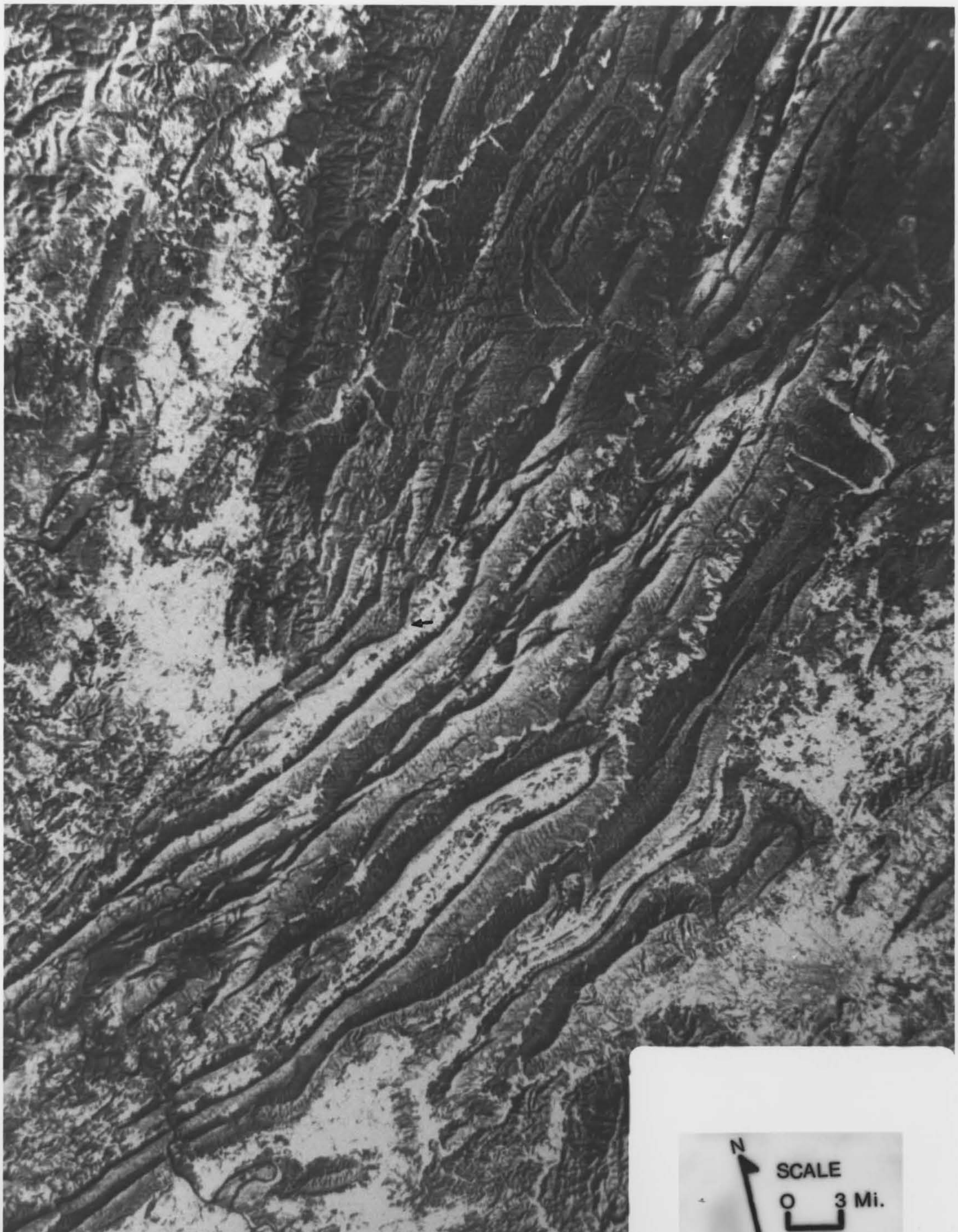
Covington
Sweet Springs
Union
Paint Bank
Gap Mills
MONROE
New Castle
Fincastle
West Virginia
Virginia
Newport
Salem
Blacksburg
Radford
Christiansburg
80° 30'
37°
West Virginia
Virginia

REGIONAL GEOLOGIC SETTING

The most notable feature of the Central and Southern Appalachian juncture is, of course, the abrupt change in physiographic and structural trend from N.60-65° E. in the Southern Appalachians to N.30-35° E. in the Central Appalachians (Figure 2 and Plate 2). The zone is a recess, concave to the northwest, which is remarkably narrow when compared to other changes in strike within the Appalachians, such as that occurring in central Pennsylvania. This junction zone is about 10 miles wide and cuts across strike in a roughly east-west direction at about latitude 37° 30' N. This pattern of abrupt change in strike becomes much less noticeable on the northwest as one enters the Plateau Province, except that the folds of the southeast portion of the Central Appalachian Plateau plunge abruptly into the junction zone. Gwinn (1964) termed this region the High Plateau but northwest of the Plateau structural front in the adjacent Southern Appalachians, no corresponding physiographic province is evident. The Blue Ridge Province shows a change in trend of the same magnitude as the Valley and Ridge Province. In addition the Blue Ridge Province tends to be confined to a single ridge about 5 to 10 miles wide in the Central segment, whereas in the Southern segment it broadens into an upland up to 60 miles wide (Rogers, 1970).

Less obvious, but of equal importance to the change in trend, are the contrasts in geologic "style" that occur across the juncture. Immediately south of the juncture, six major thrust faults are present

Plate 2. ERTS photograph showing the Central and Southern Appalachian juncture. Notice that the recess between High Head Mountain and Moss Mountain, in the study area (arrow), is one of the sharpest topographic bends occurring at the junction.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in southwestern Virginia (Figure 2); at least two are continuously traceable 370 miles to the southeast (King, 1961). Within the overthrust belt, penetration of the Central Appalachians by the thrust faults of the Southern Appalachians is the greatest. The Blue Ridge fault apparently loses displacement east of Staunton, Virginia. Along the northwestern edge of the Blue Ridge Province northeast of Staunton, thrust slices, in places truncated by other faults, continue intermittently along the whole extent of the Blue Ridge to the northeast (Rodgers, 1970). The Max Meadows fault extends into Botetourt County, Virginia, northeast of Roanoke, where it apparently becomes part of the Blue Ridge fault system (Spencer, 1968). The Staunton thrust, the northeast extension of the Pulaski thrust (Cooper, 1960, 1961), penetrates the Central Appalachians to northeast of Harrisonburg in Rockingham County, Virginia. Northwest of the overthrust belt and southeast of the St. Clair fault, the extensive Saltville fault dies out just east of New Castle, Virginia (Bregman, 1967; King, 1961; Lowry, 1971) (Figure 2). The Narrows fault, northwest of the Saltville fault and southeast of the St. Clair fault, apparently dies out shortly before it would have passed into Monroe County, West Virginia from Giles County, Virginia (Butts, 1940). Northeast of Rocky Gap in Bland County, Virginia, the Narrows fault bifurcates to the northeast, isolating a slice of Martinsburg between the segments. The two faults continue into Giles County with the segments paralleling each other and pass just north of Narrows, Virginia. Northeast of Narrows the southeast segment bifurcates; the northwestern segment of this bifurcation joins the northwest segment of the previous bifurcation and this combined part of the fault dies out about halfway between Pearisburg, Virginia and Peterstown, West Virginia. The southeast segment of the first bifurcation continues northeast as the main fault (Butts, 1940). Southeast of Bluefield, West Virginia the Narrows fault bifurcates for a distance of nearly 10 miles. Reger (1926) reported a reverse fault at the northeastern tip of Monroe County, passing into Craig County, Virginia, that brings Middle Ordovician limestone in contact with the Martinsburg, thus cutting out the Moccasin. He called this the Sugar Grove fault and it lies along the strike of the Narrows fault northeast of its termination, on the northwest limb of the Rich Patch anticline.

The St. Clair fault, named by Campbell (1896) for the railway junction of St. Clair on the Pocahontas folio, its type area, extends northeast through Mercer and Monroe Counties, West Virginia, paralleling the Virginia-West Virginia border, and extends into Alleghany County, Virginia in the Central Appalachians. The St. Clair fault can be traced southwest from its type area into Russell County, Virginia where it diverges into several faults, which bear different names, and form a system that eventually reconnects and extends into northwest Georgia (King, 1961). Except for the type area, where the St. Clair fault splits into two, then farther southwest into three segments, the St. Clair fault, northeast of Russell County, is generally a single break with Beekmantown dolomite faulted over Lower Devonian or Silurian formations. Losing stratigraphic displacement, the St.

Clair fault, in Alleghany County, Virginia, dies out southwest of Covington (Figure 2, Plate 1).

Northwest of the St. Clair fault in Tazewell County, Virginia, the northwest limb of the Abbs Valley anticline (complementary anticline northwest of the Hurricane Ridge syncline) is faulted. The fault, the Boissevain, is apparently an en echelon extension of the Richlands fault, and extends a little more than two miles into Mercer County, West Virginia (Campbell, 1896; Cooper, 1944; Reger, 1926). This fault on the southwest is clearly a thrust but on the northeast becomes a high angle reverse fault and is lost at the juncture of the Pocahontas syncline and the Abbs Valley anticline (Reger, 1926).

High-angle, southeast-dipping reverse faults, little recognized until recently, occur in abundance on the northwest limbs of anticlines in the Central Appalachians (Gwinn, 1964; Renton, personal communication, June 1974). Many of these reverse faults were unrecognized because they tend to crop out in incompetent Devonian shales, which thus may be greatly thickened tectonically yet leave little outcrop evidence because of deep weathering. Well data indicates that these reverse faults may be splays off deeper detachment faults (Gwinn, 1964, 1970; Perry, 1964, 1975).

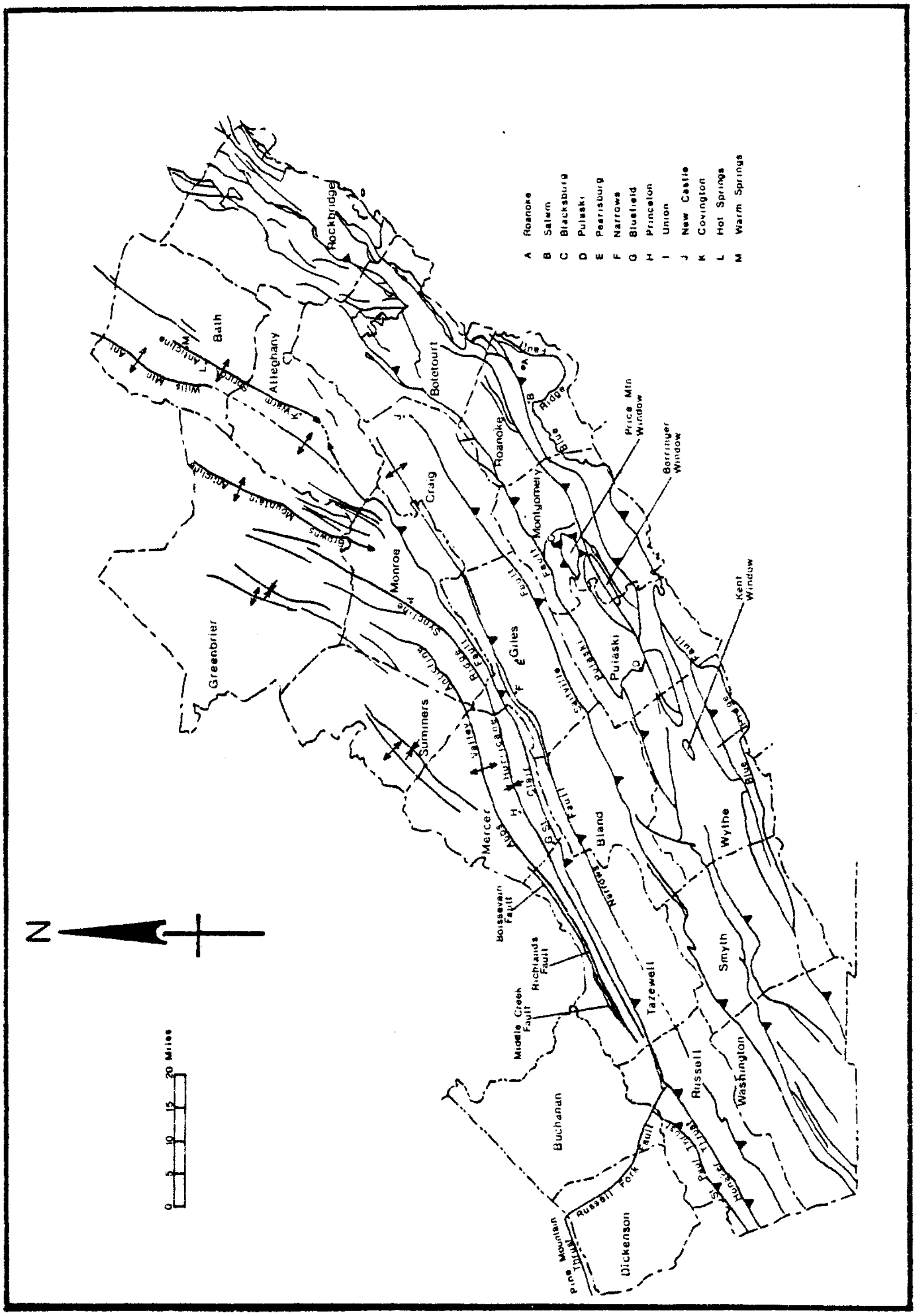
A difference in general style of folding may also be observed across the juncture. Valley and Ridge folds of the Central Appalachians tend to be more nearly symmetrical, doubly plunging, gently curving, and more open than those of the Southern Appalachians (Gwinn, 1964; Lowry, 1971).

It is interesting to note that as the anticline, here called the Morning Knob anticline, present where the St. Clair fault loses stratigraphic displacement in Alleghany County, Virginia, plunges northeast toward Covington, Virginia, the Warm Springs anticline, northeast of Covington, plunges southwest nearly parallel to the strike of the Morning Knob anticline (Figure 2). Also, as the folds generated at the junction zone on the northwest (footwall) side of the St. Clair fault begin to plunge northeast between Callahan and Greenwood, they approach the southwest plunge of the Nittany-Wills Mountain anticlinorium of the Central Appalachians. The warm springs of the study area appear to follow the St. Clair trend, northeast of the juncture, leading to the Warm Springs anticline, whereas the Nittany-Wills Mountain anticlinorium does not have any warm springs, even though Ordovician rocks are exposed, and even though the Browns Mountain anticlinorium, on the northwest, does have warm springs (Reeves, 1932). The Hurricane Ridge syncline closely parallels the St. Clair fault in the Southern segment but as it approaches the junction zone it gradually changes strike northward and passes to the northwest of the southwest plunge of the Browns Mountain anticlinorium, following a Central Appalachian strike.

Igneous intrusions occur in the Valley and Ridge Province of the Central Appalachians (Dennison and Johnson, 1971) but are as yet unknown in the adjacent part of the Southern Appalachians. Kettren (1970, 1971) documents a large number of intrusives centered in Highland County, Virginia. These include andesite porphyry, andesite, basalt, olivine basalt porphyry, and trachyte. An Eocene age for andesite porphyry from near Monterey and Hightown in Highland County, Virginia was obtained by Fullager and Bottino (1969). A basalt dike near Hightown was observed to cut across an andesite porphyry dike by Dennison and Johnson (1971), who proposed that an igneous body was the source of heat for the warm springs centered south of Monterey, Virginia. In addition to the intrusives named, kimberlites are found in the Purgatory Mountain anticline at Mt. Horeb, Rockbridge County, Virginia (Sears and Gilbert, 1973). This anticline marks the start of the Central Appalachians, immediately northwest of the Blue Ridge, near Buchanan, Virginia.

Other differences in style across the juncture include the presence of coarse post-Cambrian polymictic conglomerates in the Southern section. These include the Fincastle (Middle Ordovician), Bays (Middle Ordovician), Fagg (Lower Devonian), and Cloyd (Lower Mississippian). Fensters(windows) are rare in the Central Appalachians, whereas they are numerous in the overthrust belt of the Southern Appalachians. They include the Read-Coyner, Price Mountain, Christiansburg, and East Radford (of the Pulaski thrust sheet), and Bonsack (of the Max Meadows thrust sheet). Klippen and slices are more numerous in the Southern Appalachians with Round Hill (Roanoke), Calfe Knob, Mill Mountain and others of the Blue Ridge thrust, whereas the Central segment has only the Burketown and Dayton klippen (Butts, 1940) with several slices along the North Mountain fault (Lowry, 1971).

Figure 2. Map showing tectonic features of the Central and Southern Appalachian juncture including the major thrust faults and the major folds of importance in the study area. (Data from Cooper, 1961; Calver, et al., 1963; Cardwell, et al., 1968)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A Roanoke
B Salem
C Blacksburg
D Pulaski
E Pearisburg
F Narrows
G Bluefield
H Princeton
I Union
J New Castle
K Covington
L Hot Springs
M Warm Springs
Rockbridge
Bath
Alleghany
Botetourt
Roanoke
Craig
Montgomery
Monroe
Greenbrier
Giles
Pulaski
Summers
Mercer
Bland
Wythe
Tazewell
Smyth
Russell
Washington
Buchanan
Dickenson
Price Mtn Window
Kent Window
Boissevain Fault
Richlands Fault
Middle Creek Fault
Pine Mountain Thrust
Russell Fork Fault

Ernst Cloos, after working with deformed oolites in the Central segment, was surprised to find oolites of the Cambro-Ordovician carbonates in the Southern Appalachians were relatively undeformed (Lowry, personal communication, June 1976). Apparently deformation was less penetrative in the Southern Appalachians.

STRATIGRAPHY

The stratigraphy of the study area is outlined in Table 1. Formations exposed in the study area range in age from Early Ordovician to Mississippian and are predominantly marine clastics and carbonates. A measured section of Middle Ordovician limestone is given in Appendix 1.

Table 1. Outline of the stratigraphy of the study area.

Age		Description	Thickness
MISSISSIPPIAN	Meramecian / Osagean	Maccrady Formation This unit is composed of red and purple argillite, interbedded with yellow calcareous shales, yellow argillaceous limestones, and several poorly bedded, calcareous cemented sandstones. The calcareous units may contain marine fossils, including brachiopods, pelecypods, and bryozoans.	290-418 feet (88.5-127.5 m.)
MISSISSIPPIAN	Osagean / Kinderhookian	Pocono Group This unit, equivalent to the Price Formation of Montgomery County, Virginia, has several conglomerate zones at the base (Cloyd). The conglomerate grades upward into gray or reddish brown sandstones, many showing cross-bedding. Interbedded with the sandstones are sandy or carbonaceous shales with impure coals present locally. Plant fossils may be found and some zones may include marine fossils.	800-900 feet (244-274.5 m.)
DEVONIAN	Upper	Chemung Group Interbedded greenish gray or olive brown sandstones and siltstones with olive green or grayish green shales make up the Chemung. Sandstone beds may be more than 10 ft. thick locally but are usually 1 to 3 feet and may show ripple marks or contain conglomerate zones. Fossils may be abundant and are dominated by brachiopods. The Brallier and Chemung grade into each other over a fairly thick interval.	1500-1600 feet (257.5-488 m.)

DEVONIAN	Upper	**Brallier Formation** The Brallier is a thick sequence of olive to olive brown, finely micaceous shales, which are interbedded with greenish or tan, fine-grained sandstones in an approximately 1:1 volumetric distribution. The sandstone beds are usually less than 12 in. thick and most are less than 6 in. It is sparsely fossiliferous and what fossils there are are poorly preserved.	1700-1800 feet (518.5-549 m.)
DEVONIAN	Middle	**Millboro Formation** This unit consists of dark gray to black, fissile shale that is thin to thickly laminated. Numerous nodules and concretions occur in several zones some possibly grading laterally into thick-bedded argillaceous limestone. Marine fossils are present, usually concentrated in calcareous zones. <u>Ambocoelia</u> brachiopods and poorly preserved gastropods were commonly observed in the study area. Unweathered Millboro shale contains up to 10 percent pyrite and some of the nodules are septarian and contain iron and other heavy metal minerals.	590-1150 feet (180-350 m.)
DEVONIAN	Middle	**Tioga Metabentonite** A thinly laminated shale of volcanic origin; brownish gray when weathered and containing sand-sized mica flakes. Forms the time marker for the top of the Onesquethaw Stage.	2-6 feet (.5-1.8 m.)

System	Series	Unit	Thickness
		Bobs Ridge Sandstone This unit is a glauconitic sandstone, bright green when unweathered. Dennison (1961) thought the source of sand to be local erosion of Oriskany from islands developed in what is now Monroe County. It lies at the top of the Huntersville Chert, where present, as at Gap Mills.	1-2 feet (.3-.5 m.)
		Huntersville Chert This unit is a cream or gray, massive to medium-bedded chert. It is thin and poorly exposed in the study area.	3-10 feet (.9-3 m.)
DEVONIAN	Lower	Oriskany Sandstone (Ridgeley Sandstone) A brown or gray, medium- to coarse-grained calcareous cemented sandstone, that becomes iron stained when weathered.	0-25 feet (0-7.5 m.)
DEVONIAN / SILURIAN	Lower / Pridoli	Helderberg Group Woodward (1943) reports 65 ft. of Port Jervis Limestone, 28 ft. of Port Ewen Chert, 21 ft. of Healing Springs Sandstone, and 60 ft. of Keyser limestone and sandstone at Paint Bank, Virginia and believed these units to be present in Monroe County. Exposure in the study area is very poor and a thin, cherty, argillaceous limestone is apparently the only part resistant enough to leave outcrop in Monroe County. In Alleghany County, Virginia well developed Keyser limestone and a sandstone, probably equivalent to the Clifton Forge, are present. No evidence of these units could be	72-174 feet (21.9-53.1 m.)

System	Series	Formation and description	Thickness
SILURIAN	Pridoli	found to the southwest.	
	Pridoli	Tonoloway Formation Gray, finely laminated, argillaceous lime mudstone forms this unit. It is apparently unfossiliferous, and outcrop is poor in the study area.	40-60 feet (12.2-18.3 m.)
	Pridoli–Ludlow	Wills Creek Formation–Williamsport Formation The Williamsport Sandstone, a greenish brown, relatively unfossiliferous unit in outcrop to the northeast, and the Wills Creek, a green weathering succession of calcareous shales, mudrocks, and argillaceous limestones were not observed to crop out in the study area although Woodward (1941) believed them to be present through Monroe County.	0-99 feet (0-30.2 m.)
	Ludlow–Wenlock	Keefer Sandstone This unit consists of a fine- to medium-grained, gray-white sandstone of silica-cemented quartz grains. Clay galls and red staining are present at several localities, as well as vertical burrows.	35-50 feet (10.7-15.3 m.)
	Llandovery	Rose Hill Formation This sequence is dominated by dark red, hematite-cemented sandstones. Hematite-cemented conglomerates were also noted in several places. Clay galls may be very abundant locally in the sandstones. Interbedded with the red sandstones are thin, fossiliferous, olive shales and gray or red flaggy siltstones.	200-300 feet (61-91.5 m.)

SILURIAN	Llandovery	Tuscarora Sandstone This unit is a white, massive to medium-bedded, silica-cemented quartz sandstone. Conglomeratic zones may be present near the base. Some reddish or purplish staining is present in middle layers but a shaly interval that divides an upper and lower sandstone units in outcrop to the northeast is not present in the study area.	60-70 feet (18.3-21.4 m.)
ORDOVICIAN	Richmondian	Juniata Formation The Juniata Formation consists of interbedded red shales and fine-grained, medium-bedded, red sandstone. Cross-bedding, ripple marks, and mudcracks, may be present. It is generally thought to be non-marine in origin.	250-350 feet (76.3-106.8 m.)
	Maysville Eden Trenton	Martinsburg Formation The Martinsburg can be divided into three parts. The lower part, termed the Trenton, consists of highly fossiliferous limestone, more or less argillaceous, interbedded with calcareous shales. The middle or Eden part is recognized where limy beds diminish and yellow to gray-brown fissile shale interbeds with light brown thin siltstones and fine sandstones. When the siltstones become thicker and begin to predominate, the section is known as the upper or Maysville. In the study area, rocks of the Maysville assume the color and character of the Juniata, but may be distinguished by the continuing presence of <u>Lingula</u> and <u>Orthorhynchula</u> brachiopods.	1500-1600 feet (457.5-488 m.)

ORDOVICIAN	Trenton	**Moccasin Formation** This unit is a red, gray, or green, argillaceous mudstone, thin- to medium-bedded, with gray interbeds. It contains abundant mudcracks, fossil hash, and a thin sandstone interval.	250-300 feet (289 feet, measured section) (76.3-91.5 m.)
	Black River / Chazyan	**Middle Ordovician Limestones** A lower interval of light to medium gray mudstone with birdseyes grades into a thick section of dark gray Lincolnshire-type limestone with black chert nodules, sparse fossils and algal remains. A thin, argillaceous, flaggy lime mudstone interval occurs within the Lincolnshire that probably represents the Benbolt. The Lincolnshire-type limestone grades upward into zones of alternating limestone and dolomite, and zones of limestone with abundant evidence of the presence of algae including algal biscuit grainstones, and stromatolites (see Appendix 1).	500-650 feet (152.5-198.3 m) (601 feet measured section)
	Chazyan	**Blackford Formation** This unit consists of alternating dolomite and limestone with interbeds of chert-pebble conglomerates. It lies disconformably on the Beekmantown Dolomite and its thickness is highly variable.	0-150+ feet (0-45.8+ m.)
	Canadian	Unconformity	

		Unconformity	
ORDOVICIAN	Canadian	Beekmantown Group Sequence is massive gray dolomite with thin interbeds of lime mudstone. Abundant chert nodules, both black and light gray, are present through most of the exposure. Sandy zones and sandy soil in places suggest the presence of of thin sandstones within the formation but actual outcrops were not observed. Fossils are not abundant but include gastropods, brachiopods, cephalopods, and trilobites. Also present are stromatolites and other evidence of the presence of algae.	2400 feet (732 m.)- maximum exposed along fault in the study area.

ST. CLAIR FAULT

Type Area

The St. Clair fault (Campbell, 1896) was named for the railway station of St. Clair, Virginia during work on the Pocahontas 30-minute folio. St. Clair is located 1.5 miles southwest of Bluefield, Virginia. In the type area Campbell's map shows, in the stratigraphic nomenclature of the day, the Shenandoah limestone (Beekmantown) faulted northwest over the Kimberling shale (Brallier and Chemung) along its whole length except for a slice between St. Clair and Bluefield, West Virginia, where Middle Ordovician limestones are shown faulted over the Kimberling. This, he shows, is caused by a bifurcation of the St. Clair fault that interposes a slice of Middle Ordovician between a splay, on the southeast, and the main fault. He shows the splay dying out southeast of St. Clair, and the Beekmantown reappearing out of an anticline truncated by the main fault. Between St. Clair and Bluefield, he shows the main fault bifurcating northeastward with Upper Silurian and Lower Devonian units isolated in the middle between Middle Ordovician limestone and Brallier-Chemung. Campbell's map through this area is somewhat confusing, and parts do not appear to be logically consistent. Cooper (1944) in work on the Burkes Garden quadrangle, which includes a large part of the Pocahontas folio, gave a more complex, but logically consistent picture of the St. Clair fault in the type area. To the southwest, the

Puckett Hollow anticline is gradually truncated on the southeast by the St. Clair fault, bringing Middle Cambrian Honaker dolomite and younger formations of Cambro-Ordovician carbonates, in sequence, along the southeast side of the fault. These are thrust northwest over Brallier shale until just north of Bell Hill where the fault bifurcates. The bifurcation ends southeast of Bluefield, Virginia, formerly known as Graham. Beekmantown and Middle Ordovician limestones are caught between the main fault, on the northwest, and its splay. At St. Clair junction, the fault loses stratigraphic displacement and Millboro shale appears from under the fault on the northwest side. Stratigraphic throw continues to be lost until Beekmantown is faulted over Silurian units where the faults rejoin. Half a mile northeast of where the faults rejoin the St. Clair fault again bifurcates; this split rejoins southeast of Bluefield, West Virginia. The Hurricane Ridge syncline in this region closely parallels the northwestern (main) branch of the fault; the overturned hanging wall units form the southeast limb of the syncline. Along this part of the fault the Hurricane Ridge syncline is relatively narrow and highly asymmetrical. The Richlands and Boissevain faults cut the Abbs Valley anticline northwest of the syncline. Northeast of Bluefield the St. Clair fault remains relatively uncomplicated to its termination in Alleghany County, Virginia.

It is perhaps unfortunate that the type area for the St. Clair fault happens to be in the complicated Bluefield area, since for most of its length, northeast of Russell County, Virginia, the St. Clair fault is structurally simple; it generally consists of a single break with Beekmantown dolomite faulted over Lower Devonian shale, or Silurian and Ordovician units towards the terminus.

Southwest Extent

Southwest of its type area, the St. Clair fault can be traced for roughly 40 miles without doubt of its identity. This takes the fault through Tazewell County, Virginia. Just past the boundary of Tazewell and Russell Counties, Virginia, the St. Clair fault splits into two segments. The northwestern segment joins the Russell Fork fault which terminates the Pine Mountain thrust on the northeast (Figure 2). The southeastern segment crosses the Russell Fork fault and continues southwest, where it becomes known as the Honaker fault. Northwest of the Honaker thrust, the Hunter Valley, or St. Paul thrust, diverges from the Russell Fork fault and continues southwest, roughly paralleling the Honaker thrust (Cooper, 1961; Harris and Milici, 1977; King, 1961; Woodward, 1938). These two faults continue to parallel each other to the southwest, until after crossing the Virginia-Tennessee border the two faults join to form a single fault. Two short bifurcations recur and end to the southwest. Northwest of Knoxville, Tennessee the fault joins the Wallen Valley fault, just southeast of where the Jacksboro fault forms the southern termination of the Pine Mountain thrust (Harris and Milici, 1977; King, 1961). The now combined Wallen Valley and Hunter Valley fault continues to the southwest in a broad gentle arc, concave to the southeast. This fault finally dies out in northwestern Georgia, about 35 miles northeast of the town of Centre (King, 1961). Thus the name St. Clair is applied to the northernmost 110 miles of a fault system approximately 375 miles in total length.

Trace of the Fault Northeast of the Type Area

Northeast of its type area the St. Clair fault traverses Mercer County, West Virginia in the valley northwest of East River Mountain, roughly parallel to the Virginia-West Virginia border. Through this county, the St. Clair fault is a single break with Lower Ordovician Beekmantown Group faulted northwest over the Devonian Brallier or Millboro Formation. The fault passes through Giles County, Virginia, south of Glen Lyn, crosses the New River northwest of the Narrows, and passes into Monroe County, West Virginia, 1.5 miles southeast of Peterstown. Through this area, as shown by the exposure northwest of the Narrows, the St. Clair fault truncates the overturned southeast limb of the Hurricane Ridge syncline. At the Narrows, along U.S. Route 460, Beekmantown dolomite is faulted northwest over overturned Brallier siltstones and shales, which exhibit minor drag folding and shearing. The dip of the overturned beds, which is the approximate dip of the fault, is about 25° SE. The dip of the Beekmantown dolomite on the hanging wall is about 20° SE. Paralleling Peters Mountain, the fault continues its simple relation until two miles south of the community of Zenith, West Virginia where stratigraphic throw is gradually lost to the northeast, as Silurian Rose Hill and Tuscarora formations appear from under the fault. Before reaching the study area, Lower and Middle Silurian units are again lost beneath the fault. The St. Clair fault enters the study area at Crimson Springs, West Virginia, southwest of Gap Mills, where Beekmantown dolomite is faulted over overturned Upper Silurian strata.

The hill north of Crimson Springs is essentially the beginning of Gap Mountain; it is held up by Keefer, Rose Hill, and Tuscarora formations, which appear in succession from under the fault just north of the Crimson Springs road (Plate 1). The St. Clair fault continues straight across the valley through which the road passes. Its trace follows the streams of joining tributaries of Turkey Creek. Stratigraphic throw continues to be lost to the northeast, bringing up the Juniata and Martinsburg formations, until Beekmantown dolomite is faulted against Middle Ordovician limestones. A number of sink holes are developed in the overturned limestones, which form a valley between Gap Mountain and the Beekmantown ridges east and northeast of Crimson Springs. As the fault reaches Turkey Creek, it makes a sharp swing to the north and begins cutting out the formations on the northwest side (Plate 1). Where Beekmantown is again faulted over Martinsburg, the fault trace swings east and parallels Gap Mountain along its southeast base. The result is a lens-shaped wedge of formations trapped between the fault and an arc formed by Gap Mountain as it gains elevation. The fault continues northeast, parallel to Gap

Mountain, slowly gaining stratigraphic throw and cutting out the Martinsburg before reaching Gap Mills, a distance of 3.5 miles. At Gap Mills, Beekmantown is faulted over the Upper Ordovician Juniata Formation, which is overturned and dipping about 41° southeast, which approximates the dip of the fault. Continuing through Gap Mills, the fault passes northeast along Gap Mountain for 2.3 miles where the Martinsburg again appears along the northwest side. The fault trace moves away from the base of Gap Mountain, gradually exposing more of the Martinsburg to the northeast as Gap Mountain makes a gentle arc, concave to the southeast, above the exposed Martinsburg. Tuscarora outcrop on Gap Mountain is overturned along most of this length with dips ranging from 40° to 80° southeast. Limestone units of the lower Martinsburg crop out along the fault here and do not appear overturned, although bedding is difficult to determine because of the massive nature and rounded weathering of the outcrops. As Gap Mountain begins to swing back to the east, forming an arc concave to the southeast, Martinsburg is again lost on the northwest side of the fault. The fault trace gains elevation on Gap Mountain and stratigraphic throw is gained until the recess between High Head Mountain and Moss Mountain (Plate 2) is reached. At this point, Beekmantown dolomite is faulted northwest over the Rose Hill Formation, and the fault trace is just southeast of the mountain crest. From southwest of Gap Mills to the recess, the trace of the St. Clair fault is quite straight with a strike of about N. 64° E. The straight trace is relatively unaffected by loss or gain in stratigraphic throw along Gap Mountain.

Northeast of the recess, the fault continues along its straight trace. Tuscarora, Juniata, and Martinsburg are brought up in succession on the northwest with Tuscarora forming the crest of Moss Mountain. Southeast of the peak comprising Moss Mountain, the St. Clair fault apparently splits into two branches. The southeast segment continues on the same strike it had been following, losing stratigraphic displacement along the way. Where displacement has been lost such that Beekmantown is faulted over itself, the fault makes a sharp swing to the north, then arcs back to the east following an unnamed tributary of Cove Creek. The trace of the northwest segment swings north, gains elevation on Moss Mountain, and brings a slice of Tuscarora and Juniata to the crest of the northeast peak. Thus, along this peak the Tuscarora is doubled up (Plate 1). From the peak, the fault swings east, elevation is lost, and stratigraphic throw is gained as older units become exposed on the southeast, and progressively younger units are lost under the fault on the northwest. Along the tributary of Cove Creek, mentioned above, the two branches of the St. Clair fault rejoin and Beekmantown is here faulted over Lower Devonian strata. From there, the fault crosses Back Creek Mountain Road, where Beekmantown is faulted over Oriskany Sandstone. The fault trace passes into Alleghany County, Virginia along a steep valley between two unnamed ridges east-northeast of Moss Mountain. The trace crosses Virginia Route 311 at the sharp bend immediately preceding its intersection with Virginia Route 600. At the intersection, a profound change in the structural character of the rocks on the northwest side of the fault may be observed. Instead of being neatly overturned and stacked as the Juniata to Maccrady units are at Gap Mills, a series of very tight folds are developed. The folds, whose axial traces strike about N.30° E., plunge southeast at an acute angle to the fault, whose trace strikes about N.50° E. The fault proceeds in a gentle arc, concave to the southeast, along the southeast edge of Snake Run Ridge. As the fault trace approaches the drainage divide, caused by the ridge connecting High Point, on Peters Mountain, with Thomas Spring, on Snake Run Ridge, the Beekmantown dolomite, Middle Ordovician limestones, and Moccasin Formation are lost on the southeast. At this point Martinsburg is faulted upon itself. That a fault is still present is evidenced by the observation that belts of evergreen trees, following the carbonate units in the Lower Martinsburg, along both blocks, are offset along the fault trace; the belt on the southeast limb continues farther northeast before being truncated by loss of Martinsburg carbonates beneath the fault. As the fault trace continues toward Morning Knob, competent Silurian units on the footwall block are no longer overturned. These units on Snake Run Ridge and Peters Mountain continue to converge as though in a plunging anticline. Near the nose of the structure the Tuscarora on the northwest limb of the Morning Knob anticline becomes overturned and its outcrop trace is lost for an interval where it should have connected with the outcrop belt from Peters Mountain at Morning Knob. In a stream valley, north of Morning Knob, an outcrop of intensely brecciated Keefer Sandstone plunges into a hillside between the diverging limbs of a syncline in poorly exposed Devonian rocks. This is where all surface evidence for the St. Clair fault apparently ends.

Features Along The Fault

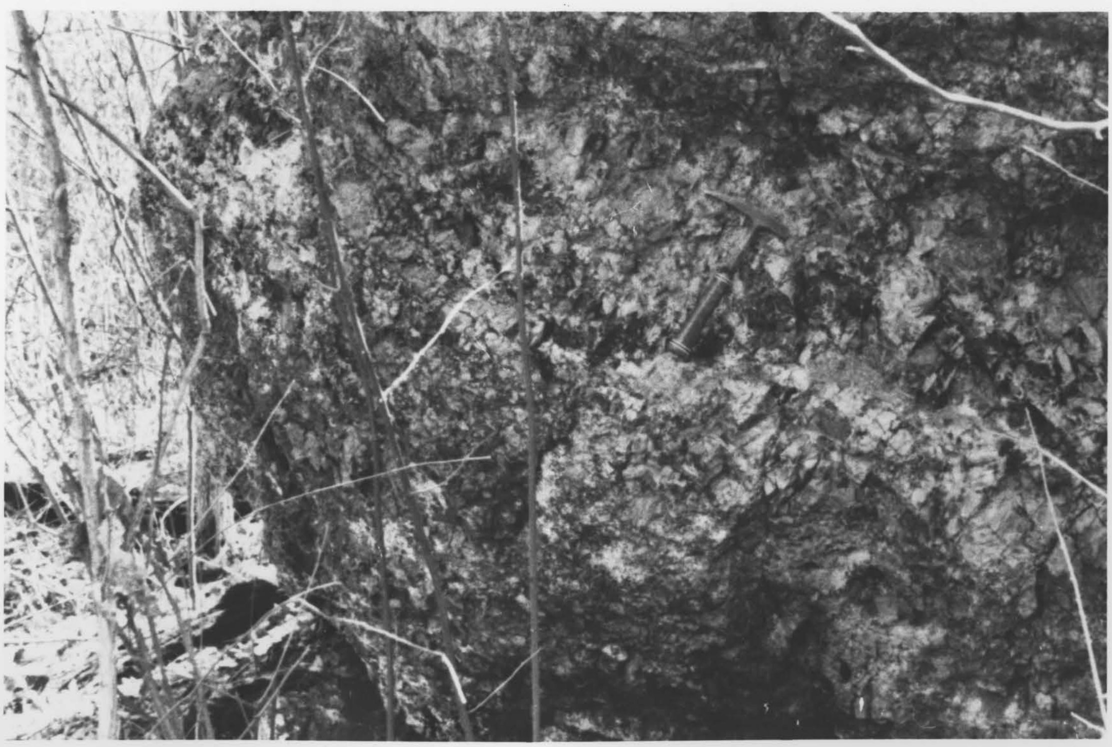
Some features that are associated with the St. Clair fault, in the study area, include brecciation, manganese and iron mineralization, and cross faulting. Brecciation and manganese-iron mineralization appear to be related phenomena along the St. Clair strike belt as well as the Narrows fault to the southeast.

Cooper (1944) described fault breccias in the type area of the St. Clair fault as including chert fragments in a matrix of psilomelane or manganite. The outcrop he describes occurs along the fault from the St. Clair station, southwest to between Tiptop and Witten Mills. He also found breccias with a hematite matrix where the fault contact included Rose Hill Formation in proximity or actual contact. Cooper also mentions deposits of brown limonite and hematite along the Narrows fault on the southeast slope of Buckhorn Mountain. At this locality, Ordovician limestone on the hanging wall is impregnated with and partially replaced by iron oxides whose apparent source is the Rose Hill, as the deposits are thickest where the fault is in contact with this formation. Brown limonite also occurs along the St. Clair fault and was mined at Bell Hill, southwest of Bluefield, Virginia.

Stose and Miser (1922) in their study of manganese deposits in western Virginia thought the manganese to have been originally disseminated in Lower Knox and Lower Devonian limestones and sandstones. It was gradually leached out by ground water and it tended to be redeposited in fractured zones of adjacent sandstones such as the Tuscarora, Keefer, or Oriskany. It may also replace weathered dolomite, and thus form a matrix for fragments of fractured chert which originally were present as nodules in the dolomite. Initial fracturing of the rock seems to have been important to both removal and redeposition of the manganese. A similar mechanism may explain the presence of breccias with a hematite or limonite matrix with the source of iron apparently being the Rose Hill and Oriskany Formations (Cooper, 1944; Reger, 1926).

In the study area, breccias similar to those described by Cooper (1944) are found at several locations. The exact distribution of breccias along the fault cannot be given, however, because deep weathering has obscured the fault contact along most of its length. The primary exposure of breccias along the fault are in manganese mines located in the recess between High Head Mountain and Moss Mountain. Prominent in this location are breccias consisting of angular chert fragments set in a matrix of psilomelane; these are similar to those described by Cooper in exposures along the St. Clair fault in its type area. These breccias and accompanying ore occur along the Beekmantown side of the fault, where the original dolomite and included chert were apparently intensely fractured. The general consensus among those who have studied these deposits is that residual

Plate 3. Examples of mineralization and brecciation occurring at the recess. The top photograph shows combined iron and manganese mineralization on the bedding plane of highly fractured Keefer Sandstone. Bottom photo shows a slumped boulder of breccia consisting of angular fragments of Keefer Sandstone cemented with hematite. This breccia forms cliffs along the northwestern slope of the recess.



weathering and solution resulted in replacement of dolomite with psilomelane, leaving fractured chert suspended in the replacing material (Ladd, 1943; Stose and Miser, 1922). The presence of angular chert fragments at this locality, at those mentioned by Cooper (1944), and at localities mentioned by Stose and Miser (1922) may indicate that original intense fracturing of the rock plays a key role in determining the location of these deposits.

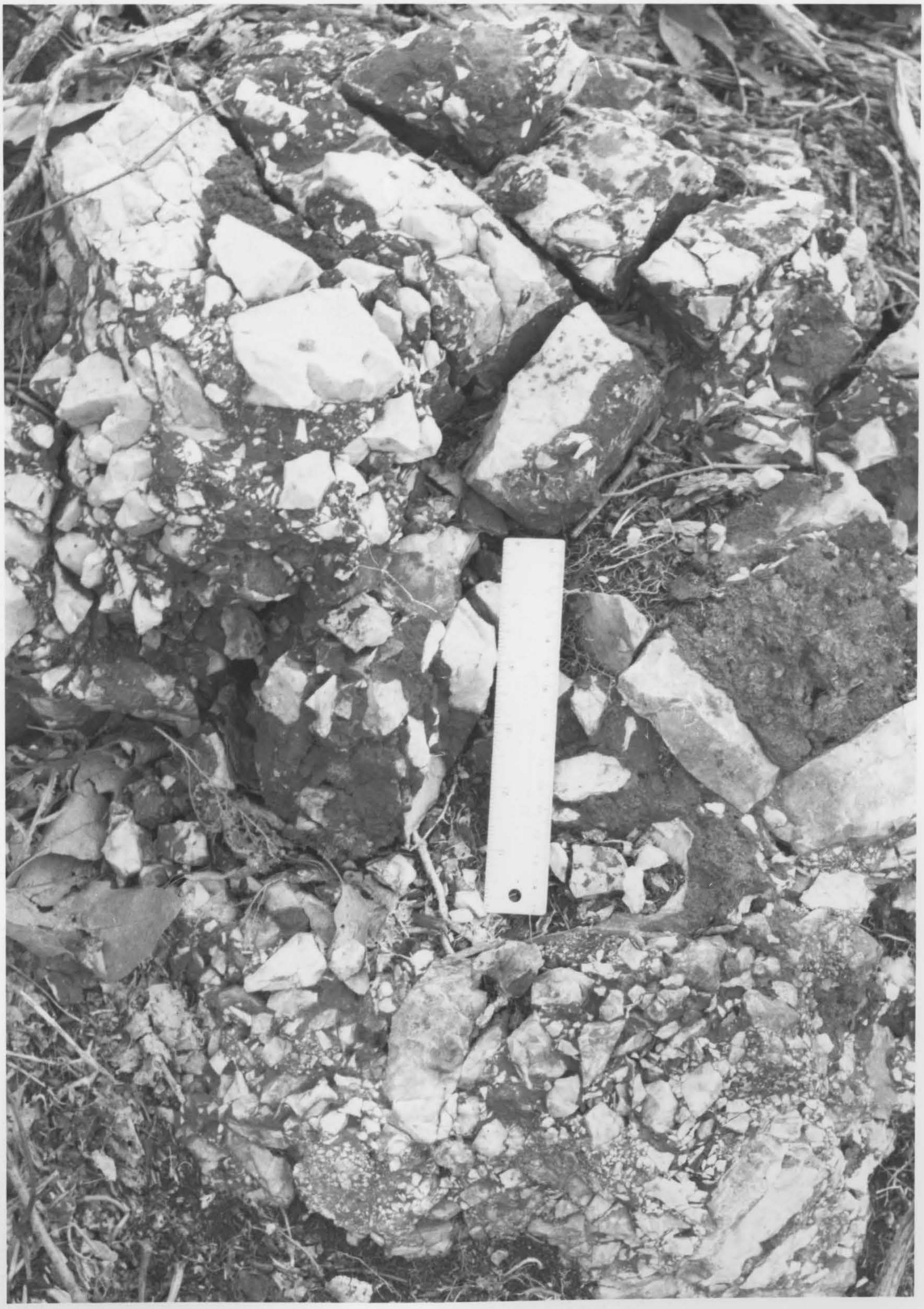
The other type of breccia, mentioned by Cooper as occurring in the type area of the St. Clair fault, consists of iron- or manganese-cemented brecciated sandstone. This type also occurs through the recess. Keefer Sandstone, which forms cliffs on the northwest side of the recess, is intensely brecciated and cemented with a matrix of hematite along this part of its outcrop. The source of the hematite is undoubtedly the Rose Hill, which crops out between the fault and the sandstone. Within the Rose Hill itself, evidence of brecciation can be found although outcrop of this formation is poor. Angular sandstone clasts may be found included in a matrix of what appears to be red mudrock. The surfaces of this red mudrock may be wavy and give the impression of a former plastic state. The sandstone fragments range in size from 1 to 7 cm., and they appear to be Cacapon-type (red hematite-cemented) sandstones, with a bleached appearance, as though some hematite cement had been leached out.

The precise structural significance of these breccias is difficult to determine since there is no quantitative way to deal with them. In addition to the brecciation, incipient crenulation cleavage may be found in some of the Devonian shales on the northwest side of the recess, although no metamorphic minerals appear to be present. This and the presence of the breccias serve to indicate, at least qualitatively, that the recess was more intensely deformed than adjacent parts along the fault.

Brecciation is also associated with a cross fault that occurs between the two peaks of Moss Mountain. This is a left lateral fault with about 150 yards of offset. Angular fragments of Tuscarora Sandstone and Rose Hill sandstones are scattered along the trace in a matrix that is apparently a mixture of hematite and psilomelane. The source of both the iron and manganese appears to be the Rose Hill (Plate 1; see photograph , Plate 4).

The most widely exposed breccias in the study area occur as zones of intense fracturing and recementation in Keefer, Tuscarora, and Oriskany sandstones, either tightly folded or overturned, along the footwall block of the St. Clair fault. Along Gap Mountain, from McGlone to High Head Mountain, the Tuscarora Sandstone, which forms the crest, is brecciated and hematite-cemented at periodic intervals. These zones of brecciation are expressed topographically as shallow saddles between regions of maximum elevation, along Gap Mountain. There is no apparent offset along these zones until Moss Mountain is reached (Plate 1). With loss of Tuscarora and Keefer outcrop, exposures of other formations becomes poor northeast of Moss Mountain; thus breccia exposure is lost. Within the tight folds of the Snake Run area on the footwall block of the St. Clair fault in Allegheny

Plate 4. Example of breccia occurring along the cross fault between the two peaks that comprise Moss Mountain. Fragments of Tuscarora Sandstone are scattered along the trace in a matrix of hematite and manganese oxides.



County, Virginia, breccias again become evident. Along the northwest side of Snake Run Ridge, the Keefer sandstone is brecciated and re-cemented with hematite in numerous zones. The Tuscarora does not exhibit nearly as much brecciation as the Keefer, but contains what appear to be pressure solution seams, or stylolites, that spread through the rock. Along the unnamed ridge northwest of Snake Run Ridge, brecciation does not appear to be significant. In the valley between the two ridges, however, the Oriskany Sandstone exhibits intense brecciation in places, with either an iron or manganese or combination matrix. An exposure of this breccia may be seen along Virginia Rt. 604 between Iron Hill Springs and Earlhurst. In the Crow Run Valley, northwest of Snake Run Ridge, breccia float was found that included fragments of Oriskany, Huntersville Chert, and Rose Hill, with a hematite cement. Outcrop of this breccia was not observed and it is possibly lithified colluvium rather than a tectonic breccia. The breccias in this area appear to be associated with tight folding of brittle units and no outcrop evidence could be found to suggest that a fault or faults are present and responsible for the presence of the breccias, although this possibility must be aknowledged.

The last major outcrop of breccia occurs at the nose of the Morning Knob anticline, where evidence for the continuation of the fault is lost. This outcrop consists of brecciated Keefer Sandstone with a hematite matrix; it occurs in a stream valley just north of Morning Knob in Alleghany County, Virginia. The source of the hematite is, again, apparently the Rose Hill.

A number of questions need to be answered before an understanding of the significance of these breccias can be achieved. One major problem is the formation of the matrix. Stose and Miser (1922) have fairly well established that the psilomelane-manganite cemented chert, in the Beekmantown Group, is formed by a replacement process. In the hematite-cemented sandstones, however, the mechanics and timing of matrix formation is less clear. For example, in some of the breccias the resulting rock is clearly grain-supported, with the matrix forming a filling of interstices. In other examples, however, the matrix may constitute a major portion of the rock and the sandstone fragments "float" within it. This discrepancy makes it difficult to ascertain the timing sequence of matrix formation. In view of the widespread occurrence of these breccias, it is surprising that a large scale study of them has not taken place. Large scale mapping with petrographic studies of these breccias would surely shed light on the structural development of the Appalachians.

Termination of the St. Clair Fault

As already stated, the St. Clair fault loses stratigraphic displacement and dies out down the plunge of an anticline in Alleghany County, Virginia (Plate 1). At the nose of this structure, the Tuscarora outcrop is overturned, and a segment is missing where Tuscarora of both blocks should have connected as in a simple plunging anticline. Further evidence of shear at the core of this structure is the already described outcrop of brecciated Keefer which occurs to the northeast. Tracing of this shear zone becomes impossible as blanketing Devonian shales cause loss of outcrop. Due to the incompetence of these shales they may act as a cushion and further mask any shear occurring within the more competent units in the subsurface. Drag folds asymmetric both to the northwest and southeast as well as minor thrusts are present in the Martinsburg along the northwest side of Peters Mountain. These may attest to relative differential movement between the competent Lower and Middle Ordovician carbonates and Upper Ordovician and Silurian clastics. The incompetent Martinsburg clearly acted as a cushion or lubricant during deformation. Thus where Martinsburg became faulted upon itself as stratigraphic displacement was lost towards the apparent termination, the development of an anticlinal terminus in formations younger than Martinsburg may have been hastened, and a fault may exist at depth northeast of its obvious termination at the surface.

In comparing the termination of the St. Clair fault with the terminations of the other major faults of the Southern Appalachians, one finds a general similarity. The Pulaski-Staunton fault passes east of Harrisonburg, Virginia, with Conococheague carbonates faulted northwest over Beekmantown carbonate. Northeast of Harrisonburg, stratigraphic displacement is lost until about 2.25 miles southwest of Endless Caverns, where Conococheague and Chepultepec carbonates are lost on the hanging wall side. At this point, Beekmantown is apparently faulted upon itself. Two miles to the northeast, at Endless Caverns, the Beekmantown plunges out in what is apparently a normal anticline (Brent, 1960). Brent mentions the occurrence of breccias along the fault but does not elaborate as to kind nor does he mention any presence of breccia at the termination.

The Saltville fault likewise dies out down the plunge of an anticline at New Castle, Virginia. As the Sinking Creek anticline plunges out, considerable stratigraphic displacement has been lost along the fault so that it takes on the character of a high angle reverse fault (Bregman, 1967). As the Ordovician and Silurian units plunge out, Bregman found that these units are offset at the fault contact where they would have joined in a simple plunging anticline. Bregman interpreted this as a component of oblique slip on the fault plane. Like the St. Clair, evidence for the continuation of the Saltville fault is lost under the cover of Devonian shales at the nose of the anticline. Bregman does not mention the presence of breccias at the termination but, apparently, exposure of the fault is poor.

Detailed mapping of the Narrows fault termination has not been done but Butts (1940) shows the fault abruptly losing stratigraphic displacement near the border of Giles County, Virginia and Monroe County, West Virginia, and dying out down the plunge of a local culmination that forms part of the Rich Patch anticline, in Middle and Upper Silurian units in Craig County, Virginia.

Plate 5. The outcrop of brecciated Keefer Sandstone that occurs at the apparent surface termination of the St. Clair fault. The angular fragments of sandstone are of various sizes. In parts of the outcrop the hematite matrix is a filling of interstices in a grain-supported rock but in other parts the sandstone fragments "float" within the matrix.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From the similarity of the terminations, it seems that thrust faults of the Southern Appalachians are analogous to the major anticlinoria of the Central Appalachians. Apparently fault movement increases southwest of their noses but limits exist as to the amount of movement on any one fault, with less relative movement on succeeding faults from southeast to northwest. Also, faults of the overthrust belt penetrate much farther into the Central Appalachians than do the faults occurring to the northwest. The northwestern faults appear more strongly affected by the Central and Southern Appalachian juncture and die out either before, at, or slightly northeast of the junction zone.

Displacement Along The St. Clair Fault In The Study Area

Estimating actual slip along a thrust fault using only surface data is difficult. Comparing the age of the rocks on the hanging and footwall block is unfortunately misleading. For example, if the southwestern end of the study area, where Beekmantown is faulted over Tuscarora, were compared with the Snake Run Ridge area where the same situation is found, qualitatively, one could conclude that slip is about the same. The fault has steepened considerably, however, and as the fault soon dies out to the northeast, real slip must be considerably less at Snake Run Ridge than to the southwest. About the only way to estimate the amount of slip is to extrapolate a cross section at depth and determine the stratigraphic separation apparent across the fault. This value is essentially the minimum amount of slip that is present. In the study area, estimates of stratigraphic separation have been made at cross-sections A-A' and C-C' (Plate 1B). At A-A' approximately 6600 feet of stratigraphic separation is present along the projected fault plane. At C-C' the same units as at A-A' are in fault contact but because the fault has steepened, the stratigraphic separation is only slightly over 4000 feet. The latter amount is still considerable separation considering that the fault apparently dies out shortly to the northeast. This may be further indication that the Martinsburg does cushion, somewhat, the fault movement in the older units.

REGIONAL STRUCTURES: THEIR RELATION TO THE STUDY AREA AND BEHAVIOR AT THE JUNCTURE

Introduction

The behavior of regional structures as they approach and traverse the junction zone is important to the understanding of this feature. Although the major structural feature of the study area is the St. Clair fault, observations on surrounding regional structures should provide insights concerning the reasons for the observed structural changes along the fault. Of most importance are the Hurricane Ridge syncline and Abbs Valley anticline, but also significant in this area along the northwestern part of the Valley and Ridge Province, are the Browns Mountain, Wills Mountain, Warm Springs, and Rich Patch anticlines.

Description

The Hurricane Ridge syncline is a long, broad, doubly plunging structure intimately related to the St. Clair fault in the Southern Appalachian segment. Named by Campbell (1896) for its occurrence along Hurricane Ridge in Mercer County, West Virginia, this feature originates in southwest Virginia at about the Russell-Tazewell County line, 3 miles south of Richlands. Striking northeast, the axis of the fold proceeds 35 miles where it enters Mercer County, West Virginia, northwest of Bluefield. Passing south of Princeton, the axis crosses the New River 1 mile north of Glen Lyn and passes through Peterstown into Monroe County, West Virginia. Following Rich Creek and paralleling Little Mountain, the axis continues northeast in Monroe County. Northwest of Rock Camp, the axis begins a slow change of strike to the northwest and passes just northwest of Union. Reger's map (1926) shows the axis then changing strike back to the northeast and passing into Greenbrier County, West Virginia northwest of Pleasant Valley School. Ogden (1976), however, found that the axis does not make this northeast divergence but instead continues a more northerly trace and passes into Greenbrier County near the town of Patton. Reger (1926) thought that the Hurricane Ridge syncline died out shortly after passing into Greenbrier County. Ogden's repositioning of the axis suggests it may connect with the Caldwell syncline, shown dying out at the Greenbrier-Monroe County border, near Patton, on the West Virginia Geologic Map (Cardwell, Erwin, Woodward, 1968). This information was derived from the Greenbrier County Report (Price and Heck, 1939). If this is the case, the Hurricane Ridge syncline extends approximately 17 miles farther north than previously thought, to just southeast of Gardner in northern Greenbrier County. The total length of this fold would then be 109 miles instead of the 92 miles originally estimated by Reger. In the Southern Appalachians the Hurricane Ridge syncline is strongly asymmetrical; its southeast limb is overturned and broken by the St. Clair fault. The northwest limb is here wide and gently dipping to the southeast. As the syncline changes strike to the northwest in Monroe County, the southeast limb is no longer overturned and the dip gradually becomes gentle to the northwest. Units exposed in the Hurricane Ridge syncline range in age from Silurian and Devonian along the northwest side of the St. Clair fault to the Upper Mississippian Bluestone Group member of the Mauch Chunk. Thomas (1959, 1966) reports that Lower Pennsylvanian sandstones, which cap several topographic highs northwest of Bluefield, lie angularly unconformable on the Mississippian. Ryan (1969) examined one of these outcrops near the Mercer County Airport and thought the Pottsville Sandstone was out of place float, thus placing the unconformable relation in question. The Mauch Chunk of the Hurricane Ridge syncline includes a composite thickness of over 3800 feet of strata, predominantly deltaic-fluvial clastics. Paleoslope, facies gradient, and transport indicators show sediment influx from the southeast (Swires, 1972). The maximum structural depression in the syncline occurs between the towns of Bluefield and Princeton in Mercer County, West Virginia, according to structural contours on the Avis Limestone (Reger, 1926). This region roughly corresponds to the area of maximum thickness of post-Maccrady Mississippian units exposed in the trough of the syncline (Cooper, 1961; Thomas, 1959, 1966). Turbidity flow deposits, mudflow conglomerates, and penecontemporaneous slump structures indicate that the synclinal axis and axis of maximum sediment accumulation are coincident (Thomas, 1966). Polymictic conglomerates indicate exposure of pre-Mauch Chunk Paleozoic rocks in the source area. Cooper (1961) thought that pre-

Mississippian stratigraphy indicated that the area where the Hurricane Ridge syncline is now located was near the edge of the Paleozoic foreland shelf. Although sediments of Mauch Chunk age are widespread in the Appalachians, the unique character and thickness distributions of the sediments in the Hurricane Ridge syncline indicate that it formed a distinct basin with a nearby source area to the southeast.

The Abbs Valley anticline is the complementary fold to the northwest of the Hurricane Ridge syncline, south of the juncture, and provides an interesting insight into the contrast in geologic "styles" along strike from southwest to northeast. This fold was named by Campbell (1896) for its occurrence in Abbs Valley, in Tazewell County, Virginia, south and southeast of Pocahontas. Traced southwest, this anticline is entirely replaced by the Richlands fault 5.75 miles southwest of the town of Boissevain (Harnsbarger, 1919). The Boissevain fault, an en echelon extension of the Richlands fault, follows the northwest limb of the Abbs Valley anticline to the northeast into Mercer County, West Virginia. The Richlands fault and the Boissevain fault parallel each other to the southwest with the Boissevain fault bifurcating 1.5 miles east of Sayersville. The new fault on the northwest, thus formed, was named the Middle Creek fault by Harnsbarger. The three faults continue southwest and rejoin to form a single fault at Raven, Virginia near the Tazewell-Russell County line. The fault dies out shortly thereafter, northwest of the southern end of the Hurricane Ridge syncline. Thus, from the juncture southwest, the transition is from single fold to fold and fault; fold and fault to two faults (one replacing the fold); and two faults to three faults with the three segments only rejoining and dying out just north of the Pine Mountain thrust block. Three major culminations occur on the Abbs Valley anticline, in two cases exposing Greenbrier Limestone at the core. One occurs from just south of Pocahontas, Virginia to just north of Princeton, West Virginia. A saddle northeast of Princeton divides the major culmination from the two to the northeast in Monroe County, West Virginia. One is centered on Chestnut Hill, near the Monroe County-Summers County border; the other, centered on Johnson Crossroads, northwest of Union (Reger, 1926). Like the Hurricane Ridge syncline, the Abbs Valley anticline gradually changes strike to the northwest as the junction is approached (Reger, 1926; modified by Ogden, 1976). The Abbs Valley anticline and its southwest replacement and extension, the Richlands fault, together form the complementary structure to the northwest of the Hurricane Ridge syncline throughout their length southwest of the juncture. This relationship is lost as the folds diverge to the northwest in central Monroe County.

Reger (1926) mapped four folds that plunge to the southwest from the Central Appalachian segment; these interfinger with and separate the Abbs Valley anticline and the Hurricane Ridge syncline for the length of their plunge. These folds, traces modified by Ogden (1976), form a wedge-shaped zone of divergence, at the juncture, separating folds closely related for long distances in the Southern segment.

The Abbs Valley anticline plunges out in northern Monroe County, southeast of Alderson (Reger, 1926).

The Browns Mountain anticlinorium has been considered by various workers as belonging to the Valley and Ridge Province (Cecil, 1971), the Plateau Province (Rodgers, 1970), or as a separate sub-province, the High Plateau of Gwinn (1964). Of interest in this context is the fact that the Hurricane Ridge syncline, considered to be the first fold northwest of the Allegheny Structural Front in the Southern segment, and its possible extension, the Caldwell syncline, form the first major fold northwest of the Browns Mountain anticlinorium at its southwestern nose. Consistency of definition would argue for including the Browns Mountain anticlinorium in the Valley and Ridge Province. Units exposed on the flanks and core of the structure are primarily of Silurian and Devonian age. A small exposure of Upper Ordovician Juniata and Martinsburg formations occurs in the bed of Knapp Creek near Minnehaha Springs (Cecil, 1971). Stratigraphic units show considerable depositional thickening relative to units exposed in Monroe County, particularly in the Middle to Upper Silurian and Lower Devonian. The Rochester Shale and McKenzie Formation appear; Upper Silurian and Lower Devonian carbonates are very well developed in comparison to exposures in Monroe County. An interesting feature of the Browns Mountain anticlinorium is the presence of well documented thrust fault systems occurring throughout. Multiple repetition of units is common on the northwest limbs of anticlines, as well as bedding-plane thrusts of competent Silurian units over Devonian shales (Cecil, 1971; Renton, personal communication, June 1974). As the anticlinorium plunges southwest from its maximum development in northern Greenbrier County and Pocahontas County, units up through Middle Devonian are lost just south of White Sulphur Springs. A series of folds persist in Upper Devonian and Lower Mississippian units southwest into Monroe County. Plunging out east and southeast of Union, these folds separate the Hurricane Ridge syncline, now diverging off to the northwest, from a series of folds developed en echelon to the southeast. These folds, of short length, include the Kates Mountain syncline, Glace anticline, Pedro syncline, Nigger Mountain anticline, Wolf Hills syncline, and Dameron Mountain anticline (Cardwell, et al, 1968; Ogden, 1976; Reger, 1926)(Plate 1, Figure 2).

Southeast of the Browns Mountain anticlinorium, the southwest extension of the Nittany anticlinorium, of Pennsylvania, separates into two distinct en echelon folds known as the Wills Mountain anticline, on the northwest, and the Warm Springs anticline, on the southeast (Rodgers, 1970). The Wills Mountain anticline is first recognized as a persistent fold near Cumberland, Maryland. Extending southwest through Virginia and West Virginia, the fold nearly plunges out into Lower Devonian shale north of Hot Springs in Bath County, Virginia. An en echelon extension appears immediately to the southwest and this low amplitude fold persists from Hot Springs to Callaghan in Alleghany County, Virginia. At Callaghan, the fold increases in amplitude and Silurian rocks are exposed at the core. This sharp anticline forms the northeast extension of Peters Mountain that terminates at the Thomas Spring-High Point saddle in the study area (Plate 1). Thus this fold terminates on the northwest side of the St. Clair fault about where it loses most of its stratigraphic displacement. The Warm Springs anticline proceeds southwest, paralleling the Wills Mountain anticline to the northwest. As the Wills Mountain anticline plunges out northwest of Hot Springs, the Warm Springs anticline increases amplitude beginning northeast of Warm Springs, and Ordovician carbonates are exposed in the core. From the culmination east of Healing Springs, the anticline gradually plunges out toward Covington. Interestingly, this culmination of the Warm Springs anticline occurs southeast of where the Wills Mountain anticline nearly plunges out. As the Warm Springs anticline plunges out towards Covington, the Wills Mountain anticline gains amplitude. The Lower Devonian is lost down the plunge of the Warm Springs anticline south of Covington. The exact relationship between the Warm Springs anticline and the St. Clair fault is unknown, but their connection by low amplitude folds in the Upper Devonian is a strong possibility. Thus, as the St. Clair fault loses its stratigraphic throw, the last fold generated on the hanging wall connects with the Wills Mountain anticline and the anticline down whose plunge the fault is lost is probably related to the Warm Springs anticline; both of these folds extend for a long way into the Central Appalachians and are traceable through Pennsylvania as the Nittany Mountain anticlinorium (Butts, 1940; Cardwell, et al, 1968; Reeves, 1932; Rodgers, 1970; Stose and

Miser, 1919)(Plate 1). The axis of the Warm Springs anticline follows a strike of about N.35° E., which is a typical Central Appalachian strike. As the fold plunges out near Covington, it abuts the Rich Patch anticline whose axis follows a Southern Appalachian strike of about N.59° E. The Rich Patch anticline plunges northeast at Longdale, Virginia, northeast of Iron Gate. A local culmination occurs centered on the town of Rich Patch in Allegheny County, Virginia, where Ordovician rocks are exposed at the core. To the southwest a second culmination that exposes Ordovician rocks is centered on the Monroe County, West Virginia-Craig County, Virginia border, southeast of Paint Bank. A reverse fault, called the Sugar Grove fault by Reger (1926), cuts the Ordovician rocks at this exposure. Continuing to the southwest, through the southeast extension of Monroe County, the anticline proceeds into Giles County, Virginia. The Narrows fault here cuts the northwest limb of the anticline, apparently dying out before entering Monroe County to the northeast (Butts, 1940).

Rodgers (1970) thought that the Narrows fault-Rich Patch anticline and the St. Clair fault-Morning Knob anticline are analogous in their relationship to the Wills Mountain-Warm Springs anticlinal pair. As work in the study area (Plate 1) and previous generalized mapping show, this is not strictly true. The St. Clair fault gives rise to two Central Appalachian structures at its termination, the Wills Mountain and Warm Springs anticlines. The Rich Patch anticline plunges to the northeast along a Southern Appalachian strike and appears to have no direct correlation with any Central Appalachian feature.

Implications From The Large Scale Features

A number of observations on the nature of the juncture appear from the large scale structural changes across it. Most obvious is that folds of both the Central and Southern Appalachians plunge at or near the juncture and tend to interfinger rather than connect to form uniform bends at the change of strike. An exception is the Hurricane Ridge syncline and possibly the Abbs Valley anticline. The Hurricane Ridge syncline changes strike and penetrates the Central Appalachians northwest of the Browns Mountain anticlinorium. Central Appalachian folds plunge out to the southwest and separate the Hurricane Ridge syncline from the Abbs Valley anticline and from the St. Clair fault. Also interesting are the changes that occur along the Abbs Valley anticline-Richlands fault. It is obvious that deformation along the narrow zone represented by this system increases to the southwest. Also interesting is the fact that the Richlands fault dies out northwest of the southwest plunge of the Hurricane Ridge syncline, which is immediately northwest of where the St. Clair fault bifurcates just before connecting with the Russell Fork fault. This suggests some kind of relationship between movement on the St. Clair fault and the development of structural features to the northwest. A major paradox of the juncture is the observation that although the St. Clair fault appears related to the Wills Mountain and the Warm Springs anticlines, the St. Clair fault, in its relation to the Hurricane Ridge syncline, is replaced by the Browns Mountain anticlinorium in the adjacent Central segment. Some workers have suggested a difference in timing of deformation to explain the discontinuity at the juncture, but if this were the case, one would expect a multiply deformed zone of intersection at the juncture. As this does not appear to be present, an alternative is to suggest a marked differential response to the applied stress, between the two segments. This differential response would produce folds, simultaneously formed, but not necessarily in phase, thus producing intersecting and plunging, rather than connecting folds at the juncture.

DETAILS OF STRUCTURE IN THE STUDY AREA

Introduction

The most interesting and significant aspect of the structural geology of the study area is the change in style of deformation that occurs along the northwestern side of the St. Clair fault. The changes that are evident in the study area are typical of, and closely mirror, the larger scale contrasts between the Central and Southern Appalachians across their juncture.

Description Of The Features

Southwest of the study area, Little (Middle) Mountain, which forms the first ridge northwest of Peters Mountain, is the overturned southeast limb of the Hurricane Ridge syncline whose axis here parallels the St. Clair fault. Stratigraphic displacement is abruptly lost on the St. Clair fault 4.5 miles southwest of Crimson Springs, where the study area begins. Coincident with this, to the northwest, is the northward change in strike of the Hurricane Ridge syncline. At the southwestern end of the study area, along the Crimson Springs-McGlone Road, the Silurian to Mississippian units of the southeastern limb are strongly overturned. Numerous shear zones as well as small antiforms and synforms are developed in the overturned Devonian shales. East of Union, a series of folds are present that all plunge southwest approximately along latitude 37°35' N. These folds represent a continuation of the plunging Browns Mountain anticlinorium as well as short length folds that occur between the Browns Mountain strike belt and the St. Clair-Wills Mountain strike belt.

The dips of the Devonian-Mississippian units along Little (Middle) Mountain gradually increase from being overturned 22° SE. at the southwestern corner of the study area to 82° SE. at Gap Mills and the beds are not overturned north of Gap Mills, where the dip is steep to the northwest. The structural depression formed by the northwest dipping units along Middle Mountain and the southeast dipping units of the southeast limb of the Glace anticline, to the northwest, is termed the Pedro syncline (Reger, 1926). Mississippian units as young as Greenbrier Limestone are preserved in the trough. Maximum depression occurs precisely northwest of the recess, as expressed on Gap and Middle Mountains. The syncline persists from about 2 miles northeast of Red Mill to the drainage divide of a tributary of Cove Creek 0.4 mile west of Antioch Church in the extreme southwestern corner of Alleghany County, Virginia. The Browns Mountain folds, the Kates Mountain syncline, and the Glace anticline all follow Central Appalachian strikes. The Pedro syncline parallels the bend in Middle Mountain that occurs at the recess; it strikes about N.65° E. southwest of the recess and about N.35° E. on the northeast. Within the Wolf Hills, immediately northwest of the recess between High Head Mountain and Moss Mountain, two folds appear in the bulge of Upper Devonian formations bounded on the southeast by the Gap

Mountain recess and Middle Mountain on the northwest. In the Wolf Hills these folds are indistinct due to the numerous minor folds present. Apparently the converging segments created a space problem within these Upper Devonian shales and sandstones and resulted in the formation of many anomalous small folds as well as some shear zones (Plate 1). The main folds, termed by Reger (1926) the Nigger Mountain anticline, on the northwest, and the Wolf Hills syncline, on the southeast, become distinct to the northeast although some drag folds and minor faults are also present and may be observed along W. Va. Route 603 on Slaty Mountain and in the railroad cut at Allegheny, Virginia. Along Cove Creek the folds are clearly asymmetrical. The northwest limb of the Nigger Mountain is of steeply dipping units (greater than 55° to the northwest) while the dips on the southeast limb are generally between 20 and 30 degrees to the southeast. The Wolf Hills syncline rapidly broadens and Mississippian rocks are exposed along Cove Creek in the trough of the fold where units as young as Maccrady are preserved. An exposure of red shale of the Maccrady Formation occurs at the intersection of Rt. 603 and the Virginia-West Virginia border on Slaty Mountain. The syncline narrows somewhat at the drainage divide formed between Big Ridge and Slaty Mountain; then broadens into its maximum depression in the valley of Miller Branch Creek which is called Tucker Hollow. The maximum depression, in which units up to Maccrady are preserved, is centered on Va. Rt. 311, which forms the northeastern boundary of this part of the study area. As the syncline broadens, the Nigger Mountain anticline diverges north and merges with another anticline; the merger forms the northern termination of the Pedro syncline. This anticline continues as the complementary anticline northwest of the Wolf Hills syncline. It becomes breached by erosion, exposing Devonian Brallier Formation in the core along the valley of Tygers Creek before it changes course at the railroad cut near Alleghany, Virginia. At this railroad cut, along the entrance to Alleghany Mountain Tunnel, reverse faults in the southeast limb of this anticline may represent a last vestige of influence of the Nigger Mountain anticline as a separate feature. Butts (1940) shows that the Devonian Chemung, which forms the trough of the Wolf Hills syncline and the southeast limb of the anticline, is lost in northwestern Alleghany County. This series of folds continues to the northeast in the Devonian Brallier Formation. The Chemung is still present as the northwest limb of the anticline but is completely eroded off to the southeast, thus testifying to the continuance of the general asymmetry of the folds.

The northwest dipping Chemung that forms Slaty and Dameron Mountains is the northwest limb of an anticline that has been breached by erosion. Except for a remnant at its southwest nose, where Back Creek and Cove Creek join, the Chemung has been entirely eroded from the southeast limb of this anticline. The crest parallels Dunlap Creek in the valley below Dameron Mountain, with formations as old as Millboro exposed at the core. Northeast of the study area, the the Brallier Formation forms the crest, and the fold persists a short way into northwestern Alleghany County, as a low amplitude fold, before apparently plunging out. To the southeast, on the other side of Dunlap Creek Valley, a syncline in the Millboro Formation forms part of the valley floor. The southeast limb of this syncline forms part of what can only be described as a tightly folded anticlinorium, which brings up competent Silurian units to form a series of resistant ridges, the most southeasterly of which is called Snake Run Ridge. This anticlinorium is small and the folds are very tight. The anticline forming the Peters Mountain extension, northeast of Thomas Spring, is the only fold of length; it slowly plunges into northern Alleghany County. It is apparently related to the Wills Mountain anticline of the Central Appalachians. The anticlinorium is roughly triangular in shape with the corners at Thomas Spring and the communities of Hematite and Earlhurst. The major ridges form a "V" with the apex to the southwest at Earlhurst. Snake Run Ridge is formed as the St. Clair fault loses stratigraphic displacement such that Silurian Tuscarora and Keefer sandstones are exposed. Although overturned at Iron Hill Springs, the Silurian ridge-forming sandstones begin to dip to the northwest as stratigraphic displacement begins to be lost on both sides of the fault. The overturned or northwest dipping units form the southeast limb of a tight syncline that parallels Snake Run Ridge on the northwest side. A very sharp anticline, with extreme brecciation of the Silurian sandstones, occurs northwest of this syncline. Outcrop on this anticline is very poor and bedding is difficult to recognize in the highly deformed Keefer Sandstone, and in fact a fault may be present but no clear cut evidence of this could be found. In any case, the northwest limb of this fold forms a deep syncline in the valley of upper Crow Run, where units as young as Millboro are preserved in the trough. The maximum depression occurs along upper Crow Run, outcrop narrows somewhat to the northeast, and the axial trace of the syncline passes through a narrow divide between two subsidiary ridges that divide Crow Run drainage from Little Crow Run drainage (see Plate 1). The major ridge northwest of the source of Crow Run is an anticline with Tuscarora Sandstone exposed along the crest, just to the northwest of the ridge. This anticline plunges out to the northeast as it crosses Crow Run where the stream changes direction to connect with Little Crow Run. Northwest of the nose of the major anticline, three smaller anticlines are formed en echelon. These form the smaller ridge southeast of Crows; the strike of the fold axes are at an angle to the ridge itself and they are all roughly parallel to the strike of Snake Run Ridge. Silurian outcrop is lost down the plunge of these folds approximately at a line between Thomas Spring and Hematite. Northeast of this plunge, the folds persist in incompetent Devonian units as subsidiary folds on the northwest limb of the anticline that is the Peters Mountain extension. This Peters Mountain anticline plunges southwest at Thomas Spring. Its southeast limb is the northwest limb of a syncline that occupies the drainage area of Cast Steel Run. The southeast limb of this syncline is a continuation of the units brought up along the northwest side of the St. Clair fault. The Tuscarora Sandstone, on the southeast limb of this syncline, forms a ridge as the northwest limb of the Morning

Knob anticline. This belt of outcrop, as previously described, joins the Peters Mountain outcrop belt at Morning Knob, in an apparently plunging anticline, with intense brecciation at the core; this is the surface termination of the St. Clair fault. The Morning Knob anticline plunges out between the diverging limbs of a syncline, the northwesterly segment of which is the syncline along Cast Steel Run. The southeastern segment of this syncline occupies the valley of the tributary of Cast Steel Run that parallels the jeep trail leading to the top of Morning Knob. A subsidiary anticline forms the ridge northeast of Morning Knob and rapidly plunges toward Virginia Route 614 and Potts Creek Valley. Silurian Keefer and Rose Hill Formations form the crest of this anticline along the highest elevations and plunge out under Devonian shales to the northeast.

Folding along the southeast side of the St. Clair fault appears generally related to movement along it. Low amplitude folds occur mainly in two areas along the southeast block of the fault in Sweet Springs Valley, within the study area. On the southwest, a series of folds occurs in the Beekmantown dolomite and Middle Ordovician limestones where the valley widens south of Gap Mills. This series of folds occurs southeast of where stratigraphic throw is temporarily gained along the St. Clair fault. The second series of folds, on the northeast, occurs southeast of the juncture and the Moss Mountain bifurcation of the fault. A number of minor folds are developed in the Beekmantown just southeast of the juncture. The largest fold, an anticline, plunges northeast into the diverging limbs of a syncline within which Middle Ordovician limestone is exposed. Farther northeast, smaller subsidiary folds are present on either side of the syncline at the town of Sweet Springs. These folds are best developed southeast of where the two segments of the St. Clair fault have rejoined and stratigraphic displacement has increased whereby Beekmantown dolomite is faulted over Oriskany Sandstone. The valley narrows as stratigraphic displacement is lost along the fault to the northeast and the folds die out just over the border into Alleghany County, Virginia. Thus the development of folds on the southeast block of the fault appears to be strongly correlated with those areas where stratigraphic displacement is increased (see Plate 1).

Conclusions

The structural geology of the study area provides an excellent small scale example to aid in reaching an understanding of the Central and Southern Appalachian juncture on the larger scale. The study area includes the two most important features of the juncture, namely the change in strike and the transition from thrust fault-dominated deformation to fold-dominated deformation. The transition begins where stratigraphic displacement is abruptly lost on the St. Clair fault southwest of Zenith in Monroe County, West Virginia. Simultaneously, the Hurricane Ridge syncline and Abbs Valley anticline, which had both paralleled the St. Clair fault for a long distance to the southwest, diverge to the north and assume Central

Appalachian strikes. Also, as folds from the Central Appalachians plunge out, they interfinger with and separate the above mentioned features which are so closely related in the Southern segment. Northeast of Gap Mills, a sharp recess is developed in the units overridden by the St. Clair fault along Gap Mountain. From this point northeast to the termination of the St. Clair fault, the units northwest of the fault are no longer overturned but rather are thrown into a series of sharp folds that give way to a lower amplitude, broader series of folds to the northwest that are capped by younger units and whose axes have Central Appalachian strikes. Although it may seem redundant to state that loss of stratigraphic displacement on the St. Clair fault seems to be correlated with the development of folds on the northwest, a number of possible conclusions follow from this observation. Southwest of the juncture, deformational shortening seems concentrated on the fault. As one approaches the juncture, however, the St. Clair fault becomes increasingly unnecessary as shortening seems also to be accomplished by folding on the northwest. Thus stratigraphic displacement appears to be lost on the fault because some of the stresses, which were relieved by movement on the fault to the southwest, are relieved by folding on the northwest. If for some reason the ability of folding on the northwest to relieve stress is increasing along strike to the northeast, then a change in strike will occur as folds will be constrained to develop farther northwest to the northeast. From a thin-skinned tectonic view, it is interesting to postulate that for some reason the block of units above a major detachment zone was more difficult to translate northwestward, perpendicular to strike, in the Southern Appalachians, and the juncture represents a point where northwestward translation of the entire block became easier to the northeast. Thus folds would be constrained to follow a Central Appalachian strike because slip along a detachment zone increased to the northeast.

WARM SPRINGS

Introduction

The presence of springs, whose average annual temperature is greater than the surrounding average annual air temperature, in the Appalachian Valley and Ridge and Piedmont, from Pennsylvania to Georgia, has long been known. Rogers (1842) was the first to compile and document the physical and chemical characteristics of the thermal springs of Virginia (which then included West Virginia). Reeves (1932) conducted a similar study utilizing the detailed knowledge of Appalachian structure and stratigraphy obtained in the intervening 90 years. Both concluded that the source of heat was the normal thermal gradient that occurs with depth, but differed on models for the deep circulation of meteoric water.

The average annual air temperature varies from year to year and with latitude but generally falls between 48 and 54° F. (9-12° C.) in the Appalachian region. Rogers (1842) used 51° F. as the temperature above which springs could be considered warm, thus reflecting the climatic fluctuation in which temperatures were generally lower during the first half of the 19th century. Reeves (1932), using temperature data collected over the intervening years, considered an annual average spring temperature of 55° F. as the minimum to be considered warm. The warm springs in Virginia and adjacent West Virginia range up to a maximum temperature of 106° F. (41° C.).

Rogers (1842) noted that the warm springs nearly always occur along the axes of anticlines, generally issuing from the northwest side of the folds, where the oldest rocks in the core are exposed. Recently Geiser and Costain (1977) and Costain (1979) have noted that the warm springs line up in linear, northwest trending zones that appear as linears on air photos and form major water gaps through the mountain ridges. This pattern may be seen from a map of the warm springs locations (see Reeves, 1932).

The geologic formations from which the springs flow are almost invariably from one of two segments of the stratigraphic column. These are the Cambro-Ordovician carbonates and the Devonian Oriskany and Helderberg Formations where these units are brought up in the cores of anticlines.

Features of the Warm Springs in the Study Area

The warm springs in the study area occur in three groups with an overall total of nine individual springs. These groups, known as Sweet Springs, Sweet Chalybeate, and Iron Hill Springs, occur in Sweet Springs Valley northeast of the Moss Mountain recess. All the warm springs but one issue from Beekmantown dolomite or Middle Ordovician limestone on the hanging wall block of the St. Clair fault, southwest of its termination. The exception, included with the Iron Hill Springs, issues from Oriskany Sandstone in the Snake Run gap along Va. Rt. 604 about half a mile northwest of the St. Clair fault and the Iron Hill Springs. The spring with the highest temperature is Sweet Chalybeate with an average annual temperature of 75° F. (Reeves, 1932). The temperatures of the other springs, as reported by Reeves (1932), are 71° F. for the Sweet Springs, 65° and 66° F. for the Iron Hill Springs and 59.5° F. for the spring that issues from the Oriskany. Additional physical features of the warm springs (discharge, gas content, ect.) are also reviewed in Reeves.

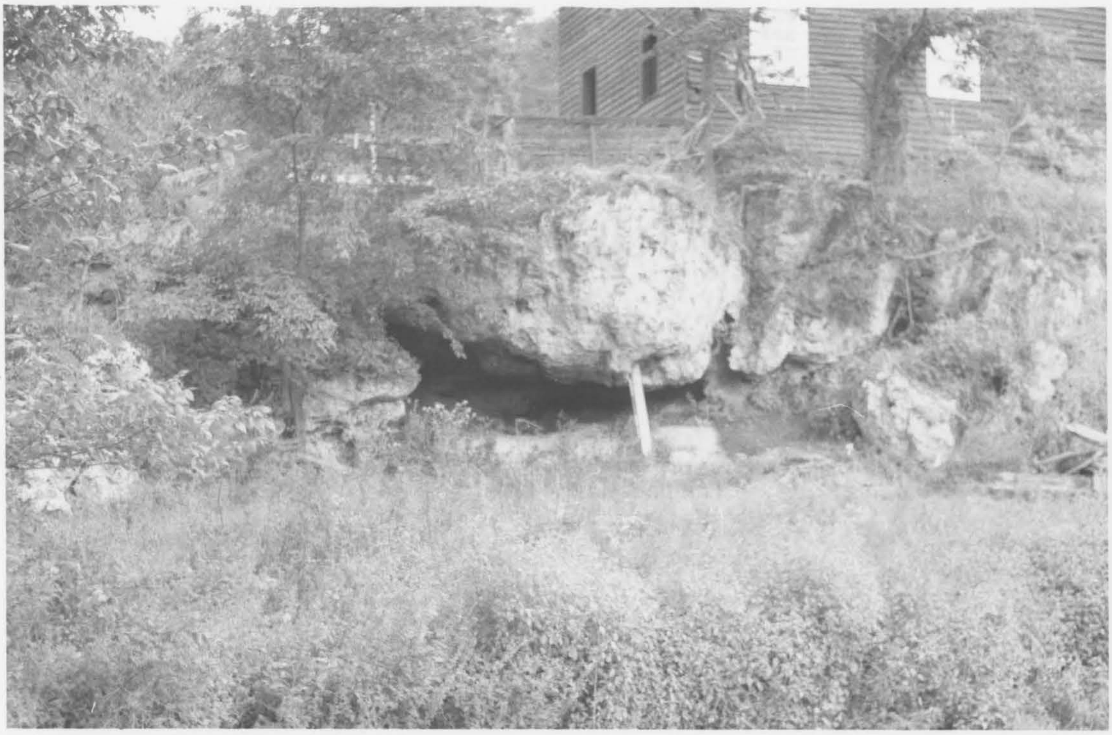
Of most interest, in the context of this study, is the structural location and setting of these springs. The Sweet Springs are located in the series of minor folds developed southeast of the St. Clair fault where it gains stratigraphic displacement northeast of Moss Mountain. Sweet Chalybeate and Iron Hill Springs, successively to the northeast, converge on the fault as the valley narrows where the folds die out. The Iron Hill Springs are located in the Beekmantown dolomite very near, if not on, the fault trace. The warm spring that emerges from the Oriskany Sandstone, near Iron Hill Springs, is quite close to the brecciated unit mentioned in the section on breccias. In view of the proximity of the Iron Hill Springs to the fault it is possible that the brecciated Oriskany represents a minor splay of the St. Clair and that some Iron Hill Spring water is diverted along the splay to the Oriskany spring. Additional near surface flow may account for the somewhat lower temperature of this spring. Rogers (1842) remarked on the fact that to the southwest along the St. Clair fault no additional warm springs are to be found. A possible explanation for this may be that the northwest trending fracture zones, apparently necessary for the presence of these springs, are not developed southwest of the juncture. White Sulphur Springs, Sweet Springs, Walter Givens Spring at New Castle, and H. J. Old Spring near Haymakertown, Virginia appear to follow a northwest trending lineament just northeast of the Central and Southern Appalachian juncture. Southwest of the juncture, warm springs in the Valley and Ridge are rare.

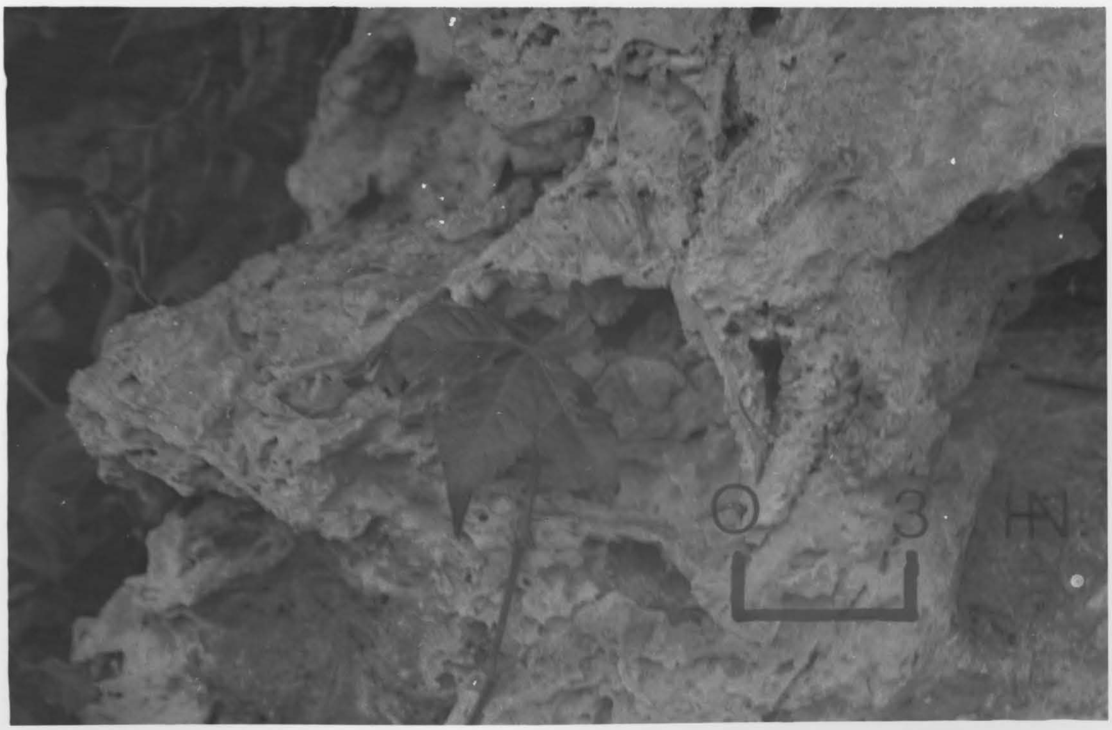
An additional feature associated with the warm springs in the study area is the thick accumulation of calcareous tufa in the valley floor. Deposits of this material, up to 25' or more thick, may be observed at Beaverdam Falls (Plate 1, Plate 6). Calcareous tufa is generally found associated with warm springs. In those cases where warm springs are not present, faults or fracture zones in limestone may account for higher proportions of carbonate in solution in ground water which is then deposited either chemically or organically. It is difficult to ascertain whether the tufa is being actively deposited at present in the study area. Erosion has cut through some deposits but the bottom of Sweet Springs Creek contains patches of apparently fresh tufa. Very little work has been done on calcareous tufa deposits but knowledge of age and rates of formation could provide information on past history of the warm springs.

Discussion of Ideas on the Circulation of Water and Source of Heat

Although a number of plausible models have been presented over

Plate 6. Deposits of calcareous tufa in Sweet Springs Valley and associated with the warm springs may be greater than 20 feet thick as in these photographs of the deposits at Beaverdam Falls.

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the years to account for the heating and circulation of the thermal spring water, none of the explanations thus far presented have been definitely established. The reasons for this are first, a lack of subsurface information, so that ideas presented are based solely on surficial knowledge, and second, as Dennison and Johnson (1971) noted, the same general structural setting in which abundant warm springs occur in Virginia and adjacent West Virginia do not yield numerous warm springs in other parts of the Valley and Ridge, such as in central Pennsylvania.

Rogers (1842), operating from the general lack of detailed geologic knowledge at the time, tried to correlate the proximity of high ridges with the presence of warm springs. In his view, meteoric water entered fractures along the high ridges and sank until reaching a permeable bed where it would rise up the dip of the unit to an adjacent anticlinal valley as high as the hydrostatic head would allow. Thus the warm springs would occur in permeable formations wherever they cropped out at elevations lower than their recharge areas, provided these units rose from sufficient depth to account for the heating.

Reeves (1932) also concluded that the thermal springs were composed of meteoric water circulated at depth but thought the recharge to be directly into a permeable unit along its outcrop on the flank of one anticline where it would circulate through the complementary syncline, become heated, and rise hydrostatically up the flank of the next anticline where a thermal spring would appear at an outcrop elevation lower than the elevation of recharge. Reeves discusses this idea in detail for many of the thermal springs. Of interest to this study is that he attributes the occurrence of the thermal springs in the study area to recharge on the Rich Patch anticline to the southeast where the Middle Ordovician limestones crop out in the core several hundred feet higher in elevation than in the Sweet Springs Valley.

Although Rogers and Reeves ideas are similar, Reeves is more sophisticated geologically and for many years his view was considered to be more probable. There has always remained, however, the lack of substantiating subsurface information. Although Reeves accounts for the occurrence of thermal springs within the Oriskany-Helderberg fairly convincingly, he must assume extensive fracture systems in the subsurface to account for circulation through the Cambro-Ordovician carbonates that, in outcrop, appear impermeable. Also is the problem of accounting for the localization of the Warm Springs (Valley and Ridge Province) in Virginia and adjacent West Virginia. In addition, it became apparent that Reeve's estimate of the geothermal gradient of 1° F./75 ft. was too high. The most recent determination in this area (Warm Spring anticline)(Costain et al., 1976) of 1° F./180 ft. (10° C./km.) is less than half that used by Reeves. It was these considerations that led Dennison and Johnson (1971) to propose that a large, still cooling pluton, responsible for the Tertiary intrusions of Highland County, Virginia, was also the source of heat for the system of warm springs. They estimated the pluton to be centered in

Bath County, Virginia (also the center of the warm spring localization) and correlated this with a negative simple Bouguer anomaly also centered in Bath County. Geiser and Costain (1977) reported that a heat-flow determination made within the Warm Springs anticline gave a normal heat flow of 1.15 $\pm$ .02 μcal/cm.-sec. which thus argues against the presence of a still cooling pluton at depth. Dennison and Johnson have themselves apparently abandoned the idea (Lowry, personal communication, June 1979).

Geiser and Costain (1977), Geiser (1978), and Costain (1979) have found that the warm springs of the Warm Springs anticline are localized by zones of transverse fracturing that may be identified as photo-linears on U-2 and ERTS imagery and on the surface as water gaps, east-west trending valleys, and perturbations in structural trends. They found by drilling that warm water is encountered only in these fracture zones, of up to 2 km. in width, and in no other locations on the structure. In addition they find that other warm springs are also localized on similar linear trends. Although the origin of such features are obscure, Geiser (1978) mentions flexing, deep-seated transcurrent faults, and tear faults associated with thrusting as possibilities. He rejects chance alignment, step-ups due to thrusting, and local perturbations due to interactions between growing folds as possible explanations for the lineaments.

Costain (1979) reports on a model proposed by Perry, et al. (1979, in press) to account for the heating in which meteoric water descends along the steeply dipping units within the axial part of the anticline, then intersects a transverse fracture zone at depths of at least 3 km., before gradually rising along the fracture lineament to the low elevation outcrop of the springs within water gaps. Differing temperatures of the various springs can easily be accounted for by considering the depth of intersection and/or degree of near surface mixing of the water.

Conclusion

Although many unknowns remain in achieving a full and satisfactory explanation for the origin of the warm springs, including the remaining lack of sub-surface information, the recognition of the localization of the springs on transverse lineaments is an important key. Of interest is the fact that the most southwesterly such lineament, on which a string of warm springs occurs, is localized along the Central and Southern Appalachian juncture. Gwinn (1964) considered the lineaments in this part of the Appalachians to be tears associated with thrusting along a major detachment. In view of their location near the change of strike this seems the most likely explanation for them. Perhaps as slip along a major detachment increased to the northeast (with a major change in slip occurring at the juncture) sharp discontinuities in pore pressure or some other criteria resulted in zones of differential slip that formed tears in the deforming "skin" of sediments. Possibly these tears form zones of enhanced permeability through the synclines in the Cambro-Ordovician carbonates, which accounts for the localization of the warm springs, assuming the circulation of the water to be similar to that proposed by Reeves (1932). An additional possibility is that flow of meteoric water along the major detachment (fed by splays) is tapped along the tears where they intersect subsurface splays associated with the major anticlinoria of this part of the Central Appalachian Valley and Ridge. The water would certainly be circulated deep enough to account for the heating and in addition this would explain why in similar structural settings in other parts of the Appalachian Valley and Ridge warm springs are not present since the deep tears are necessary to tap the heated water at depth.

THE CENTRAL AND SOUTHERN APPALACHIAN JUNCTURE: CONCLUSIONS

Introduction And Review Of Ideas Presented

The Central and Southern Appalachian juncture, with its sharp change of strike and contrasts of geologic "style", has long been recognized as an anomalous feature of this mountain chain (Rogers, 1842). The problem of accounting for this juncture, and similar changes of strike elsewhere, has traditionally been regarded as a subset of the problem of accounting for the development of mountain chains in general. Older ideas on the juncture problem could be related to the possible answers to two basic questions. These are: 1) Was shortening accomplished along two principal stress orientations and 2) Is there any difference in timing of deformation between the two segments. Rogers (1842) did not think that there was any difference in timing of deformation across the juncture since, although some structural features plunge out or intersect with those of the other section, other features smoothly traverse the juncture. Willis (1894) suggested that the changes in strike and structural style evident between the Central and Southern segments reflect thickness and facies contrasts within the sedimentary column. He points to the extreme thinning of stratigraphic units above the Cambro-Ordovician carbonates from Central Pennsylvania through southwest Virginia to Alabama, particularly in the Devonian, as evidence of the contrasts. Keith (1923) postulated that the fundamental change of strike was caused by the intrusion of the granite batholiths in the Carolinas and Georgia. Although Keith envisioned expansion lateral to the axis of the intrusions to have acted compressively in deforming the Southern Appalachians, which is unlikely, a more modern version of this idea would be to consider the batholiths as representing a center of gravity spreading. One could postulate two linear spreading centers, one for the Central Appalachians and one for the Southern Appalachians, which are arranged at an angle. Unfortunately the geology of the Piedmont of the Central Appalachians is not sufficiently worked out to allow evaluation of this idea. In addition, difficulties with gravity mechanisms, related to the slope problem, have not been successfully overcome in the view of many geologists (Root, 1973).

With the most recent developments in plate-tectonic theory, a new generation of ideas have been proposed for the development of changes of strike. The two basic questions of timing and stress orientation remain but the framework for possible answers has changed. Changes of strike have been considered to be of two types. Salients are bends convex toward the craton and recesses are bends concave toward the craton (Rodgers, 1975; Williams and Doolan, 1979). Dewey and Burke (1974), Williams and Stevens (1974), Rankin (1975), Rodgers (1975), Thomas (1975) all suggest that the salients and recesses in the Appalachian Mountain belt somehow reflect the irregular shape of an older continental margin which was constructed and destroyed during late Precambrian and Paleozoic time. Rankin (1975, 1976) suggested that sharp changes in trend of the forming continental margin could have originated as triple junctions of spreading centers where one "arm" fails to rift. In recesses the failed arm is carried away by rifting, leaving a buttress of continental crust projecting into the new ocean. In salients the failed arms are present as buried aulacogens. Rankin mentions the presence of Precambrian or Eocambrian metamorphosed rhyolites in the Blue Ridge which are found only within salients such as at Mt. Rogers, Virginia; South Mountain, Pennsylvania; and the Sutton Mountains in Quebec, Canada, as evidence for the presence of old failed arm troughs.

Thomas (1977) agreed that salients and recesses reflect an orthogonally zigzag continental margin framed by transform faults along a rift system initiated in the late Precambrian. In addition he shows that facies and thicknesses of late Precambrian and Paleozoic sedimentary rocks closely reflect the old postulated continental margin outlines and basin shape such that units are thickest in salients with their thicknesses decreasing cratonward and along strike across recesses. The fact that the clastic-volcanic sequence, carbonate bank, and clastic wedges all follow the same general thickness pattern indicates to Thomas that the original framework of the geosyncline was pre-depositionally established and that the postulated orthogonally zigzag continental margin is the best explanation for the resulting pattern of sedimentation. This pattern may be observed from any of the regional thickness maps that have been done, such as those by Colton (1961, 1970). Colton's thickness map for the

Cambro-Ordovician carbonates has been included for reference as Figure 3.

One development from a large scale gravity and magnetic study in West Virginia and adjacent Virginia by Kulander and Dean (1978) was a refinement of the basement depth map over this area that includes the northwestern part of the Central and Southern Appalachian juncture (Figure 4). They found that a northeast plunging arch is developed on the basement along southern and eastern West Virginia. This arch makes a sharp bend at the Central and Southern Appalachian juncture and parallels, but does not precisely coincide with, the Appalachian Plateau Structural Front. Among the conclusions they reached were that the basement could play an indirect role in localizing thin-skin cover structures, control the length of decollement blocks, or deflect Cambrian decollements upward. They also suggest that regional basement relief could play a role in the larger scale features of the Appalachians such as the northward widening of the folded Plateau and Central Valley and Ridge or the trend change of the Central and Southern Appalachians.

Evidence From The Study Area

As seen from the geology of the study area (Plate 1), the units on the northwest side of the St. Clair fault, south of the recess, form a broad syncline, which is obviously the complementary fold that was forming simultaneously with the St. Clair structure. As the

Figure 3. Thickness map of the Cambro-Ordovician carbonates from Colton (1970). Note thinning of these sediments over the Central and Southern Appalachian juncture or recess.

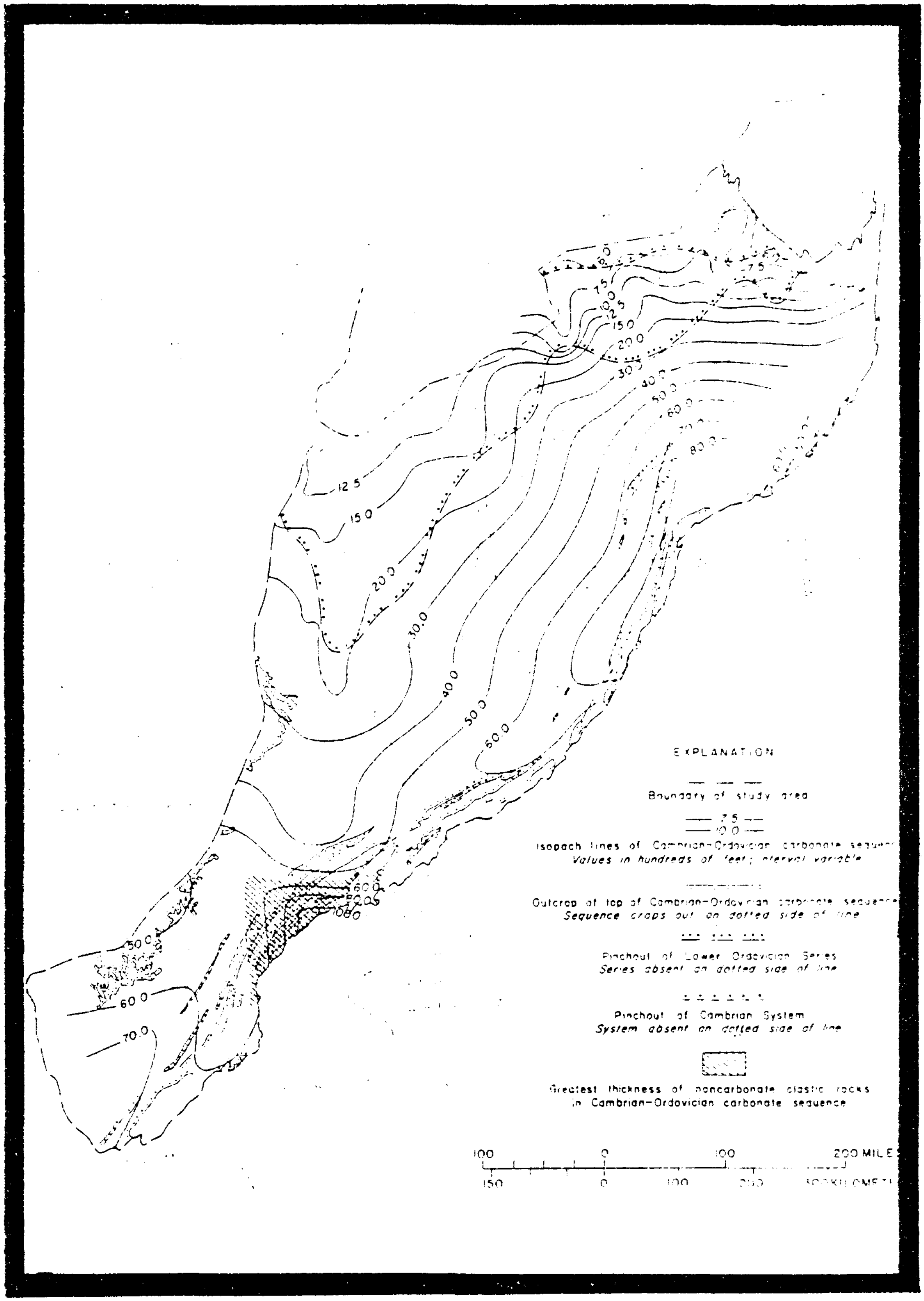
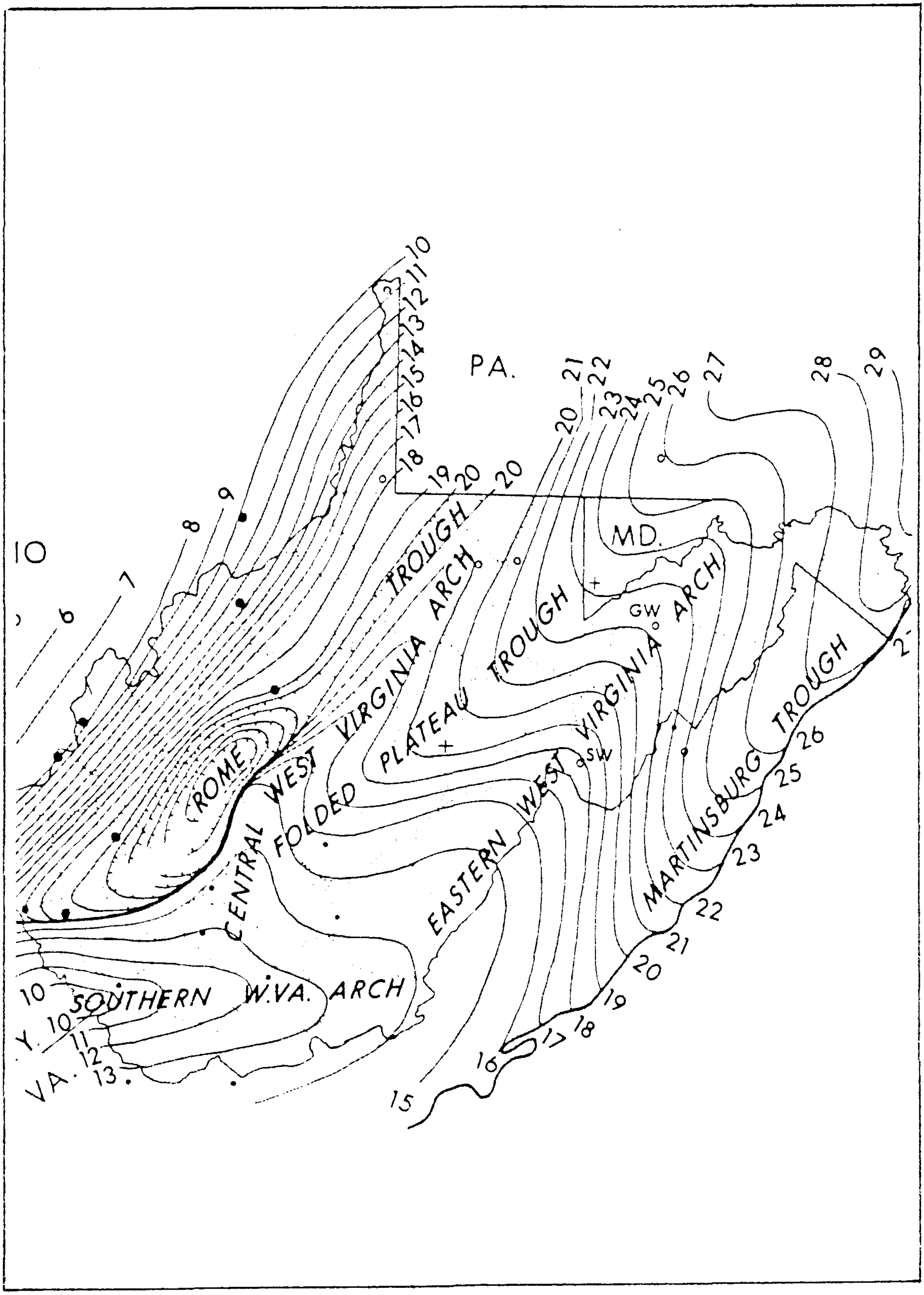

12.5
15.0
20.0
30.0
40.0
50.0
60.0
70.0
EXPLANATION
Boundary of study area
Values in hundreds of feet; interval variable
Outcrop of top of Cambrian-Ordovician carbonate sequence
Sequence crops out on dotted side of line
Pinchout of Lower Ordovician Series
Series absent on dotted side of line
Pinchout of Cambrian System
System absent on dotted side of line
Greatest thickness of noncarbonate clastic rocks
in Cambrian-Ordovician carbonate sequence
100 0 100 200 MILES

Figure 4. Revised basement map taken from Kulander and Dean (1978). Note the sharp change in trend of the West Virginia Arch nearly coincident with the juncture in Monroe County, West Virginia. (Contour numbers are depth in thousands of feet using sea level as datum.)


PA.
MD.
ROME
TROUGH
CENTRAL WEST VIRGINIA ARCH
FOLDED PLATEAU TROUGH
EASTERN WEST VIRGINIA ARCH
MARTINSBURG TROUGH
SOUTHERN W.VA. ARCH
GW
SW
VA.

juncture is approached, the axis of this syncline changes strike to the north and interfingers with folds of the Central Appalachians that plunge out into the juncture. Northwest of the recess, Central Appalachian striking synclines occur along the northwest side of the St. Clair fault for most of its length to its terminus. The anticline that plunges out toward the fault north of Sweet Chalybeate and the plunging Peters Mountain anticline strike into the fault but are nevertheless not truncated by it. It is apparent from this that the anticline that broke and formed the St. Clair fault and the folds that occur northwest of the fault, northeast of the recess, developed simultaneously (or nearly so) along different structural strikes.

Conclusions

Integrating the recent work on the recess problem, especially that of Kulander and Dean (1978) and Thomas (1977), with that of the present study, the following conclusions are reached:

1. The change of topographic and structural trend across the Central and Southern Appalachian juncture does not require any significant difference in timing of deformation.
2. There probably is no significant difference in orientation of principal stress across the juncture but rather the change of trend and differences of geologic "style" reflect contrasts in thickness and facies within the sedimentary column and contrasts involving basement topography which indirectly influence cover structure.

3. The St. Clair fault terminates because the northwest mobility of the "skin" of deforming sediments increases such that shortening is spread over a broader region to the northeast along strike. Thus shortening may be accomplished without significant concentration of deformation along narrow belts such as thrust faults.

4. The change of strike occurs because as northwest mobility of the deforming "skin" of sediments increases to the northeast, individual folds are translated farther northwest and are thus constrained to follow Central Appalachian strikes.

The conclusions reached are general and it is obvious that subsurface information is badly needed to supply details. In addition, it is apparent that experimental modeling could be of much use in working out the details of what occurred at the juncture. Past modeling attempts have overlooked such factors as irregular basement topography and thickness or facies changes in the interest of simplicity. It should be apparent now that such factors may be of much greater importance than heretofore recognized.

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APPENDIX 1

Measured Section

Section begins at junction of Waiteville and Zenith roads, three miles southwest of Gap Mills, West Virginia, on the Gap Mills 7-1/2 minute quadrangle. Section was measured up the northwest slope of Peters Mountain parallel to Waiteville road. Total measured thickness was 890.0' (271.2m).

Unit	Martinsburg Formation	Thickness	
	Moccasin Formation 302.3' (92.3m)		
53	Covered interval	42.9'	(13.1m)
52	Limestone, light gray skeletal wackestone, poorly exposed, sandy, fossil fragments silicified: limestone partly replaced by silica.	7.2'	(2.2m)
51	Covered interval	104.2'	(31.8m)
50	Lime mudstone and laminated mudrock, thin-bedded, argillaceous, light grayish green, wavy bedded, abundant mudcracks.	4.5'	(1.4m)
49	Covered interval	19.5'	(6.0m)
48	Thin sandstone unit, fine-grained, calcite-cemented, dark gray where fresh; weathers buff.	1.6'	(0.5m)
47	Lime mudstone, thin-bedded, alternating pinkish, red, or greenish colors; red units show abundant mudcracks.	41.8'	(12.7m)
46	Covered interval	3.7'	(1.1m)
45	Limestone, light gray wackestone, thin-bedded, grains of algal derived material.	3.0'	(0.9m)
44	Covered interval	52.4'	(16.0m)
43	Limestone, light to medium gray lime mudstone. argillaceous, thin-bedded, no	21.5'	(6.6m)

Unit		Thickness	
	fenestrae or fossils		
	Middle Ordovician Limestones 587.7' (178.9m)		
42	Limestone, medium to dark gray wackestone: thin, irregular mottled dolomite bands (15%) and some medium-bedded, fine-grained dolomite interbeds (20%).	36.5'	(11.1m)
41	Limestone, medium-bedded, medium to dark gray wackestone: algal material and fragmented bryozoans present.	1.9'	(0.6m)
40	Covered interval	26.8'	(8.2m)
39	Limestone, light to medium gray packstone (15%), and wackestone (65%), with thin, irregular, mottled dolomite bands (20%), and dolomitized horizontal burrows on bedding; dolomite layers become very irregular toward top of unit.	24.4'	(7.4m)
38	Covered interval	15.1'	(4.6m)
37	Limestone, dark gray wackestone (50%), and packstone; 20--25% thin irregular mottled dolomite bands, fossil algae, abundant cabbage-head type stromatolites, imperfectly formed.	9.2'	(2.8m)
36	Limestone, dark gray wackestone and packstone; 20-25% thin, irregular, mottled dolomite bands; fossil algae in lime mudstone interbeds; a few imperfectly formed cabbage-head type stromatolite-bearing units are apparently replaced laterally by cross-bedded grainstone units of shell hash	20.5'	(6.2m)

Unit		Thickness	
	and algal biscuits or algal materials.		
35	Covered interval	1.0'	(0.3m)
34	Limestone, dark gray skeletal wackestone and packstone, 5% thin, irregular mottled dolomite interbeds, fragments of gastropods, ostracods, brachiopods, cephalopods, algal biscuits and algal derived material.	7.8'	(2.4m)
33	Covered interval	19.5'	(5.9m)
32	Limestone, dark gray skeletal wackestone and lime mudstone; poorly exposed.	9.7'	(3.0m)
31	Covered interval	17.5'	(5.3m)
30	Limestone, dark gray skeletal wackestone and packstone with abundant black chert nodules; in lower part chert forms nearly continuous intervals, becomes less abundant toward top; thin zones with abundant algal biscuits; also zones with silicified bryozoans and rarely brachiopods.	21.4'	(6.5m)
29	Limestone, dark gray skeletal wackestone and packstone with discontinuous lenses of skeletal grainstones which include algal biscuits up to 0.5 in. in diameter; black chert nodules appear and increase in abundance toward top of unit.	20.0'	(6.1m)
28	Limestone, dark gray skeletal wackestone and packstone with discontinuous lenses of grainstone containing bryozoan, brachiopod, and gastropod fragments, as well as algal biscuits up to 0.5 in. in diameter.	44.9'	(13.6m)
27	Covered interval	22.6'	(6.9m)
26	Limestone, dark gray skeletal wackestone	0.8'	(0.2m)

Unit		Thickness	
	with fragments of brachiopods and bryozoans.		
25	Covered interval	19.4'	(5.9m)
24	Limestone, medium to dark gray lime mudstone, argillaceous and flaggy bedded; minor interbeds of argillaceous skeletal wackestone.	1.2'	(0.4m)
23	Covered interval	4.4'	(1.3m)
22	Limestone, dark gray packstone and wackestone with highly fractured fossil fragments; black chert nodules present but not abundant except for a nearly continuous chert interval at 249'; a lenticular unit containing silicified fossils was present at 250' and samples taken supplied the following specimens: conodont fragments, _Glyptorthis_ sp.,(?) _Mimella_ sp., (?) _Rhipidomena_ sp., and _Multicostella_ sp.	31.3'	(9.5m)
21	Limestone, dark gray wackestone and grainstone; black chert nodules abundant at base and become less common to top of unit; highly fractured fossil material and crossbedding in grainstone units; algal biscuits and algal derived material also present.	46.0'	(14.0m)
20	Limestone, dark gray packstone (50%) and some wackestone; black nodular chert present throughout; nodular to ribbon bedding; fossils include cephalopods, gastropods, and silicified bryozoan fragments.	7.9'	(2.4m)
19	Covered interval	3.6'	(1.1m)
18	Limestone, dark gray crystalline grainstone; poorly exposed.	0.4'	(0.1m)
17	Covered interval	9.5'	(2.9m)
16	Limestone, dark gray crystalline grainstone with scattered coarse fossil hash.	2.0'	(0.6m)

Unit		Thickness	
15	Covered interval	7.5'	(2.3m)
14	Limestone, dark gray skeletal wackestone and packstone; massively bedded with black chert nodules.	0.8'	(0.2m)
13	Covered interval	1.6'	(0.5m)
12	Lime mudstone, light gray, massively bedded, unfossiliferous, with birdseyes.	51.5'	(15.7m)
11	Lime mudstone, medium gray, wavy bedded and algal laminated.	0.5'	(0.1m)
10	Lime mudstone, light gray, massive, unfossiliferous, abundant birdseyes.	4.3'	(1.3m)
9	Covered interval	4.8'	(1.5m)
8	Chert, light gray, massive, irregular bedding surface.	0.4'	(0.1m)
7	Lime mudstone, light to medium gray; some thin beds within massive unit; grainstone lens containing abundant ostracods was sampled for conodonts revealing the following specimens: Rhipidognathus apparatus, and the form genera Erismodus sp., Curtognathus sp., and Trucherognathus sp. Lens was found at 90.2' in the section.	9.7'	(3.0m)
6	Lime mudstone, medium gray with irregular seams of dolomite and intraclasts (tear-ups) of dolomite within the limestone; a scour surface is located at 75.0'.	9.7'	(3.0m)
5	Lime mudstone, medium gray; abundant birdseyes; massively bedded and unfossiliferous.	1.6'	(0.5m)
4	Covered interval	4.0'	(1.2m)
3	Lime mudstone, medium gray, abundant	35.3'	(10.8m)

Unit		Thickness	
	birdseyes; massively bedded and unfossiliferous.		
2	Covered interval	4.6'	(1.4m)
1	Lime mudstone, medium gray, argillaceous and dolomitic near base; less dolomitic and lighter gray, with birdseyes, in upper part.	26.1'	(8.0m)

Beekmantown Group

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GEOLOGY OF THE TERMINUS OF THE
ST. CLAIR FAULT: A STUDY ACROSS THE CENTRAL
AND SOUTHERN APPALACHIAN JUNCTURE,
VIRGINIA-WEST VIRGINIA

by

Gary M. Olson

(ABSTRACT)

Geologic mapping along the northeasternmost 25 miles of the St. Clair fault, which traverses the Central and Southern Appalachian juncture at about the middle of this segment, was accomplished to observe the changes in geologic style and structural trend that occur across the juncture in this northwesterly Valley and Ridge strike belt. The study area is an excellent smale scale area for observations on the nature of the juncture over the larger scale as it includes most of the features that characterize this juncture such as change of physiographic and structural trend and transition from thrust fault-dominated deformation to fold-dominated deformation. The juncture or recess is prominent in the study area as a sharp bend in Gap-Moss Mountains and is in fact one of the sharpest bends occurring at the junction. Southwest of this recess, the stratigraphic units on the northwest of the St. Clair fault are overturned and a broad syncline is formed on the northwest, known as the Hurricane Ridge. The axis of this fold closely parallels the strike of the St. Clair fault. As the junction is approached the Hurricane Ridge syncline changes

axial strike to the north and passes northwest of the Browns Mountain anticlinorium which is plunging out into the junction. Just northeast of the recess the St. Clair fault bifurcates and its strike is slightly changed when the segments rejoin. Northeast of this point, the St. Clair fault loses stratigraphic displacement and instead of a single broad fold northwest of the fault and parallel to it, there are numerous small folds developed that strike 20-30° more northerly than the fault. The fault does not, however, truncate any of the folds. The St. Clair fault extends 13 miles into the Central Appalachians where it dies out down the plunge of an anticline at Morning Knob in Alleghany County, Virginia. A strong shear zone is evident in the core of the structure at Morning Knob but is lost as the competent Silurian units plunge under Devonian shales.

Integrating this information with other recent work on the juncture it may be concluded that: 1. The change of topographic and structural trend across the Central and Southern Appalachian juncture does not require any significant difference in timing of deformation. 2. There is probably no significant difference in orientation of principal stress across the juncture but rather the change of trend and differences of geologic "style" reflect contrasts in thickness and facies within the sedimentary column and contrasts involving basement topography which indirectly influence cover structure. Thus the changes evident across the juncture are seen to be the result of differential physical response to the applied stress.

PLATE IA

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