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STRUCTURE OF THE HOT SPRINGS WINDOW, MADISON COUNTY, NORTH CAROLINA*

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ABSTRACT. The Hot Springs window, in western Madison County, North Carolina, and eastern Cocke County, Tennessee, lies near the northwest margin of the Blue Ridge physiographic province.

The rocks within the window include a pre-Cambrian crystalline complex and a thick overlying sequence of sedimentary rocks, which is composed, in ascending order, of about 5200 feet of clastic rocks of unknown age (Snowbird and Sandsuck formations), at least 4300 feet of clastic rocks of Early Cambrian age (Unicoi, Hampton, and Erwin formations), and an unknown thickness of carbonate and fine-grained clastic rocks of Early and Middle Cambrian age (Shady, Rome, and Honaker formations). The rocks framing the window belong to the same formations, up to and including the Unicoi formation.

The Hot Springs window is unusual in that it is framed by not one, but four different thrust sheets. The rocks at and near the thrust faults are considerably fractured and mylonitized in most exposures. Where granitoid rocks of two thrust sheets are adjacent to each other, mylonite belts are useful in tracing the intervening fault. Mylonitized pre-Cambrian crystalline rocks, however, are difficult to distinguish from mylonitized Snowbird arkose in many places. The fractured and mylonitized nature of the rocks along the contact between the Snowbird formation and the pre-Cambrian crystalline complex within the window suggest that this contact also may be a thrust surface, rather than an unconformity. If this contact is a fault, then the pre-Cambrian crystalline rocks adjacent to it occur in a small window within the Hot Springs window.

The Hot Springs window may be compared with a few other windows with multiple faulting. Both the Hot Springs window and the nearby Mountain City window are analogous in certain respects to the Engadine window of the Central Alps. All are framed by more than one thrust fault and are therefore eyelid windows. The sequence of tectonic events which led to the formation of the Hot Springs structure may have been comparable to that of the Engadine window, as interpreted by Sander.

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INTRODUCTION

Location.—The Hot Springs area lies in the western part of Madison County, North Carolina, and in the eastern part of Cocke County, Tennessee (fig. 1). The area covered by the geologic mapping on which this paper is based is elongate in an east-west direction with a length of about 10½ miles and a width of 5 miles, and thus includes about 55 square miles.

The Hot Springs area lies near the northwest margin of the Blue Ridge physiographic province. The mountains of the area are part of the Bald Mountains, which are in the Unaka Range of the Blue Ridge province. To the southeast lies the Blue Ridge Plateau on which Asheville, North Carolina is situated; to the northwest, the Appalachian Valley of Tennessee.

The Hot Springs window includes one of the few southeastern exposures of Paleozoic carbonate rocks in a province underlain predominantly by clastic, metamorphic, and granitic rocks. The presence of these carbonate rocks, as well as of North Carolina's only hot springs, and the occurrence of relatively good exposures have long attracted the interest of many geologists. However, previous work in the area was essentially of a reconnaissance nature whereas the present paper is based on a detailed study.

Previous work.—Keith (1904, p. 8) was the first to recognize the unusual nature of the structure around Hot Springs, N. C.; he mapped a single fault almost completely around the area of the Hot Springs window, but did not join the ends on the southeast side. Yet he believed that on the north side the thrust sheet had been overthrust from the north, and on the south side, from the south. "The area inclosed by the fault plane thus represents a downthrown mass upon which the adjoining rocks were piled high from all sides." The trace of the fault was described as an almost complete oval and "its planes, if extended upward, would almost unite in a dome".

The lithologic similarity between mylonitized granitoid rocks and sheared arkose (see below) led Keith to map the former as long, thin isoclinal synclines of Snowbird rocks in the Max Patch granite. As a result, several thrust faults were overlooked and the many "whiskers", or thin outcrop areas, of Snowbird rocks on Keith's map make the geological structure appear overly complex.

The Hot Springs area was first shown as a window on the

Geological Map of the United States (1932) but it was not described as such until 1944 (Stose and Stose, 1944, pp. 385-386). The window is described more fully, however, in a paper by Stose and Stose (1947) on the origin of the hot springs. In that paper they describe (pp. 624-625) the structural unit as "... the Hot Springs window of the Great Smoky overthrust block which has been domed and later eroded, exposing overridden rocks in an oval window". The long narrow isoclinal synclines of Snowbird rocks on Keith's map are interpreted by them as mylonite zones along subsidiary thrust faults which offset the trace of the Great Smoky thrust fault along the southern margin of the window. Their interpretation of the structure of the western part of the window is based upon Keith's map.

Stose and Stose, as well as Keith, were misled in their interpretation of the structure of the south-central part of the

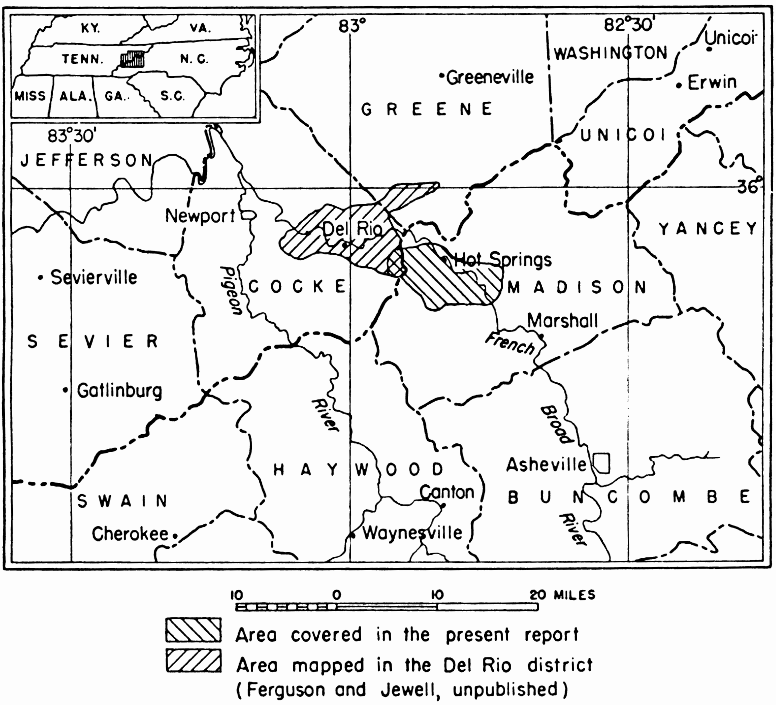


Figure 1. Index map of western North Carolina and eastern Tennessee.

window by their belief that a belt of granitic rocks extends continuously from Bluff to the segment of the river between Stackhouse and Sandy Bottom; the present writer found that the western flank of Spring Creek Mountain, east of Bluff, is underlain by sedimentary rocks of the Snowbird formation (fig. 2).

In a manuscript soon to be published as a bulletin of the Tennessee Division of Geology, Ferguson (Ferguson and Jewell, in press) describes in detail the geology of the Del Rio district, Cocke County, Tennessee, including the westernmost portion of the Hot Springs area (fig. 1). Ferguson points out that the Hot Springs window is framed on the west by at least two thrust faults, and that one intersects and has overridden the other. His competent field mapping and detailed discussions of the structural and stratigraphic relations of the thrust blocks lying to the northwest of the Hot Springs area will be invaluable to future regional studies.

Field work.—The field study of the Hot Springs window by the author was made over a period of five months, between June and November, in 1948. Detailed stratigraphic studies were restricted to the rocks within the window. Readily traceable lithologic units, especially resistant quartzite beds, were utilized as formational boundaries and followed along their strikes. Discordant contacts between rocks of different lithologies were also mapped in detail.

The topographic base used throughout the study was that of the Tennessee Valley Authority and the U. S. Geological Survey prepared on a scale of 1:24,000 from aerial photographs.[1]

Acknowledgments.—The writer is grateful for the assistance of many individuals and particularly to John Rodgers for enthusiastic aid, advice, and helpful criticisms throughout the study. Field work was financed by the North Carolina Department of Conservation and Development from funds pledged for cooperative work with the Tennessee Valley Authority; J. L. Stuckey, state geologist, C. E. Hunter, Benjamin Gildersleeve, and the late H. S. Rankin of the T.V.A. were most cooperative. Office and laboratory work was financed

[1] Specific localities mentioned in this paper but not shown in figure 2 may be found on the following topographic sheets of the TVA-USGS series: Paint Rock (182NW), Lemon Gap 182SW), Hot Springs (182NE), Spring Creek (182SE), White Rock (191NW), and Marshall (191SW).

by the Shell Oil Company, Inc., in the form of a fellowship at Yale University during the academic year 1948-1949. J. B. Cathey served as a conscientious field assistant. H. W. Ferguson, assistant state geologist of Tennessee, supplied invaluable unpublished data on the Del Rio district, and made available his field maps of the Tennessee portion of the Hot Springs window. John Rodgers, C. R. Longwell, E. B. Knopf, P. B. King, J. B. Hadley, and E. L. Reed read the manuscript or portions thereof. The illustrations were drafted by Mrs. Marian Wheeler, of the Office of Geologic Cartography, U. S. Geological Survey. To all of these, and others, the writer wishes to express his gratitude.

STRATIGRAPHY

Inasmuch as the structural features of the Hot Springs window are the primary concern of the present paper, only a brief outline of the stratigraphy is presented here. The reader is referred to Bulletin 60 of the North Carolina Department of Conservation and Development (Oriel, 1950) for more detailed discussions of the stratigraphic relations on which the conclusions presented here are based.[2]

All the formations shown in table 1, from the pre-Cambrian crystalline complex up to and including the Honaker limestone, are represented within the Hot Springs window. The outcrop belts of the formations trend approximately east-west, with the youngest formations to the north (fig. 2). In the northern part of the window, the beds dip steeply to the north and are slightly overturned in places. Dips decrease southward within the window. Outside the window, only the Unicoi and older formations are present. Here too, the youngest formation, the Unicoi, is on the northwest and is succeeded by older formations to the southeast.

Although the Hot Springs area forms a part of that described in the Asheville folio (Keith, 1904), the names applied to the rocks in the present paper differ from most of those in Keith's report. The reasons for the changes in terminology are discussed in the aforementioned bulletin (Oriel, 1950).

In general, all but the lower three units used here correspond to those recently described in detail by geologists in eastern

[2] The bulletin also contains petrographic data and descriptions of the geography, topography, mineral resources, and hot springs of the area herein described.

TABLE 1.

Generalized section of the geologic formations in the Hot Springs area.

Age	Group	Formation	Member	Character	Thickness in ft.
Middle Cambrian		Honaker limestone		White, gray, and blue-gray limestone with silty and shaly laminae and concentrically banded chert nodules.	?
Middle Cambrian		Rome formation		Red, maroon, and brown siltstone and shale with interbedded light gray and blue-gray dolomite and greenish shale.	?
Early Cambrian		Shady dolomite		Blue-gray, light gray, white and ribboned dolomite with some interbedded limestone.	1975 (max.)
Early Cambrian	Clastic Group of Lower Cambrian Series	Erwin formation		Dark green siltstone, silty and sandy shale, white vitreous quartzite, and purple ferruginous quartzite, with calcareous siltstone (Helenmode member) at the top.	1700-2100
Early Cambrian	Clastic Group of Lower Cambrian Series	Hampton formation	Upper shale	Alternating dark green siltstone, silty and sandy shale, and thin-bedded quartzite.	200-300
Early Cambrian	Clastic Group of Lower Cambrian Series	Hampton formation	Middle quartzite	Crossbedded medium- to coarse-grained feldspathic quartzite and arkose with pebbly beds and vitreous quartzite.	500-750
Early Cambrian	Clastic Group of Lower Cambrian Series	Hampton formation	Lower shale	Interbedded dark green siltstone, argillaceous shale, and sandy and silty shale.	210-380
Early Cambrian	Clastic Group of Lower Cambrian Series	Unicoi formation		Coarse feldspathic and vitreous quartzite, conglomerate (some with slate inclusions), siltstone, slate, and micaceous sandstone.	1400-2600
	Unconformity (?)				
Unknown	Clastic Group of Unknown Age	Sandsuck formation		Dark green and blue-green slate, shale, and well-laminated siltstone with gray sandy and black slaty bands; includes conglomerate and limestone lenses.	(about) 700
Unknown	Clastic Group of Unknown Age	Snowbird formation		Interbedded pebbly, vitreous, and feldspathic quartzites, arkose, shale, siltstone, slate, micaceous and calcareous sandstones, and mylonite.	1500-4600 (min.)
	Unconformity (?)				
Pre-Cambrian		Crystalline complex		Sericitized and epidotized granitoid, aplitic, pegmatitic, and basic rocks (undifferentiated in this report) and mylonite.	

Tennessee (King *et al.*, 1944; Rodgers, 1948; Ordway, unpublished; Ferguson and Jewell, in press). King (1949), however, places the writer's "clastic group of unknown age", *i.e.* the Snowbird and Sandsuck formations, in the late pre-Cambrian Ocoee series, whereas Stose and Stose (1949) retain the Sandsuck in the Lower Cambrian Chilhowee group and abandon the name Snowbird.[3]

The Hot Springs window contains a rather isolated inlier of relatively young carbonate and finely clastic rocks in a region where clastic and highly metamorphosed rocks predominate. Except for a few occurrences near the tops of thrust sheets elsewhere in the Unaka Range (Ferguson and Jewell, in press), outcrops of the Shady, Rome, and Honaker formations are restricted largely to the Valley and Ridge province.

The Hot Springs area also includes the southeasternmost exposures of known, relatively unmetamorphosed, Cambrian clastic rocks. These rocks lie along the projected axis of the Mountain City window (King *et al.*, 1944, pp. 10-13) which, except for the Grandfather Mountain window, also contains the southeasternmost-known exposures of relatively unmetamorphosed Cambrian sedimentary rocks.

Unlike greatly deformed areas in the Valley and Ridge province, the Hot Springs area includes exposures of true basement rocks (pre-Cambrian crystalline complex) which were involved in the thrusting.

STRUCTURE

General Features of Window

The Hot Springs window is 10.4 miles long, along its east-west axis, and has a maximum width of 6.4 miles in a north-south direction. However, the area within the window is somewhat less than 50 square miles.

The window is framed by not one but four different thrust sheets (fig. 3). Moreover, if the contact between the sedimentary and the crystalline rocks inside the window is a thrust fault, as the writer believes, then there are two major structural units within the window.

Other structural features in the area are closely related to the thrusting. The orientation of axial planes of folds near the faults suggest a genetic relation to the thrusting. Where

[3] This problem too is discussed more fully elsewhere (Oriel, 1950).

evident, shear planes in mylonite closely parallel trends of the thrust surfaces. Cleavage developed in the area may be attributable to the forces responsible for the thrust faults. Moreover, the mineralization in the area is closely related to the thrust faults—at least geographically if not genetically.

The structural features here described cannot be dated accurately from evidence in the Hot Springs area. Inasmuch as all the rocks have been affected, deformation is post-Honaker, or post-Middle Cambrian in age. Thrusting in the Southern Appalachians, northwest of the Piedmont, is generally assigned to the Late Paleozoic (Appalachian) orogeny, but the possibility that at least some may have taken place during earlier orogenic pulses is by no means eliminated.

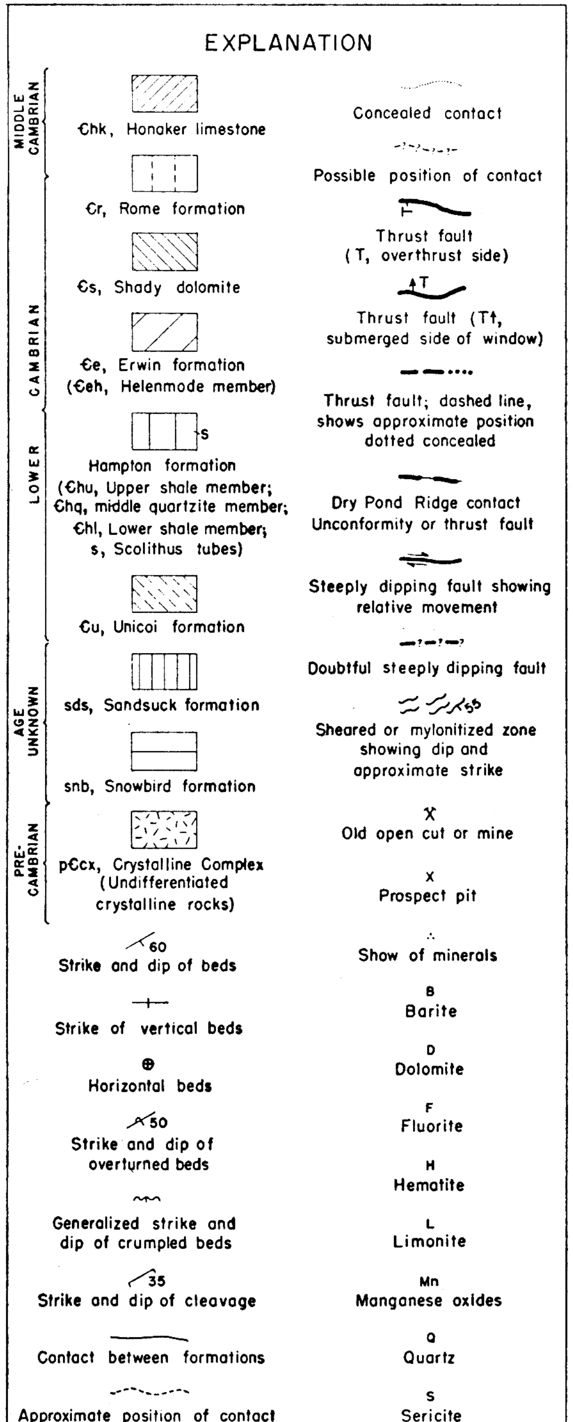
Thrust Faults

Faults framing window.—The four thrust faults and thrust sheets that frame the Hot Springs window are shown in figure 2 and shown and named in figures 3 and 4.

The Mine Ridge thrust fault is the most evident and best-documented thrust fault in the Hot Springs area. The fault trace extends three-fourths of the distance around the window, beginning at Wolf Creek on the west and passing eastward and southward to Coley Gap on the south side of the window. The fault separates rocks of the Snowbird, Sandsuck, and Unicoi formations outside the window from the predominantly younger rocks within, and truncates younger formations inside the window. Only on the southeastern side of the window, where Snowbird rocks above the fault overlie pre-Cambrian crystalline rocks, do younger rocks overlie older. On the north, the Mine Ridge thrust fault dips gently northward, whereas on the south and east sides it dips steeply to the southeast.

The Mine Ridge thrust fault forms the base of the Del Rio thrust sheet, named by Ferguson (Ferguson and Jewell, in press) for the town of Del Rio, Cocke County, Tennessee. In the Hot Springs area, only the Unicoi, Sandsuck, and Snowbird formations are present in the Del Rio sheet. In the area mapped by Ferguson, however, other formations up to and including the Rome are present.

The Brushy Mountain thrust fault was named by Ferguson for exposures on Brushy Mountain, Cocke County, Tennessee. In the course of his investigation, Ferguson traced the fault



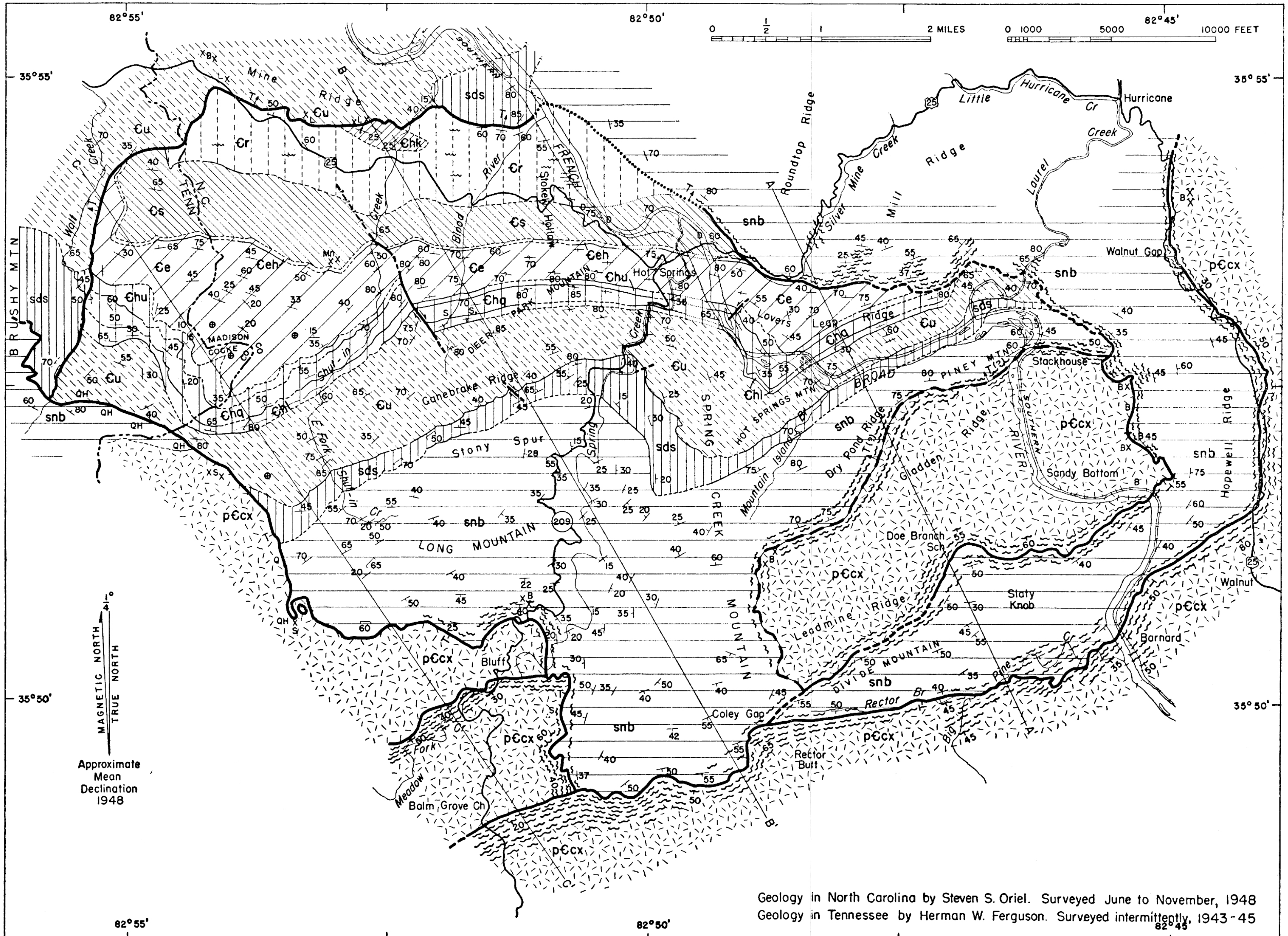


Figure 2. GEOLOGIC MAP OF HOT SPRINGS AREA, MADISON COUNTY, NORTH CAROLINA

as far east as the old barite mine north of Bluff. The fault can be traced only a short distance beyond the mine to the point where it is truncated by the Meadow Fork thrust fault. As discovered by Ferguson, the trace of the Brushy Mountain thrust fault truncates the trace of the Mine Ridge fault at the west end of the window and it also truncates sedimentary contacts within the window. Almost everywhere along the fault in the area, sedimentary rocks within the window dip toward (under) the older crystalline rocks outside the window. In most places the fault dips to the south and southeast.

Above the Brushy Mountain fault is the Brushy Mountain thrust sheet. The sheet is present only in the southwestern part of the area mapped by the present writer and includes here only pre-Cambrian crystalline rocks and part of the Snowbird formation. The Brushy Mountain thrust sheet overlies the Del Rio thrust sheet as well as rocks within the window.

Only a small portion of the Meadow Fork thrust fault is exposed in the southern part of the Hot Springs area. The fault truncates the southeastern portion of the Brushy Mountain fault. It is probable that the fault is at least as extensive as the "synclinal" belt of "Snowbird" rocks shown on Keith's map (1904) extending six miles southwestward from Puncheon Camp Branch. Evidence is given below that this belt is a mylonite belt.

The Meadow Fork thrust sheet is here defined as the thrust sheet immediately overlying the Meadow Fork fault. The sheet consists entirely of pre-Cambrian crystalline rocks which are in part mylonitized. These rocks overlie rocks of the Brushy Mountain thrust sheet as well as those of the Snowbird formation within the window.

The Rector Branch thrust fault is named for the branch which follows the fault trace for over a mile in the south central part of the Hot Springs area. The trace of this thrust fault truncates the traces of both the Meadow Fork and Mine Ridge thrust faults, as well as bedding trends in the Snowbird rocks within the window. Projected dips, as well as several outcrops along U. S. Highway 25-70, show that the pre-Cambrian crystalline rocks above the fault overlie Snowbird rocks below the fault throughout much of its extent. The Rector Branch fault probably continues northward outside the area mapped in this study, at least as far as Little Hurricane Creek, as shown on Keith's map (1904). On the southwest, it is possible that the fault continues across and beyond Hogback Mountain, but more detailed field work is necessary to test this view.

The hanging wall of the Rector Branch thrust fault is here designated the Rector Branch thrust sheet. Inasmuch as the Rector Branch fault was used as the approximate southern limit of the area covered by the writer, little can be said about this thrust sheet except that, where seen, it is made up of pre-Cambrian crystalline rocks. The thrust sheet directly overlies the Meadow Fork and Del Rio thrust sheets, as well as Snowbird rocks in the southern part of the window. Thus, it is the uppermost structural unit in the entire area.

Mylonite.—Immediately adjacent to the thrust faults throughout much of the area are thick zones of mylonite.[4] These proved to be useful in mapping the thrust faults, especially where granitoid rocks of the pre-Cambrian crystalline complex are in fault contact with other granitoid rocks.

The mylonite in the Hot Springs area was formed by the microbrecciation of pre-Cambrian crystalline rocks and of Snowbird feldspathic quartzite and arkose. Superficially the rock, despite its original nature, resembles vitreous feldspathic quartzite in appearance; it differs from such quartzite in the presence throughout of well-developed shear planes (which may, however, resemble bedding). In many places it is extremely difficult to distinguish between the mylonite derived from pre-Cambrian granitoid rock and that derived from Snowbird arkose. One useful criterion, however, was afforded by thin sheets of pegmatitic pink feldspar that are not uncommon in the crystalline complex. Because feldspar is one of the minerals most resistant to microbrecciation, these sheets persist as thin and fairly continuous laminae and lenticles of pink feldspar parallel to the shear planes in the mylonite. Recognition of these laminae and lenticles enables one to identify mylonitized pre-Cambrian crystalline rock.

The close resemblance between mylonite and undeformed

[4] Mylonite is defined as a strongly coherent, fine-grained, conspicuously laminated rock formed by extreme microbrecciation and milling of rocks during movement on fault surfaces, with little or no growth of new minerals (see Turner, 1948, p. 201; Waters and Campbell, 1935, pp. 474-476, 478). Petrographic descriptions and photomicrographs of the mylonite in the Hot Springs area appear elsewhere (Oriel, 1950).

feldspathic quartzite led Keith (1904) to map some of the mylonite belts as narrow isoclinal synclines of Snowbird rock in granitic rock. The writer too was deceived by the resemblance during the first half of the field season.

Mylonite is best developed along the bases of the thrust sheets. The distribution of these deformed rocks is indicated by the wavy symbol on figure 2. Closely spaced concentrations of these symbols indicate localities where the mylonite is best developed and thickest. As suggested by figure 2, the writer was able to recognize the presence of the Meadow Fork thrust fault and to trace the western part of the Rector Branch fault largely on the basis of mylonite along the faults.

Other rock behavior near thrusts.—Not all the rocks near the thrust faults are mylonitized; in many places broken, brecciated and somewhat sheared, though unmylonitized, rocks are present. Although rocks are somewhat fractured almost everywhere in the area, the degree of mashing and brecciation is increased with proximity to the faults.

In general, deformed competent beds appear to have yielded by shattering. For example, where the vitreous quartzite beds of the upper part of the Erwin formation lie almost immediately beneath the Mine Ridge thrust surface, they are shat-

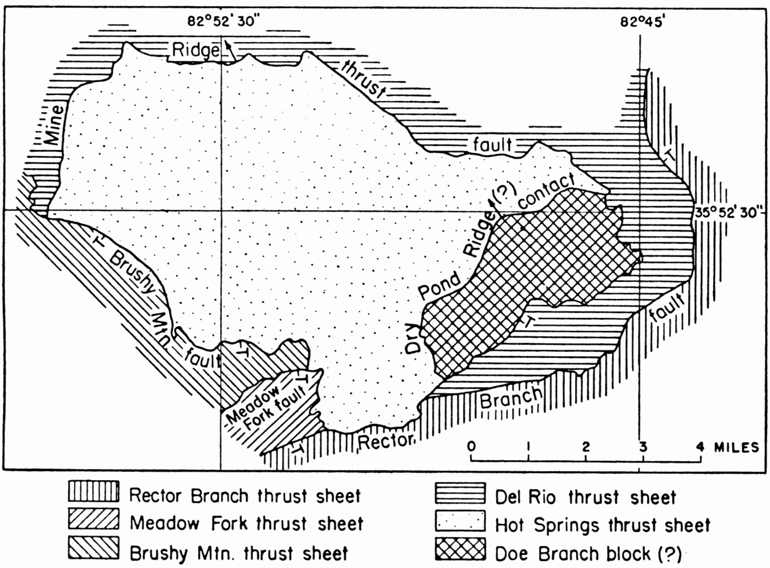


Figure 3. Generalized structural map of the Hot Springs window.

tered and form a fault breccia. Sharply angular fragments of quartzite, ranging in size from minute slivers to blocks several feet long, are embedded in a ferruginous matrix. Such breccia is well exposed about 1200 feet south of U. S. Highway 25-70 and in ledges near the top of the northernmost slope of Lovers Leap Ridge.

Crush breccias have been formed from somewhat less competent beds of arkose and quartzite with some interbedded slate. One good example is exposed immediately below the Rector Branch thrust fault in a road cut on U. S. Highway 25-70, 2200 feet southeast of Walnut Gap.

Incompetent slate, shale, and thinly bedded siltstone are considerably folded, crinkled, and somewhat fractured near the faults, and in places are subphyllitic. The Sandsuck beds exposed in railroad cuts near Runion are an example. That these rocks belong to the Sandsuck formation is clearly shown by exposures of overlying basal Unicoi conglomerate a few hundred feet up the mouth of Big Laurel Creek.

Barite and other mineralization.—In many places throughout the area, fault surfaces and fractures in rocks adjacent to the faults are loci of mineralization (fig. 2). Structural control of the barite mineralization in the Hot Springs district was pointed out by Stuckey in 1942 (p. 107). Specular hematite, fluorite, sericite, secondary quartz, calcite, and traces of pyrite and chalcopyrite are also found in the rocks along the faults in assemblages which may or may not include barite.

As mapped in the present study, most of the barite mines in the Stackhouse area, the most productive in Madison County, are located precisely on the Mine Ridge thrust fault. Ferguson and Jewell (in press) describe mylonite zones up to 9 feet thick along the Brushy Mountain fault in Cocke County, Tennessee, in which mineralizing solutions deposited barite, quartz, hematite, and sericite. In Madison County, the old barite mines and prospect pits north of Bluff are located in the fractured rocks immediately beneath the same fault. Moreover, four "talc" prospects were found along the base of the Brushy Mountain thrust sheet. Petrographic, chemical, and x-ray analyses show this "talc" to be almost pure sericite. Similar sericite aggregates are found locally along the Meadow Fork thrust fault. The Gahagan barite mines lie near the base of the Rector Branch thrust sheet, north-northeast of Walnut Gap. Traces of specular hematite, barite, sericite, and secondary quartz are also found in many other places along the Rector Branch fault.

Attitudes of thrust faults.—Although the thrust faults can be located accurately within a few feet in many places, the attitudes of the fault surfaces can be measured at only four localities within this area. The well-developed banding in the mylonite, however, suggests a means of determining the dips of the faults. In many places the bedding of the sedimentary rocks and the banding of mylonite below a thrust fault parallel the mylonite banding above it. It appears logical to assume that these well-developed s-planes parallel the thrust surface.

This assumption was tested at the four localities where the thrust surfaces can be observed. At the road cut on U. S. Highway 25-70, 2200 feet southeast of Walnut Gap, the shear planes in both overlying crystalline rocks and underlying sedimentary rocks trend N 40°W and dip 30° NE. The surface of the Rector Branch fault here is not a plane but curves with dips decreasing downward. The average attitude of the fault, however, is about N40°W 25°NE. The Brushy Mountain thrust fault is exposed at Beck Branch and in Turkey Cove, northwest of Bluff. At both localities the fault surface parallels the banding of the silicified mylonite and trends N65°E and dips 45°SE. The most important barite vein exploited in the area lies along the Mine Ridge thrust fault in the Stackhouse mines. Shear planes in the adjacent rocks parallel the vein and the thrust fault which dip 55 degrees to the east.

Thus, the assumption appears to meet the field tests at localities where it can be tested. Nevertheless, the assumption must be considered only tentatively true and is here used as an expedient. Mylonite dips are shown in figure 2. Although 20 degree dips are recorded, the thrust faults dip 40 to 50 degrees in most localities.

In the accompanying structure sections (fig. 4), the major thrust faults are depicted as decreasing in dip downward to a roughly horizontal surface from which the imbricate sheets were upthrust. The representation of the faults beneath the surface profile is, of necessity, hypothetical. The thrusts may dip more steeply even at the depths shown and are probably by no means smooth and planar.

Dry Pond Ridge Contact

Within the Hot Springs window, the contact between the Snowbird formation and the pre-Cambrian crystalline rocks is difficult to interpret. Because it parallels the southeastern flank of Dry Pond Ridge, the name Dry Pond Ridge contact is used here to facilitate discussion of its character. The mapped extent of the contact is shown in figures 2 and 3.

Keith (1904) and Stose and Stose (1947, p. 628) show the

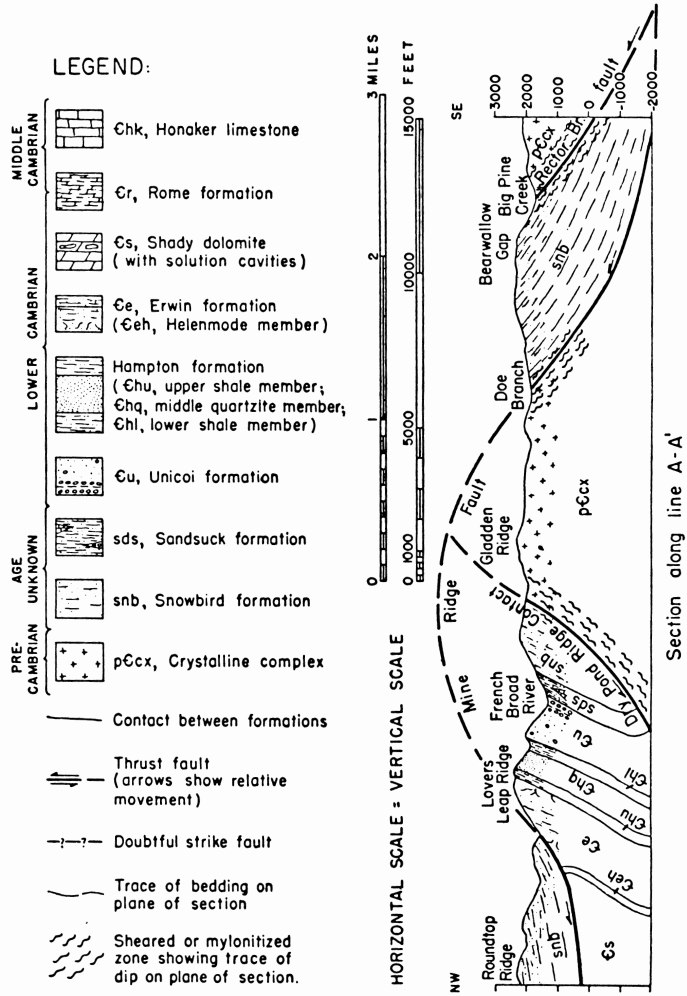
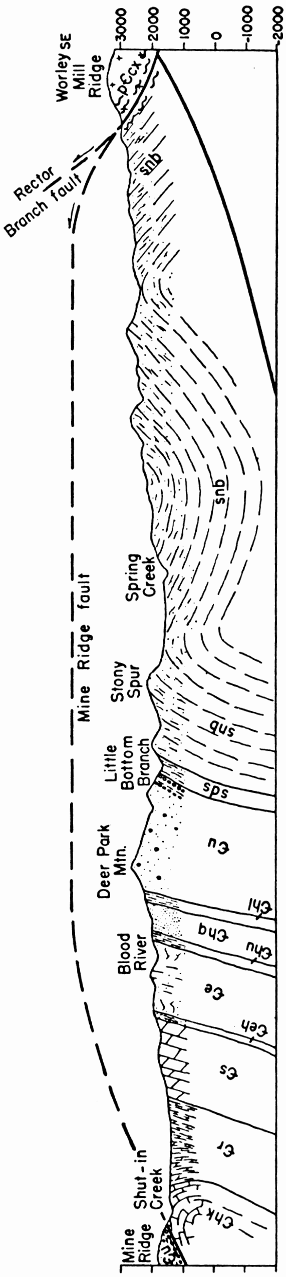
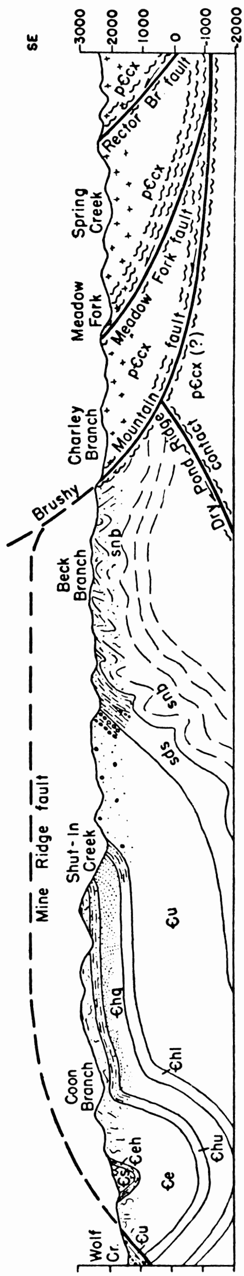


Figure 4. Geologic structure sections across the Hot Springs window. Lines of sections are shown in figure 2.



Section along line B-B'



Section along line C-C'

contact as an unconformity on their maps. On the basis of the following lines of field evidence, however, the writer questions this interpretation:

1. The rocks along the contact, especially the underlying crystalline rocks which have no bedding surfaces along which to slip, are considerably fractured and in many places mylonitized.

2. At least four occurrences of barite are present at or near this contact. Barite, fluorite, and quartz fill fractures in the crystalline rock exposed in the railroad cut 1000 feet southwest of the Stackhouse station. Two barite prospect pits lie in a gully about half a mile northeast of Goforth Cemetery (on the contact) and another lies about a mile west-northwest of Doe Branch school. All other occurrences of barite found in the Hot Springs area are known to be along thrust faults or in the fractured rocks immediately adjacent thereto.

3. The thickness of Snowbird rocks exposed above the contact southwestward from the French Broad River at Stackhouse is not constant (see fig. 2). Although this difference of thickness would easily be explained by faulting, the possibility that the sediments were deposited on an uneven surface cannot be eliminated with available data. However, the lowest beds found are only slightly pebbly and comparable to other beds in the formation; in no way do they resemble the basal conglomerate one might expect on such an uneven surface.

The nature of the contact is difficult to establish because younger beds overlie older. This is always true in unconformities which have not been overturned, and crossbedding indicates that the Snowbird rocks here are right side up. Nevertheless, it by no means eliminates the possibility that the contact is a thrust fault. Billings (1933) cites many known examples of younger rocks thrust upon older.

It may be argued that the evidence of shearing along the contact and the occurrence of barite is not conclusive proof of a thrust fault. In rocks subjected to extraordinary stresses, as those of the Hot Springs area obviously have been, one might expect a certain amount of shearing along a surface of weakness such as an unconformity. The minor slip planes developed along this surface, one might further argue, would localize later mineralizing solutions.

Although this line of reasoning is tenable, the writer nevertheless believes that the Dry Pond Ridge contact is a thrust fault. A third possibility, of course, is that a major thrust fault may have developed along an unconformity.

Despite the lack of conclusive evidence, the Dry Pond Ridge contact is shown as a thrust fault in the structure sections illustrated in figure 4, and the aggregation of sedimentary rocks within the window is here designated the Hot Springs thrust sheet (fig. 3). The mass of crystalline rocks exposed between the traces of the Dry Pond Ridge contact and the southeastern part of the Mine Ridge fault is here designated the Doe Branch block. There is no evidence to indicate whether the Doe Branch block is part of still another thrust sheet or part of the autochthonous rocks underlying the Hot Springs area.

The Hot Springs sheet is overlain on the west, north, east, and southeast by the Del Rio thrust sheet, and on the southwest and south by the Brushy Mountain, Meadow Fork, and Rector Branch thrust sheets.

Other Faults

In addition to the thrusts, four minor faults were mapped in the rocks within the window. The most extensive of these faults is the one trending northwest from the southwestern end of Deer Park Mountain across Shut-in Creek to Dry Branch. Although the fault surface itself was not seen in any outcrop, the writer believes the fault well substantiated by the abrupt offset of the Hampton formation (especially the easily traceable middle quartzite member) and of the upper ledge-forming quartzites of the Erwin formation. The apparent relative displacement of the southwest block is to the northwest. Truncation of formational boundaries occurs along a comparatively straight line despite moderately rugged topography, thereby suggesting that the fault has a steep dip.

Another fault with a smaller relative displacement in the same direction occurs just north of Stony Spur and west of Spring Creek. The presence of the fault is easily recognized where the lower Unicoi conglomerate beds on the northeast side of the fault are in contact with Sandsuck slate southwest of it.

The other two faults strike northeast and the apparent relative displacements of the southeastern blocks are to the northeast. The fault south of Hot Springs and just east of Spring

Creek was recognized by the slight offset of the basal Unicoi conglomerate beds across their strike. The evidence for the fault southeast of Hot Springs and east of French Broad River is the abrupt change from Hampton middle quartzite beds to upper Hampton shale beds along a contact normal to the strike of the bedding.

Although all four of the faults described here have steep dips, the lack of other data makes it difficult to classify them except as dip faults. The fault first described, however, offsets nearly vertical beds for a considerable distance and its displacement is probably at least partly, if not wholly, strike-slip.

The writer was unable to find any evidence to support the cross fault inferred by Stose and Stose (1947, pp. 641-644) in their discussion of the origin of the hot springs.

Folds

The magnitude of the folds developed in the strata of the Hot Springs area ranges from microscopic to several miles. Inasmuch as the largest folds are quite evident on the geologic map (fig. 2) and in the structure sections, the discussion which follows deals largely with the others.

The rocks of the Honaker formation are horizontal, or nearly so, where exposed in Mine Hollow, whereas the underlying rocks, as far southward and down the section as the Unicoi formation, dip steeply to the north. Efforts to determine whether the Honaker limestone beds are right side up proved unsuccessful. If the beds are right side up, then the outcropping Honaker beds lie along the axis of a normal syncline. If the beds are upside down, however, then the fold in which they appear is an "anticline", as shown in figure 4, section B-B′. Both are possible. However, the writer believes the "anticline" interpretation the more likely because one would expct vertical beds to be affected by the northward drag near the over-riding thrust fault.

The word anticline is placed in quotes above because in this interpretation the structure is really an upside-down syncline. A normal anticline is a fold with older rocks toward the center of curvature. In the fold shown in figure 4, section B-B′, one passes into younger rocks in going towards the center of curvature.

Comparable folds may be present in other localities in the area. The structure of upper Erwin strata exposed in the long road cut near the Hot Springs school, on U. S. Highway 25-70, is described by Stose and Stose (1947, pp. 630, 641-642) as anticlinal. Although the beds are arched up, the possibility that the sequence is overturned is suggested by the downward pinching out of quartzite beds which somewhat resemble coarse upside-down crossbedding. Moreover, in the poorly exposed but critical portion of the outcrop, on the north side of the large fold, there is a suggestion that the strata swing up again. South of the axis of the fold, all strata dip steeply to the north and are right side up. Nowhere, south of the U. S. Highway bridge across Spring Creek, are dolomitic rocks of the Shady formation present in the fairly continuous exposures along the bluffs of Spring Creek, as one would expect if the fold were a normal anticline.

Folds in the Shady dolomite are exposed along the east bank of the French Broad River opposite the town of Hot Springs. The folds measure tens of feet from crest to crest and the attitudes of their limbs are approximately N-S 30-35°E and E-W 50-70°N. The axial planes of these folds thus dip to the southeast. The proximity of these folds to the Mine Ridge thrust fault suggests that they were formed as a result of drag along that fault surface.

In the area mapped, rocks of the Rome formation are highly contorted. Folds are intricate and range in magnitude from a few inches to at least tens of feet. The multifarious trends of the axial planes of the folds make it difficult to determine the relation of these folds to the broader structural features of the area.

The writer found no structural evidence supporting Keith's (1904) interpretation of a syncline which repeats the Shady dolomite in a belt along the northernmost part of the window. Stratigraphic observations, on the other hand, indicate the presence of Honaker limestone within the window and show that the Rome formation includes interbedded Shady-like dolomite beds which Keith may have assigned to the Shady formation, along with the Honaker, where the enclosing shale was not exposed.

Cleavage

Cleavage is present in the fine- and very fine-grained clastic rocks beneath the Shady dolomite in many, but not all, localities in the area. The cleavage appears to be best developed in the rocks of the Sandsuck formation. The nature of the cleavage differs with the lithology. In the predominantly argillaceous beds, cleavage planes are closely spaced and parallel the planes of the preferentially oriented sericite plates. In rocks with larger silt and sand fractions, cleavage planes are not so numerous and somewhat resemble closely spaced joints.

In general, cleavage planes strike to the northeast and dip about 50 degrees to the southeast. Local exceptions include rocks in which cleavage parallels bedding which does not dip to the southeast and rocks in which cleavage intersects bedding and dips to the east. Where bedding does dip to the southeast, cleavage closely parallels the bedding.

In some shales and slates, cleavage surfaces are folded and crinkled. The crinkles appear to have developed by minor slip along the bedding (which in most places forms a steep angle with the cleavage) after the cleavage planes formed in the rock.

Relative Direction of Thrust Movement

The following points support the conclusion that the relative movement of each thrust sheet in the Hot Springs area was approximately from the southeast to the northwest with respect to underlying rocks:

1. Most of the thrust faults dip to the south, southeast, and east. One notable exception is the Dry Pond Ridge contact, if it is a thrust fault, which dips to the northwest and west, but it is possible that the root zone for this fault is concealed beneath the southeastern part of the Del Rio sheet. The other exception is the northern part of the Mine Ridge thrust fault which dips to the north and northwest, but the root zone is exposed in the southeastern part of the area mapped. An attempt is made in later pages to explain the northward dips of these faults.
2. In general, cleavage planes dip to the southeast and east.
3. Axial planes of drag folds in the Shady dolomite, just below the Mine Ridge thrust fault, dip to the southeast.
4. Almost all the thrust sheets described northwest of the Piedmont in the Southern Appalachians are believed to have moved relatively to the northwest (*e.g.* Butts, Stose, and Jonas, 1932, p. 7; Butts, 1940, pp. 440-464; King *et al.*, 1944, p. 11). From these and other structural features, it has been concluded

(Chamberlin, 1928, p. 90) that the region was subjected to stresses which might be described as a couple in vertical planes trending NW-SE. Forces near the surface were directed northwestward while deeper in the crust they were directed southeastward. According to this interpretation, it is not likely that any of the major thrust sheets in the Hot Springs area moved relatively to the southeast.

Therefore, it is concluded from both field observations and regional considerations that the movement of the thrust sheets in the Hot Springs area was northwestward relative to the rocks below them.

It does not appear possible, on the basis of existing data, to determine the magnitude of the fault displacements, nor their southeastward extent. However, it is likely that the minimum figure would be a few, or possibly tens of miles.

Summary of Structural Data

From the foregoing discussion, it is evident that the Hot Springs window is not a simple window which has formed by erosional penetration through a single thrust sheet to expose the underlying, overridden rocks. The frame is made up not of one, but of four different thrust sheets. Moreover, the existing data which suggest that the Dry Pond Ridge contact is a thrust fault also indicate that a smaller window, framed by two different thrust sheets, may be exposed within the Hot Springs window.

Noteworthy features of the window which will be further discussed below may be summarized as follows:

1. The window is framed by more than one thrust fault.

2. Both the axis of elongation of the Hot Springs window and the general bedding of the rocks within the window strike across the regional structure of the Southern Appalachians. The general bedding and the axis of elongation of the window strike about east-west whereas regional structures strike predominantly NE-SW.

3. Fault surfaces around the window dip steeply (40° to 50°) away from the window.

4. The fault surfaces framing the window converge downward at a considerable angle and merge to form the major movement zone (fig. 4).

5. Mylonite is present along portions of each of the thrust faults.

6. The Hot Springs thrust sheet within the window may be arched over the granitoid rocks of the Doe Branch block. This cannot be proved inasmuch as the rocks beneath the Del Rio sheet and southeast of Doe Branch are concealed. However, trends of the Dry Pond Ridge contact and the overlying sedimentary rocks suggest that a southwest plunging anticline may be present within the window.

7. Reference to a regional geologic map (see Geologic Map of the U. S., 1932, or Tectonic Map of the U. S., 1944) indicates that the Hot Springs window lies along the projected axis of the Mountain City window in northeastern Tennessee. Except for the Grandfather Mountain window, the rocks in the Hot Springs and Mountain City windows constitute the southeasternmost exposures of known Cambrian formations in this segment of the Appalachians.

COMPARISON WITH OTHER COMPLEX WINDOWS

Before attempting to trace the sequence of tectonic events which led to the formation of the Hot Springs structure, the writer found it instructive to examine a few other windows with multiple faulting. Such complex windows are not unknown although comparatively few have been described.

Southern Appalachian Examples

Rose Hill district.—The Rose Hill district in Lee County, Virginia (Miller and Fuller, 1947), is notable both for the complex structural relations and for the oil production obtained from the Cambrian and Ordovician carbonate rocks beneath the Pine Mountain thrust fault. Thirteen windows, some of which are small windows within larger ones, are present within five miles almost along the axis of the Powell Valley anticline. "In much of the fenster area the Pine Mountain overthrust consists of a fault zone having well defined upper and lower planes of movement, between which there are slices of folded and faulted rocks" (*op. cit.*). These upper and lower movement planes are roughly parallel. Some of the windows, *e.g.*, the Hamblin Branch and Possum Hollow fensters, are framed by only one plane of movement. Others, *e.g.*, the Dean, Fourmile, and Sugarcamp fensters, are parts of the stationary block framed by both the upper and lower branches of the Pine Mountain thrust, *i.e.* each is bounded on one side by rocks of the Cumberland thrust block and on the other by the fault slices.

Moreover, these latter windows lie within a larger window framed only by the Cumberland thrust block.

Draper Mountain structure.—The Draper Mountain structure in southeast Virginia is described by Cooper (1939, p. 71) as a "breached anticlinal compound fenster" which has been "formed by the crenulation of two thrust sheets and subsequent erosion through both of them". The breached window is almost completely framed by the Pulaski and the Max Meadows thrust faults which roughly parallel each other. It is possible that the Max Meadow fault is merely a lower plane of movement and forms, with the Pulaski fault, a single zone of movement, comparable to the Pine Mountain fault zone.

Roanoke district.—Unlike the aforementioned windows, the Round Hill and the Coyners-Mills fensters, as well as the Goose Creek breached fenster, in the Roanoke area, Virginia ((Woodward, 1932, plate 1, figs. 4, 5, pp. 80-90; Butts, 1932, map and sections J-J′), have each been mapped as windows framed by a single thrust sheet. The first two lie beneath the Pulaski thrust sheet, whereas the Goose Creek breached fenster is almost completely bounded by the Blue Ridge thrust sheet. Despite the presence of simple windows, the area is mentioned here because of the multiple faulting. The Blue Ridge thrust sheet lies above the Pulaski sheet, which in turn overlies the Saltville fault block. Although the Blue Ridge and Pulaski faults do not unite at the surface, they may at depth; indeed, they are so shown in the structure sections by Woodward and by Butts. Thus, it is probable that the Roanoke structure compares with the Hot Springs structure in the downward merging of the faults underlying the imbricate thrust sheets.

Mountain City window.—The Mountain City window in northeast Tennessee (King *et al.*, 1944, pp. 11-13, fig. 2, plate 1) is comparable to the Hot Springs window in several ways, although it is considerably larger and more complex. The window is framed on the northwest by the Iron Mountain thrust fault and on the southeast by the Stone Mountain thrust fault. The structure is complicated, however, by the cross faults which offset the framing thrusts and by the many thrust faults within the window. The Iron Mountain and Stone Mountain faults unite at the surface on the south and northeast sides of the window and thus converge downward and merge to the southeast (*op. cit.*, plate 1, sections D-D′ and E-E′). Moreover, within the Mountain City window lies another, the Limestone Cove window. This window too is immediately overlain by two different thrust sheets: the sheet overlying the Limestone Cove thrust fault on the northwest and the Stone Mountain sheet on the southeast. The faults beneath these thrust sheets also converge to the southeast and merge, albeit upward due to folding of the thrusts. Thus, in the Mountain City and Hot Springs windows, as well as in the Roanoke area, the convergence of the faults is in the direction from which the thrust sheets are believed to have moved.

Engadine Window

The Hot Springs and Mountain City windows are closely analogous in form to the classic Engadine window of the Central Alps. For this reason, a somewhat fuller discussion of that window is presented here. Much of the material which follows was drawn from a detailed study by Hammer (1915) and from summaries by Sander (1921, pp. 193-195, 198, 213-214) and Klebelsberg (1935, pp. 139-146).[5]

Geology of Engadine window.—The Engadine window is subovate in form and trends NE-SW in a region (only part of which is represented in figure 5) where E-W trending structures predominate. The rocks within the window are named the Bündner Schiefer and include calcareous schist, mica schist, chlorite schist, and phyllite of Mesozoic age. The Bündner Schiefer forms a large symmetrical anticline whose limbs dip steeply and uniformly to the northwest and southeast; the axis of the anticline trends NE-SW and passes almost through the middle of the window.

The frame on the north side of the window consists of the Silvretta mass of Early Paleozoic gneisses. The Silvretta mass is a rootless thrust sheet which has moved from the southeast to the northwest. The Oetztal mass frames the window on the southeast and is made up of rocks similar in age and lithology to those in the Silvretta. The older rocks of both the Oetztal and Silvretta masses rest upon the Bündner Schiefer above thrust surfaces which dip steeply (40° or more) away from the

[5] Less comprehensive summaries of the geology of the Engadine window have been published in the English language by Collet (1927, pp. 27, 215, 230-231) and by Heritsch and Boswell (1929, pp. 27-28, 66, 70-76, 102-105, 153-154).

window. Only in a few localities do the thrust faults dip more gently. Mylonite is fairly well developed along the base of both thrust sheets. Northeast and southwest of the window, the Oetztal mass has been thrust over the Silvretta. Thus, the Silvretta gneiss has been thrust over the Bündner Schiefer and both have been overridden by the Oetztal gneiss. As in some of the aforementioned structures, the fault beneath the Oetztal mass diverges upward to the northwest from the fault beneath the Silvretta, *i.e.* the faults converge downward and merge in the direction from which the thrust sheets are believed to have moved.

Definition of eyelid window.—The Engadine fenster, then, is not a simple window but one framed by two different thrust surfaces. For this reason, Sander (1921, p. 193) proposed the term shear-window (*Scherenfenster*) and defined it as a window whose rocks are directly overlain by more than one thrust sheet. Sander emphasizes that the term is descriptive and not genetic. Shear-window is rather an unfortunate term, however, inas-

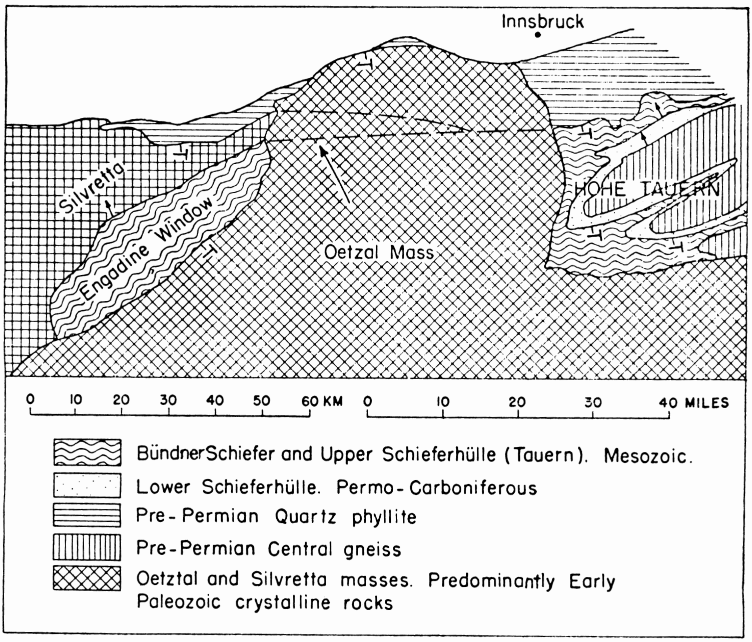


Figure 5. Generalized structural map of the western Tyrol, showing the Engadine window and part of the Tauern. (Modified from Sander, 1921.)

much as shearing is implicit in the formation of any and all windows.

Another term is suggested by Sander's description (1921, p. 212) of the ends of the window. He points out that the framing thrust sheets overlap, as in an iris diaphragm. A more restricted translation of the components forming the word *Irisblende* could be interpreted as "eyelid". The writer has heard several geologists use the expression "eyelid window" but he has been unable to find any reference to it in the geological literature. Therefore, it is here proposed that *eyelid window* be defined as Sander defined *Scherenfenster* and that the latter term be abandoned. The proposed name has the merit of suggesting the analogous form of two eyelids (thrusts) over the enclosed eye (rocks within the window). The analogy may be criticized, however, because it suggests movement from opposite sides of the window, whereas known examples are believed to have formed by thrusting in one direction.

American examples of eyelid windows, as described above, are the Hot Springs window and the enclosed Doe Branch block window, the Mountain City window and the enclosed Limestone Cove window, and the Fourmile, Dean, Sugarcamp, and Martin Creek fensters in the Rose Hill district.

Origin of Engadine window.—Sander's interpretation of the origin of the Engadine window (1921, pp. 193-196, 212-214, 219), though not the only one published,[6] is in some ways applicable to the Hot Springs window. Sander stresses the significance of the data which suggest that the Bündner Schiefer of the Lower Engadine window is connected directly with the Schieferhülle of the Hohe Tauern (indicated by dashes in figure 5), although the continuity of this structure is masked by the overlying Oetztal thrust sheet. This continuous structure, as well as other data, indicates that the first orogenic pulse in the region produced marked east-west trending deformation zones. One of these was the anticlinal mass extending from the Engadine to the Tauern areas.

The subsequent orogenic pulse may be subdivided into two subphases. During the first, the Silvretta-Oetztal mass was thrust northwestward as a unit and rode over the resisting Engadine-Tauern structural zone. During the second subphase (which

[6] Two more recent, but conflicting, interpretations are those by Staub (1937, pp. 18-108) and Krasser (1940, pp. 181-185).

was probably continuous with the first in time) the frictional resistance along the major thrust surface, beneath the Silvretta-Oetztal mass, became too great and the Oetztal subsidiary thrust sheet split off and rode over the base of the main mass. The sliver left beneath the Oetztal mass is the Silvretta thrust sheet. The tangential force couple that emplaced the Oetztal thrust sheet acted in a NW-SE direction in the Engadine area (fig. 6), producing a counter-clockwise rotation of the underlying Bündner Schiefer mass so that it no longer parallels the closely related east-west zones. Sander and other Austrian geologists emphasize that the present imbricate structure is the result of the formation of subsidiary thrust sheets when the frictional resistance became too great along the main movement horizon. They deny that it formed by the piling up of far-travelled thrust masses developed from recumbent folds, as the Nappists believe.

POSSIBLE TECTONIC EVENTS IN HOT SPRINGS AREA

Any attempt to describe the sequence of tectonic events which led to the formation of the Hot Springs structure must, of necessity, be based on a certain number of assumptions as well as on available field observations. There are serious gaps in our knowledge of the geology of the Blue Ridge mountain region. What, for example, is the relation of the thrust faults in the Hot Springs area to those of northeastern Tennessee and the Mountain City window? Does the Hot Springs thrust sheet form an arch over the Doe Branch block, the southern limb of which is concealed by the overlying thrust sheets? Are the Brushy Mountain and Meadow Fork thrust sheets not exposed

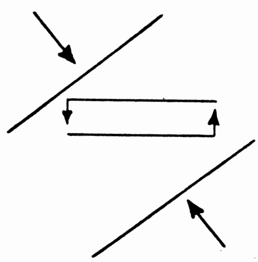


Figure 6. A simplified sketch of the tangential forces applied to earlier formed east-west structural zone (as indicated by arrow in figure 5). The stresses in the NW-SE direction resulted in the counter-clockwise rotation of the structures in the Engadine window. (After Sander, 1921, p. 194.)

outside the eastern half of the window because they have been overridden by the Rector Branch sheet, or do their eastern limits mark the line of a partially concealed tear fault? The answers to these and comparable questions would probably establish or disprove the validity of the statements that follow.

It is the writer's belief that the Hot Springs window was formed in much the same way as the Engadine window, according to Sander's interpretation. The steps in its formation are conceived to be somewhat as follows: If the Dry Pond Ridge contact is a major thrust fault, an early tectonic event was the thrusting of the Hot Springs sheet over the Doe Branch crystalline rocks. After this movement, forces applied in a NW-SE direction compressed the rocks of the Doe Branch block and the Hot Springs sheet to form a large NE-SW trending anticline with steeply dipping limbs. This anticline may have been formed at the same time as, and may have been continuous with, comparable structures in the Mountain City window vicinity.

The first phase was followed by the relative northwestward movement of the Del Rio sheet along the Mine Ridge thrust fault and across the arched Hot Springs sheet, truncating the latter and partially severing it from its root. The absence of the Del Rio sheet beneath overlying thrust faults in the southwestern part of the area and the decrease in the width of the sheet as exposed southwestward from the French Broad River suggest that the Del Rio sheet may wedge out southward. Thus, the remaining thrust sheets may be interpreted as imbricate blocks of the same mass or as parts of another major thrust mass which bevelled off the Del Rio sheet. The former of these possibilities is illustrated in the accompanying structure sections (fig. 4).

The incongruous east-west trends of some of the structures in the Hot Springs area may be attributable to the clockwise rotation of earlier structures by forces applied in a north-northwest direction during the thrusting of the Brushy Mountain-Meadow Fork-Rector Branch mass along the Brushy Mountain thrust fault. As this large mass met increasing frictional resistance along its base and as it impinged against the structural front already developed, it ruptured, forming the Meadow Fork and the west end of the Rector Branch thrust fault.

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