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STRUCTURE AND METAMORPHISM FROM JAMAICA TO THE ATHENS DOME, VERMONT

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INTRODUCTION

Western New England was visited by two major Paleozoic deformations, the Ordovician Taconic orogeny and the Devonian Acadian orogeny. The effects of the Taconic orogeny are most clearly recognized in an elongate belt along the border of New York with Connecticut, Massachusetts, and Vermont and into north-central Vermont (as shown on Fig. 2, compiled by Laird,1988). Taconian deformation is characterized by westward directed thrusting (e.g. Zen 1967; Stanley and Ratcliffe, 1985). In contrast, Acadian deformation and metamorphism are most intense in New Hampshire and central Massachusetts and Connecticut, and crustal shortening is usually attributed to large-scale recumbent folding (e.g. Thompson et al., 1968; Robinson and Hall, 1980).

There is a zone of overlap in north-central Vermont, southeastern Vermont, and western Massachusetts and Connecticut where both the Taconic and Acadian orogenies have left their mark. As many geologists working in this zone have discovered, it is not always easy to determine which orogeny is responsible for specific structural and metamorphic features. Yet, if we are to develop reasonable tectonic reconstructions of western New England, we must sort out the physical conditions of each orogeny. The purpose of this field guide is to describe the evidence in southeastern Vermont for polydeformation and polymetamorphism, emphasize the strengths and weaknesses of the data, and make some suggestions on how to distinguish between the effects of the Taconic and Acadian orogenies.

An important aspect of the field trip is to assess (and debate?) stratigraphic and contact relationships. The field trip crosses units mapped by Doll et al. (1961) as the Mount Holly gneiss, the Bull Hill gneiss, and the Tyson, Hoosac, Pinney Hollow, Ottauquechee, Stowe, and Missisquoi Formations (see Table 1, Trip B-6 herein). Our trip complements that of Rosenfeld et al. (1988), and our last two stops are the same as Stops 3 and 6 of their trip.

This year's gathering of the NEIGC marks the twentieth anniversary of the publication of Studies of Appalachian Geology: Northern and Maritime (Zen et al., eds., 1968), more popularly known as the "Billings Volume". Twenty years after its appearance, this landmark collection of papers still remains the natural starting point for geologists interested in the northern Appalachians. The issues we wish to discuss were clearly identified in several of the articles contained in that volume (e.g. Albee, 1968; Rosenfeld, 1968; and Thompson and Norton, 1968). A great deal of new information is available to help address these issues (or at least to fuel debate), which we plan to summarize, but those seeking definitive answers at this time will be disappointed. Our regret at not being able to provide more complete structural and metamorphic histories of the region is tempered by our awareness that better geologists than ourselves have been at work on these problems for some time, and they still have many questions. Our goal is to stimulate not to satisfy.

DEFORMATION

Rocks in southeastern Vermont are on the east flank of a major anticlinorial structure, the Green Mountain massif (Fig. 1). Lithologic contacts and deformational fabrics dip moderately to steeply to the east, except around the Chester and Athens domes where they dip gently to moderately away from the cores of the domes. Map-scale structures clearly reveal a history of multiple deformations: an early stage of recumbent folding and a later stage of doming (Doll et al., 1961; Rosenfeld, 1968). Because these structures involve Silurian and Devonian rocks, these deformations have been attributed to the Acadian orogeny.

At the outcrop scale the deformation fabrics clearly record multiple episodes of synmetamorphic deformation. An early schistosity (maybe not the first deformation fabric) is characteristically overprinted by a crenulation cleavage, and this younger fabric is often cross-cut by a spaced cleavage with only limited recrystallization parallel to it.

Acadian-age structures have dominated the attention of geologists in southeastern Vermont. Acadian deformation took place at garnet to kyanite grade in this region (Thompson and Norton, 1968) and produced large-

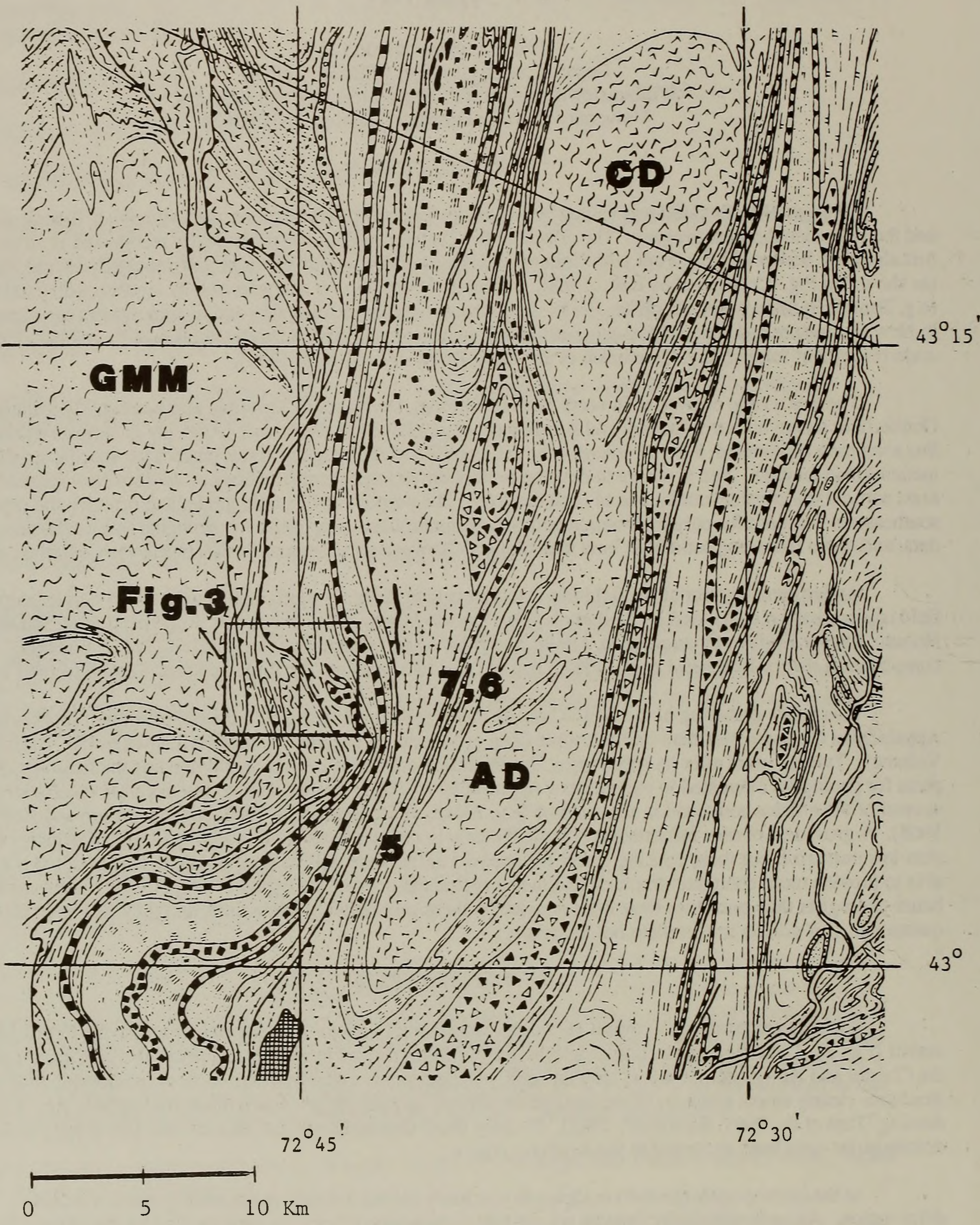

Figure 1: Geologic map of southeastern Vermont between the Green Mountain massif (GMM) and the Athens (AD) and Chester (CD) domes, with permission from Thompson et al. (1986). The same map and units as shown by Rosenfeld et al. (this volume, Fig. 2). Location of Figure 3 (Stops 1 - 4) is indicated.

scale ductile structures. Overprinting of older structures (assuming they really exist) was thorough. It seems that the first suggestions of Taconic deformation east of the Green Mountain massif stemmed from the quest for the "Taconic root zone", or a palinspastic source for the rocks now found in the Taconic klippen and emplaced during the Middle Ordovician onto coeval rocks of the Cambrian to Ordovician carbonate platform. Prindle and Knopf (1932) and Skehan (1961, 1972) mapped faults on the southeast margin of the Green Mountain massif which were candidates for this root zone, but the field evidence for Taconic deformation in southeastern Vermont was not compelling.

Rosenfeld (1968) described garnets from the Cambrian Pinney Hollow Formation on the west side of the Athens dome that contained unconformity textures unlike anything he saw in younger Silurian and Devonian rocks. (We use the age assignments of Doll et al., 1961 but are aware that fossil control is poor across our route and that paleontological studies in the Connecticut Valley trough are ongoing.) He made a bold suggestion that the early stage of garnet growth dated from the Taconic orogeny. This seems to be the first solid piece of evidence that the effects of pre-Acadian, possibly Taconic, orogeny extended to southeastern Vermont.

Karabinos (1984a) also found garnets with unconformity textures in high-alumina schists in the Hoosac Formation near Jamaica, Vermont, on the east flank of the Green Mountain massif (Fig. 2). Karabinos (1984b) used thin section textures and garnet zoning to show that the two stages of garnet growth were separated by a retrogression which partially resorbed first-stage garnet. He mapped thrust faults in the Jamaica area (Fig. 3) and argued (and continues to tell anyone who will listen) that thrusting of hot rocks to a structurally higher and cooler environment cut short the first prograde metamorphism. Thus, if the early stage of garnet growth really is Taconic and if thrusting was coeval with it, the thrusting is Taconic. Thermal modelling (Karabinos and Ketcham, 1988) suggests that such temperature fluctuations during thrusting in metamorphic belts are possible.

Mapping in the Berkshire massif and east of it during the late 1960's and 1970's by N.M. Ratcliffe, D.S. Harwood, R.S. Stanley, S.A. Norton, and N.L. Hatch was a major turning point in our understanding of the geology of western New England (see Stanley and Ratcliffe, 1985, for references). These geologists showed that the older Cambrian and Ordovician rocks contained structures not found in the Connecticut Valley trough and demonstrated that thrust faults were pervasive in western Massachusetts. These structures are presumably of Taconic age.

Since the late 1970's R.S. Stanley and his students at the University of Vermont have been mapping in pre-Silurian rocks in central and northern Vermont, and they also recognize numerous thrust faults (again, see Stanley and Ratcliffe, 1985, for references). Thrust faults have also been recognized in southeastern Vermont (e.g. Zen et al., 1983; Karabinos, 1984a; Thompson and McLelland, in press). The synmetamorphic thrust faults mapped in western Massachusetts and in Vermont are generally attributed to the Taconic orogeny (e.g. Stanley and Ratcliffe, 1985) although Ratcliffe (1979) has suggested an Acadian age for some thrusts. In some cases the evidence for a Taconic age for thrusting is good (i.e. Ratcliffe and Hatch, 1979; Sutter et al., 1985) but in many cases the evidence does not exclude an Acadian age. The common tendency to attribute thrusts throughout western New England to the Taconic orogeny appears to originate from an ingrained bias that the Taconic orogeny was dominated by thrusting and that the Acadian orogeny was dominated by recumbent folding. The next generation of research on thrusting in western New England must include tools to date fault movement.

METAMORPHISM

The effects of Acadian metamorphism are obvious in southeastern Vermont where Late Precambrian to Devonian cover rocks contain magnificent porphyroblasts of garnet, staurolite, kyanite, and amphiboles. Harper (1968) used the K-Ar method to show that "the" metamorphism was Devonian in age and also demonstrated that Ordovician metamorphism occurred in the Taconic region, but it was unclear how far east Taconic metamorphism extended. As noted in the previous section, Rosenfeld (1968) used garnet inclusion textures to argue that Taconic metamorphism reached as far as southeastern Vermont. Also, Albee (1968) recognized that a younger metamorphism had been superimposed on an older metamorphism in northern Vermont, and Lanphere and Albee (1974) used 40Ar/39Ar ages to verify this assertion and to demonstrate that the early metamorphism was Taconic and the later metamorphism was Acadian. Two other studies using 40Ar/39Ar ages (Laird et al., 1984; Sutter et al., 1985) have convincingly shown that both Taconic and Acadian metamorphism occurred in Vermont and western Massachusetts, but so far only Devonian ages have been found in southeastern Vermont above the basement.

The lack of Ordovician ages from southeastern Vermont may reflect either thorough Acadian thermal overprinting or a lack of Ordovician metamorphism. We favor the former interpretation in accord with Rosenfeld

(1968) and Rosenfeld et al. (1988). Evidence for polymetamorphism in southeastern Vermont from both pelitic and mafic schists is now widespread and can be most easily interpreted as the result of separate periods of heating.

Pelitic schists: Rosenfeld's (1968) unconformity textures in garnets from the Pinney Hollow Formation on the west side of the Athens dome (STOP 6, Rosenfeld et al., 1988) demand two separate periods of garnet growth, but it is possible that both stages of garnet growth are Acadian. Cheney (1980) also presented evidence for polymetamorphism in high-alumina schists from western Massachusetts along strike to the south. Karabinos (1984b) described unconformity textures from high-alumina schists in the Hoosac Formation near Jamaica, Vermont (Stops 2 and 4), and zoning anomalies strongly suggest that the two stages of garnet growth were separated by a period of partial resorption of first-stage garnet. Downie (1982) reported garnets with unconformity textures in the Chester dome, and Hawkins and Skehan (1985) also found evidence for two stages of garnet growth near the southeastern margin of the Green Mountain massif. In a senior thesis project at Williams College, Cook (1988) sampled high-alumina schists from around the Chester, Athens, and Wilmington domes and found that the unconformity texture is widespread in southeastern Vermont.

Cook and Karabinos (1988) created two isograd maps following a method suggested by Thompson et al. (1977). The first isograd map is based on mineral inclusions in first-stage garnet, and the second is based on mineral inclusions in second-stage garnet and the matrix assemblage. The second isograd map appears to reflect peak Acadian metamorphism. The first isograd map may record either Taconic metamorphism or an early stage of Acadian heating. Clearly what is wanted is some method to date both stages of garnet growth.

Rosenfeld is once again in the vanguard and involved in a project to modify Rb/Sr methods to date garnets and determine how long it took for them to grow (Christensen et al., 1988). This approach has many potential applications as are clearly enuciated by Rosenfeld et al. (1988) and may tell us when the first stage garnet actually grew.

Thompson et al. (1977) raised an important debate when they pointed out that unconformity textures could be produced in garnet porphyroblasts during a single prograde metamorphism. All that is required, according to their suggestion, is that an intermediate, garnet-consuming reaction interupt prograde garnet growth long enough during deformation for the matrix fabric to rotate relative to the porphyroblast. Renewed garnet growth, after the intermediate garnet-consuming reaction is no longer operating, would produce an outer shell of garnet with inclusion trails oriented at a high angle to inclusion trails in the inner garnet shell. As an example, Thompson et al. (1977) suggested that the breaking of the garnet-chlorite tie line to produce biotite and staurolite could interupt garnet growth. After consumption of chlorite by this reaction, garnet could grow again, perhaps by a continuous reaction which consumes biotite and staurolite and produces garnet. Downie (1982) extended this suggestion to include possible reactions involving non-AFM phases such as rutile.

This is an attractive alternative hypothesis to explain the unconformity textures. However, Cook and Karabinos (1988) emphasize that the unconformity texture is common throughout southeastern Vermont over a wide range of metamorphic grade and in a variety of bulk compositions at any given metamorphic grade. The timing of garnet growth with respect to deformation fabrics is also surprizingly consistent throughout southeastern Vermont. These observations are most easily explained by a change in the physical conditions of the first prograde metamorphism; it would require an amazing coincidence for prograde garnet-consuming reactions to commence in a wide variety of mineral assemblages at approximately the same time with respect to deformation.

Mafic schists: The petrology of mafic rocks at Stops 5 and 6 and along the route of field trip B-6, this volume, led by Rosenfeld et al. (1988) is presented by Laird and Albee (1981) and Boxwell and Laird (1987). Between Stops 1 and 3 (trip B-6), mafic schist changes from the epidote-amphibolite facies to the low-grade amphibolite facies, about 500 to 550°C based on garnet-biotite and calcite-dolomite geothermometry (Laird and Albee, 1981, Table 2). The change is mapped at the oligoclase isograd which is in exactly the same place for mafic rocks as pelitic rocks (mileage 4.0, Rosenfeld et al., this volume). Both albite and oligoclase occur locally above (to the south and higher grade than) the isograd. When/how did the oligoclase isograd get here from the Connecticut Valley trough (where it is mapped in mafic rocks by Mimi Boxwell and shown in Boxwell and Laird, 1987, Fig. 2)? Or did it? Near Jamaica the oligoclase isograd occurs in mafic rocks between stations 124 (with hornblende + albite) and 1001 (with hornblende + oligoclase). (See fig. 3 for sample localities.)

Along the traverse described by Rosenfeld et al. (1988, Stops 1 to 3), the change from titanite to rutile and/or ilmenite occurs within mafic rocks at about the same place as the oligoclase isograd. Hornblende is stable above and below this isograd, indicating medium-pressure facies series metamorphism. Chlorite and epidote decrease in mode southward, while amphibole increases in mode, consistent with increasing metamorphic grade. A total fusion 40Ar/39Ar amphibole age at South Windham is 376 ± 5 Ma (Laird et al., 1984, sample V107A). At West Townshend a 40Ar/39Ar age spectrum on amphibole is saddle-shaped with the "bottom of the saddle" at about 377 ± 2 Ma (Laird and Sutter, unpublished data). (See Stop 5 for further isotopic data.)

Zoned amphibole with actinolite cores and hornblende rims occurs up to Stop 3 (our Stop 5). Locally, complexly zoned amphibole (anhedral hornblende overgrown by subhedral actinolite overgrown by hornblende, Plate 2a, Laird and Albee, 1981) is interpreted to have formed by polymetamorphism. Is the hornblende core Taconian and the retrotression implied by change of amphibole from hornblende to actinolite time-equivalent with the retrogression observed in the unconformity garnets? A zone of depletion between actinolite core and hornblende rim accompanied by smaller grains of amphibole is interpreted as a hiatus, between Rosenfeld's Acadian events I and II? Alternatively, could both hornblende core and actinolite core be pre-Acadian?

Zoned amphibole with actinolite cores and hornblende rims also occur in low-grade amphibolite from the Hoosac Formation (Turkey Mountain amphibolite) at stations 124 and 1001 (Stop 3) shown of Figure 3. Coexisting amphibole and plagioclase compositions indicate medium-pressure facies series metamorphism. between the epidote-amphibolite (124) and amphibolite (1001) facies. Cores are mottled as seen in backscattered electron image and locally show symplectic textures optically. Both samples are along thrust zones.

Zoned amphibole described above is within the garnet zone. Amphibole is not extensively zoned at high garnet grade (Stop 5) or staurolite-kyanite grade (Stop 6). Compared to the low and middle garnet zone, higher grade mafic schist contains somewhat more anorthitic plagioclase (oligoclase to andesine), amphibole with a bit more Al, Na, and K, biotite with more Al(VI), and chlorite with more Al(IV). Evidence of polymetamorphism within the high-grade mafic schists is seen at Stop 5 where amphibole is locally pseudomorphed by biotite, chlorite, plagioclase, epidote, quartz, and ilmenite/hematite. However, amphibole is not pseudomorphed in most layers, and plagioclase is zoned up grade (toward more anorthitic rims).

FUTURE WORK

Dating of movement on thrust faults may be effected by obtaining absolute ages on minerals in fault zones and on "both sides" of the fault. Stratigraphy, structure, and petrology also hold keys for comparing relative metamorphic history across a fault zone.

Dating of garnets (Rosenfeld et al., 1988) are providing clues to time and duration of garnet growth. 40Ar/39Ar age spectra on unzoned hornblende give Acadian ages (if the spectrum is concordant) or saddle-shaped spectra (geologic meaning of extraneous Ar?). With a bit of luck laser studies of zoned amphibole will give metamorphic ages for the different compositional zones (Laird and Sutter, in progress).

Correlating deformation fabrics with map-scale structures and metamorphic minerals is extremely important. Rosenfeld (1968) and Rosenfeld et al. (1988) have showed how to use garnet for forensic studies. Will suggestions made herein for correlations between the geologic history of pelitic and mafic rocks "hold up" with further testing? Can the metamorphic and deformational histories of mafic rocks east and west of the Chester and Athens domes be "tied together"? Can one follow the oligoclase isograd in the Connecticut Valley trough into this isograd in pre-Silurian rocks? If so how is it related to the various deformation events suspected?

A big-picture question addressed by Stanley and Ratcliffe (1985) is why is there no evidence for high-pressure metamorphism in southeastern Vermont while the same units mapped in northern Vermont show medium-high and high-pressure facies series metamorphism (Laird and Albee, 1981)? Does this change really occur at about the present latitude of Rochester, Vermont, and if so, why?

ACKNOWLEDGMENTS

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REFERENCES

Albee, A.L., 1965, Phase equilibria in three assemblages of kyanite-zone pelitic schists, Lincoln Mountain quadrangle, central Vermont: J. Petrol., v. 6, p. 246-301.

______, 1968, Metamorphic zones in northern Vermont: *in* Studies of Appalachian Geology, Northern and Maritime, E-an Zen, W.S. White, J.B. Hadley, and J.B. Thompson, Jr. (eds.) Interscience, New York, p. 329-341.

Boxwell, Mimi and Jo Laird, 1987, Metamorphic and deformational history of the Standing Pond and Putney Volcanics in southeastern Vermont: in Guidebook for Field Trips *in* Vermont, Vol. 2, D.S. Westerman (ed.) 79th Annual Meeting, New England Intercollegiate Geological Conference, Montpelier, Vermont, p.1-20.

Cheney, J.T., 1980, Chloritoid through sillimanite zone metamorphism of high-alumina pelites from the Hoosac Formation, western Massachusetts: Geol. Soc. Amer. Abstracts with Programs, v. 12, p. 40.

Christensen, J.N., J.L. Rosenfeld, and D.J. DePaolo, 1988, Rates of tectonometamorphic processes: direct measurements using Sr isotopic profiles of garnet porphyroblasts: EOS, v. 69, p. 508.

Cook, S.M., 1988, Polymetamorphism in southeastern Vermont: B.A. Honors Thesis, Williams College, Williamstown, MA, 86 p

______, and Paul Karabinos, 1988, Polymetamorphic isograds in southeastern Vermont: Geol. Soc. Amer. Abstracts with Programs, v. 20, p. 13.

Doll, C.G., W.M. Cady, J.B. Thompson, Jr., and M.P. Billings,1961, Centennial geologic map of Vermont: Vermont Geol. Survey, scale 1:250,000.

Downie, E.A., 1982, Structure and metamorphism in the Cavendish area, north end of the Chester dome, southeastern Vermont: Ph.D. thesis, Harvard University, 291 p.

Harper, C.T., 1968, Isotopic ages from the Appalachians and their tectonic significance: Can. J. Earth Sci., v. 5, p. 49-59.

Hawkins, E.W., and J.W. Skehan, S.J., 1985, Deformation along the southeastern margin of the Green Mountain massif, southern Vermont: Geol. Soc. Amer. Abstracts with Programs, v. 17, p. 23.

Karabinos, Paul, 1984a, Deformation and metamorphism on the east side of the Green Mountain massif in southern Vermont: Geol. Soc. America Bull., v. 95, p. 584-593.

______, 1984b, Polymetamorphic garnet zoning from southeastern Vermont: Amer. J. Sci., v. 284, p. 1008-1025.

______, and R. Ketcham, 1988, Thermal structure of active thrust belts: J. Metamorphic Geol., in press.

Laird, Jo (1988) Arenig to Wenlock metamorphism in the Appalachians: *in* The Caledonian-Appalachian Orogen, A.L. Harris and D.J. Fettes (eds.), Geol. Soc. Special Publication No. 38, p. 311-345.

______, and A.L. Albee, 1981, Pressure, temperature, and time indicators in mafic schist: Their application to reconstructing the polymetamorphic history of Vermont:Amer. J. Sci., v. 281, p. 127-175.

______, M.A. Lanphere, and A.L. Albee, 1984, Distribution of Ordovician and Devonian metamorphism in mafic and pelitic schists from northern Vermont: Amer. J. Sci., v. 284, p.376-413.

Lanphere, M.A., and A.L. Albee, 1974, 40Ar/39Ar age measurementsin the Worcester Mountains; evidence of Ordovician and Devonian metamorphic events in northern Vermont: Amer. J. Sci., v. 274, p. 545-555.

Prindle, L.M., and E.B. Knopf, 1932, Geology of the Taconic quadrangle: Amer. J. Sci., ser. 5, v. 24, p. 257-302.

Ratcliffe, N.M., 1979, Field guide to the Chatham and Greylock slices of the Taconic allochthon in western Massachusetts and their relationship to the Hoosac-Rowe sequence: *in* Guidebook for field trips, G.M. Friedman (ed.), New England Intercollegiate Geological Conference, 71st Annual Meeting, Troy, New York, p. 388-425.

_______, and N.L. Hatch, Jr., 1979, A traverse across the Taconide zone in the area of the Berkshire massif, western Massachusetts: *in* The Caledonides in the U.S.A., Geological excursions in the northeast Appalachians, J.W. Skehan, S.J. and P.H. Osberg (eds.), Weston Observatory, Boston, MA, p. 175-224.

Robinson, Peter and L.M. Hall, 1980, Tectonic synthesis of southern New England, *in* The Caledonides in the U.S.A., D.R. Wones, (ed.) Department of Geological Sciences, Virginia Polytechnic Institute and State University, Memoir no. 2, p. 73-82.

Rosenfeld, J.L., 1968, Garnet rotation due to major Paleozoic deformations in southeastern Vermont: *in* Studies of Appalachian Geology, Northern and Maritime, E-an Zen, W.S. White, J.B. Hadley, and J.B. Thompson, Jr. (eds.), Interscience, New York, p. 185-202.

_______, J.N. Christensen, and D.J. DePaolo, 1988, Snowball garnets revisited, southeast Vermont: *in* W.A. Bothner (ed.), New England Intercollegiate Geological Conference, 80th Annual Meeting, Keene, N.H.

Skehan, J.W., 1961, The Green Mountain Anticlinorium in the vicinity of Wilmington and Woodford, Vermont: Vermont Geol. Survey, v. 17, 159p.

_______, 1972, Stratigraphic and structural problems of the southern part of the Green Mountain Anticlinorium, Bennington-Wilmington, Vermont: *in* Guidebook for Field trips in Vermont, B.D. Doolan and R.S. Stanley (eds.), 64th Annual Meeting, New England Intercollegiate Geological Conference, Burlington, Vermont, p. 245-267.

Stanley, R.S. and N.M. Ratcliffe, 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geol. Soc. Amer. Bull., v. 96, p. 1227-1250.

Sutter, J.F., N.M. Ratcliffe, and S.H. Mukasa, 1985, 40Ar/39Ar and K-Ar data bearing on the metamorphic and tectonic history of western New England: Geol. Soc. Amer. Bull., v. 96, p. 123-136.

Thompson, A.B., R.J. Tracy, P.T. Lyttle, and J.B. Thompson, Jr., 1977, Prograde reaction histories deduced from compositional zonation and mineral inclusions in garnet from the Gassetts schist, Vermont, U.S.A.: Amer. J. Sci., v. 277, p. 1152-1167.

Thompson, J.B., Jr. and J.M. McLelland, in press, Geologic map of the Glens Falls 1°x 2° quadrangle, New York, Vermont, and New Hampshire: U.S. Geol. Survey, Miscellaneous Investigations Map, scale 1:250,000.

_______,W.A. Bothner, Y.W. Isachsen, W.S.F. Kidd, K.D. Klitgord, J.B. Lyons, Peter Robinson, and J.S. Schlee, 1986, Adirondacks to George's Bank: Transect E-1 in a transition: Geol. Soc. Amer. Abstracts with Programs, v. 18, p. 772.

_______, and S.A. Norton, 1968, Paleozoic regional metamorphism in New England and adjacent areas: *in* Studies of Appalachian Geology, Northern and Maritime, E-an Zen, W.S. White, J.B. Hadley, and J.B. Thompson, Jr. (eds.), Interscience, New York, p. 319-327.

Thompson, J.B., Jr., Peter Robinson, T.N. Clifford, and N.J. Trask, Jr., 1968, Nappes and Gneiss domes in west-central New England, *in* Studies of Appalachian Geology, Northern and Maritime, E-an Zen, W.S. White, J.B. Hadley, and J.B. Thompson, Jr. (eds.), Interscience, New York, p. 203-218.

Zen, E-an, 1967, Time and space relationships of the Taconic allochthon and autochthon: Geol. Soc. Amer. Special Paper 97, 107p.

_____, ed., Richard Goldsmith, N.M. Ratcliffe, Peter Robinson, and R.S. Stanley, compilers, 1983, Bedrock Geologic Map of Massachusetts, U.S. Geol. Survey and Commonwealth of Massachusetts, Department of Public Works, scale, 1:250,000.

_____, W.S. White, J.B. Hadley, and Thompson, J.B., Jr., eds., 1968, Studies of Appalachian Geology, Northern and Maritime: Interscience, New York, 475 p.

ITINERARY

Assembly point is in front of U.S. Post Office in Jamaica, VT along Routes 30 and 100.

Mileage

0.0 Drive west on Route 30 and north on Route 100

1.4 Turn right onto Ball Mountain Dam Access Road

2.6 **STOP 1.** Park on left in grassy area at east end of road cut. Walk back to west to see rocks of the Middle Proterozoic Mount Holly Complex, which are here dominated by mafic to intermediate meta-igneous gneisses. The strong layering suggests that they may be meta-volcanic rocks. Contact between basement and cover rocks is east of long road cut and covered by grass. Outcrop of Tyson Formation containing quartz pebbles is first exposure of cover rocks east of basement. Here the Tyson Formation is a quartz, plagioclase, muscovite, chlorite, biotite schist with some pebbly layers.

Continue straight ahead.

3.1 End of road, go around circle.

3.3 **STOP 2.** Park on right side of road. At the west end of outcrop is a great exposure of plagioclase porphyroblast schist of the Hoosac Formation. At the east end of the outcrop is another great exposure of the high-alumina, chloritoid-paragonite schist of the Hoosac Formation, which is very similar to the Gassetts schist studied by Thompson et al. (1977). Mineral assemblages are also similar to those reported by Albee (1965) in central Vermont and by Cheney (1980) in western Massachusetts.

The contact between these two lithologies is very gradational. Both lithologies contain quartz, muscovite, chlorite, garnet, ilmenite, and epidote. The main difference between them is that the former contains the pair plagioclase-biotite and the latter contains paragonite-chloritoid. Rarely, three of these four minerals are found in the same rock. Note also the carbonate-rich pods and layers in the schist. Sphalerite is present but not common, and it may have been the source of Zn for staurolite when it appeared in higher-grade rocks. Garnets in the high-alumina schist display a textural unconformity, but it is rather subtle in many of the samples.

Return to Route 30.

4.85 Turn left, south onto Route 30 and head back to Jamaica.

6.3 Jamaica, U.S. Post Office.

8.3 Bridge over West River. High-alumina member of Hoosac Formation on left contains staurolite.

9.2 Turn left onto Turkey Mountain Road (gravel). Turkey Mountain Brook on right.

10.2 **STOP 3.** (Optional stop if weather, time, and enthusiasm permit.) Location PK1001, Fig. 3. Park along road. Cross bridge and head east upslope to top of ridge. Traverse upslope goes through the sequence: plagioclase porphyroblast schist, chloritoid schist (with staurolite), plagioclase porphyroblast schist, basement gneisses containing strong deformation fabrics, more plagioclase schist, and some mafic schist layers near the top of the ridge. Karabinos (1984a) explained this sequence by thrusting. The basement gneisses appear to be contained in fault bound slivers or horses (Fig. 3).

The amphibolite is coarse grained and amphibole is zoned with hornblende rims and actinolite cores. Plagioclase is oligoclase.

11.0 Bear right across bridge.

11.5 **STOP 4.** Park in grassy area on left. Walk north on road about 50 m and turn right, east, upslope to ledges. Very good outcrop of high-alumina schist member of the Hoosac Formation (station 120, fig. 3). Large garnets with well developed unconformity textures (this is the site of sample 120D, fig. 2, discussed by Karabinos, 1984a,b). Staurolite is present in some layers.

Turn around and return to Route 30.

13.7 Turn left onto Route 30.

14.0 Intersection with Route 100, continue straight on Route 30.

14.1 Outcrop of basement gneisses on left.

16.4 Outcrop on both side of road of the Moretown Member of the Missisquoi Formation.

17.9 **STOP 5.** Park on right side of road in lot overlooking Townsend Dam. A good place for lunch and a good place to ponder stratigraphy, structure, and petrology.

Known: 1) The west end of the roadcut is mapped as the Moretown Member of the Missisquoi Formation and is composed primarily of light gray, medium-grained quartz + oligoclase + biotite + white mica + chlorite + epidote + garnet + hematite/ilmenite schist with fascicles of hornblende pseudomorphed by biotite + chlorite + epidote + plagioclase + ilmenite/hematite and with accessory apatite, allanite, tourmaline, chalcopyrite, pyrite, and magnetite. Fine-grained white mica in the light gray schist looks like paragonite, but only muscovite analyses have been obtained by J.L. Interlayers of dark gray, medium-grained amphibolite are folded and boudinaged locally. They are composed of hornblende + epidote + biotite + chlorite + quartz + plagioclase + calcite + ilmenite with accessory white mica, apatite, pyrite, and chalcopyrite. Plagioclase is zoned outward from oligoclase to andesine.

2) Farther east are two layers (15 feet and 54 feet wide) of dark green to gray amphibolite (amphibole + epidote + quartz + plagioclase + carbonate + chlorite + ilmenite/hematite + garnet + biotite separated by light gray felsic schist (23 feet wide). These are the two amphibolite layers that are readily seen from across the street. Amphibolite interlayers occur within the felsic layer near the contacts with both amphibolites. Amygdaloidal-looking "enclaves" within the easternmost amphibolite are composed of plagioclase + quartz + minor amphibole.

3) The eastern part of the outcrop is composed primarily of a brown-weathered, light gray white mica + quartz + biotite + plagioclase + chlorite + garnet schist with rolled garnets. The rolled garnets give the rock a knotty appearance and prove to be excellent for forensic studies (Rosenfeld et al., 1988). Amphibolite occurs within the felsic layer, and the east end of the outcrop is amphibolite with cross-folial chlorite (amphibole + epidote + oligoclase + quartz + chlorite + biotite + ilmenite, rutile, pyrite, chalcopyrite, and apatite).

4) Amphibole from coarse-grained garnet amphibolite gives a concordant 40Ar/39Ar age spectrum with an age of 380 ± 2 Ma (Laird and Sutter, unpublished). Amphibole from medium-grained amphibolite gives a saddle-shaped spectrum with the "bottom of the saddle" at 389 ± 2 Ma. These data are consistent with isotopic studies presented by Rosenfeld et al. (1988) from this outcrop.

Questions: What is/are the nature of the contacts? If the west end of the outcrop is Missisquoi Formation and the thick felsic schist with rolled garnets on the east side of the outcrop belongs to the Ottauquechee Formation, there must be a fault and/or unconformity here somewhere. "Shredded" amphibolite in the two, thick amphibolite layers in the middle of the outcrop may mark faults. Yet presence of amphibolite layers within felsic layers near contacts between the two rock types suggest gradational contacts. Why does one see retrograded amphibole at the west end of the outcrop, but amphibole is "reasonably" fresh elsewhere? Cross folial chlorite and biotite altered to chlorite is seen throughout the outcrop.

Our route now follows that of Rosenfeld et al. (1988, mileage 13.1 to 21.6). Please consult that guide for more detailed discussion of the geology between Stops 5 and 6.

18.3 Cover rocks of the Hoosac Formation exposed on left side of road.

18.4 Covered bridge on right.

18.7 Sheared augen gneiss of the basement on left.

20.0 Turn left, north, onto Route 35 in Townsend, VT.

23.4 Bear left on road to Grafton.

25.2 Turn sharply left onto road heading uphill.

25.4 **STOP 6.** Park on left side of road. Very sheared augen gneiss mapped by Doll et al. (1961) as part of the Cambrian (?) Cavendish Formation. Karabinos and Aleinikoff (1988) dated zircons from this rock using the U-Pb method that gave an upper intercept age of 955 + 5 Ma. They interpreted this as the age of crystallization which indicates that this augen gneiss is not part of the Late Proterozoic to Cambrian cover sequence. It seems that we must resort to some structural explanation for the occurrence of cover rocks between the Bull Hill augen gneiss and other gneisses of the Mount Holly Complex. An interesting feature of the geochronology is that the lower intercept age suggests modern lead loss and does not record any trace of either the Taconic or Acadian orogenies.

Continue straight ahead on dirt road. In only a mile we cross the Pinney Hollow Formation at Rosenfeld's unconformity garnet (Rosenfeld et al., 1988, Stop 6) and into the Moretown Member of the Missisquoi Formation. This mile then covers the stratigraphy seen from Stops 1 to 5.

26.4 **STOP 7.** Park on dirt road along Power line. Outcrops along the power line of felsic rock with mafic interlayers very similar to the west end of Stop 5. The light gray layers are composed of: quartz + plagioclase + white mica + biotite + epidote (with allanite) + garnet + opaques + apatite). The dark-gray layers are composed of hornblende + oligoclase + quartz + garnet + epidote + biotite + chlorite (late?) +

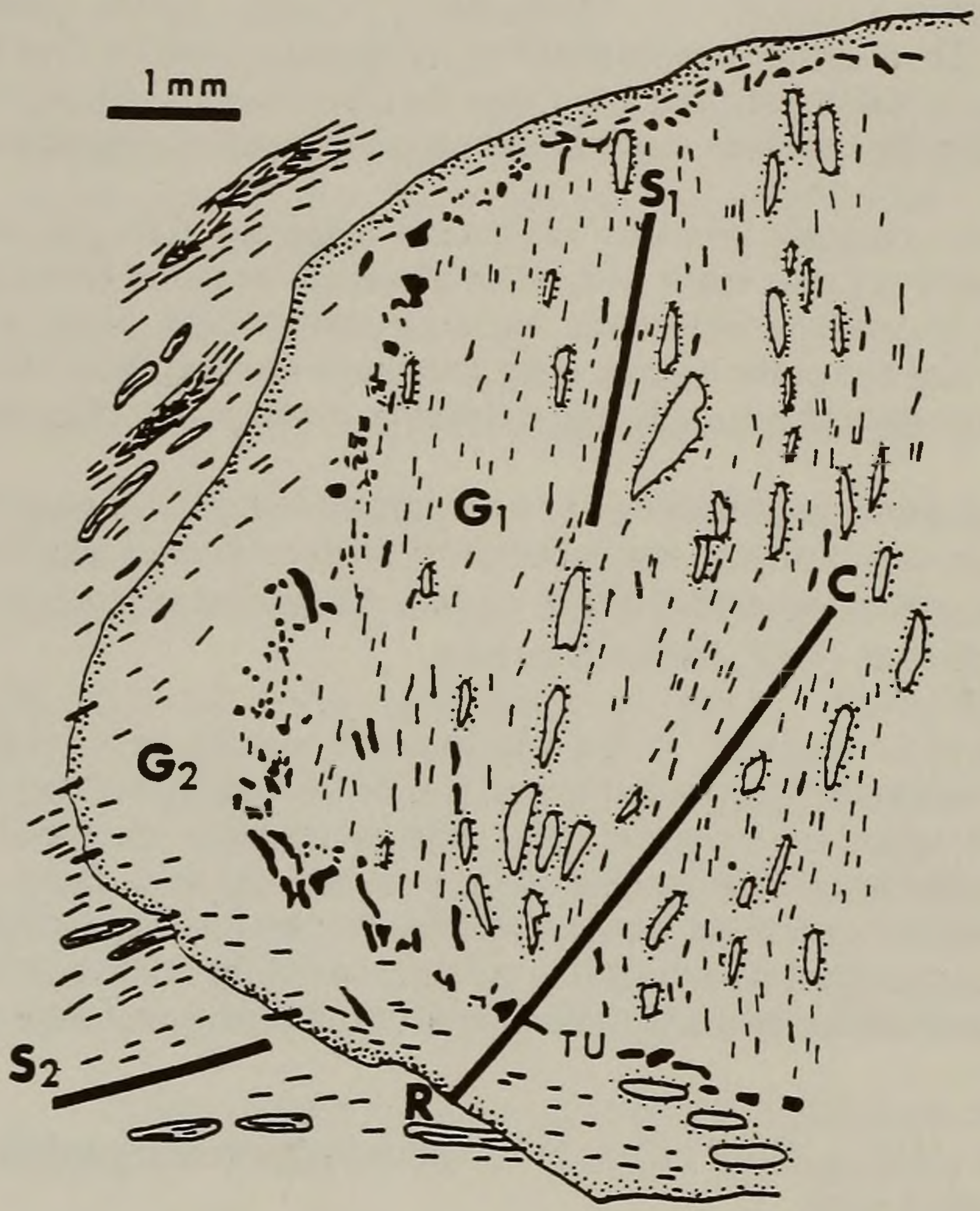
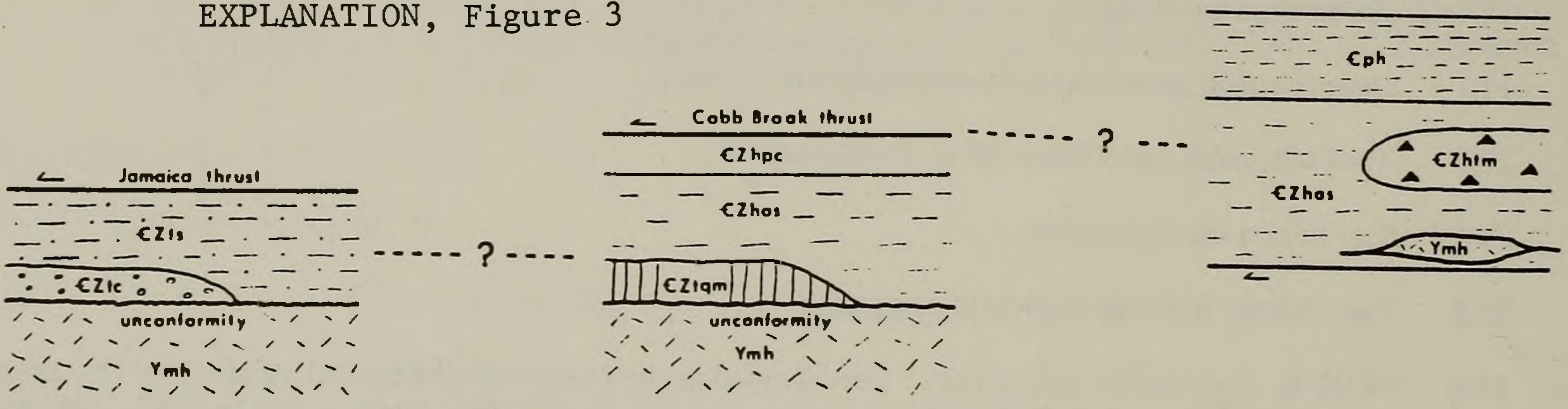


Figure 2: Drawing of garnet porphyroblast from Stop 4 (loc. 120, Fig. 3) showing early garnet growth (G1) separated from later garnet growth (G2) by a textural unconformity (TU). S1 defined by inclusions within garnet core is truncated by S2 within matrix and garnet rim along TU. Inclusions are chloritoid, white mica, and ilmenite. Analytical data along core (C) to rim (R) traverse are presented by Karabinos (1984a, Fig. 10).

EXPLANATION, Figure 3



Western Sequence

Tyson Formation	Qurtz-muscovite schist	ꞒZts
	Conglomerate	ꞒZtc
Mount Holly Complex		Ymh

Central Sequence

Hoosac Formation	Paragonite-chloritoid schist	ꞒZhpc
	Albite porphyroblast schist	ꞒZhas
Tyson Formation	Quartzite-dolomite unit	ꞒZtqm
Mount Holly Complex		Ymh

Eastern Sequence

Pinney Hollow Formation		Ꞓph
Hoosac Formation	Turkey Mountain Member	ꞒZhtm
	Albite porphyroblast schist	ꞒZhas
Mount Holly Complex		Ymh

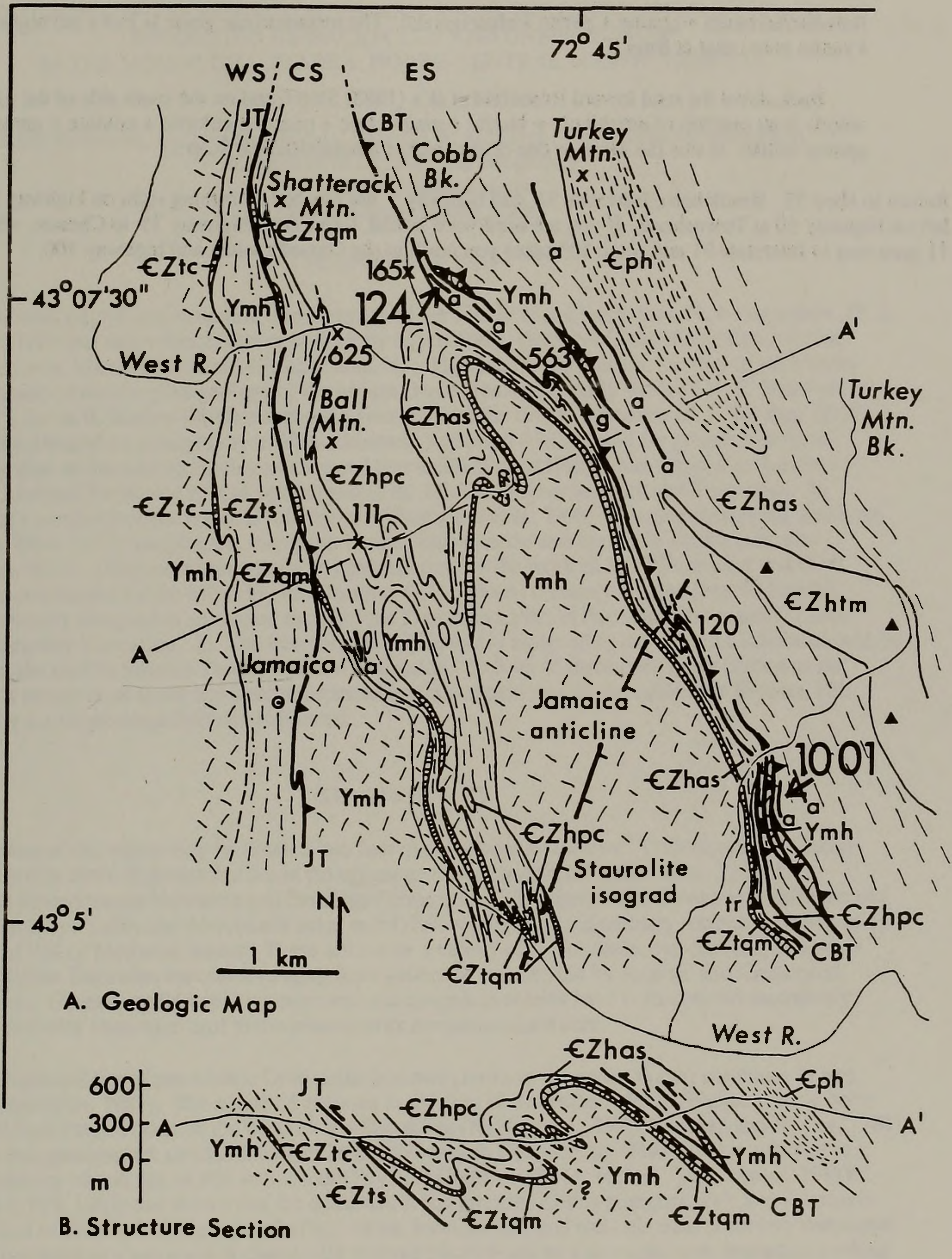


Figure 3: Geologic map and cross section (no vertical exaggeration) of the Jamaica area from Karabinos (1984a). Stops 1 and 2 (traverse west of Ball Mtn.), Stop 3 (traverse to locality 1001), Stop 4 (locality 120). Western sequence (WS) is separated from the Central Sequence (CS) by the Jamaica thrust (JT), and CS is separated from the Eastern Sequence (ES) by the Cobb Brook thrust (CBT). Explanation on previous page.

ilmenite/hematite + apatite + pyrite + chalcopyrite. The metamorphic grade is just a tad higher (staurolite-kyanite zone) that at Stop 5.

Back down the road toward Rosenfeld et al.'s (1988) Stop 6 and on the south side of the road in the woods is an outcrop of amphibole + biotite + plagioclase + quartz + chlorite + epidote + garnet + opaque + apatite schist. Is this the same as one of the thicker amphibolites at Stop 5?

Return to Hwy 35. Brattleboro, Interstate 91, and highway 9 are reached by turning right on highway 35 and then left on highway 30 at Townshend. If you are northward bound, turn left on highway 35 to Chester, where highway 11 goes east to Interstate 91 and route 103 takes you north to the Gassetts schist and highway 100.