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Structure and Petrology of the Willimantic Dome and the Willimantic Fault, Eastern Connecticut

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INTRODUCTION

The Willimantic dome is centered between the north trending Bronson Hill anticlinorium to the west and the domes of the Avalonian terrane south and east of the Honey Hill-Lake Char faults. (Fig. 1). The rocks of the Willimantic dome are divided into three units: a quartz-plagioclase-microcline gneiss or granofels (Willimantic gneiss), a plagioclase-quartz-amphibole-biotite gneiss, and the largely pelitic schists and gneisses of the Tatnic Hill formation (Fig. 2). This trip of five stops is designed as an introduction to these three rock types and to the major structural and petrologic features of the ductile Willimantic fault zone. The larger scale structure and stratigraphy are of regional interest, but are difficult to evaluate in the context of this trip. The first two stops are to gneissic units in the core of the Willimantic dome, where regional relationships can be discussed, but not tested. The latter three stops show different parts of the Willimantic fault zone on three sides of the Willimantic dome (Fig. 2).

GEOLOGIC SETTING

The circular outcrop pattern defined by the two gneissic units at Willimantic outlines the Willimantic dome. However, the smaller exposures of plagioclase gneiss SW of the dome, and outlined by the oval shaped outcrop patterns of the Willimantic fault on Fig. 1, suggest a structure more closely resembling a doubly plunging anticline. Whatever the overall geometry, the shallow dips of foliation and of lithologic boundaries suggest that it is a very low amplitude structure.

Regional correlation of the three units in the Willimantic dome suggests that they belong to the Avalonian terrane to the east rather than to the Bronson Hill sequence to the west. The composition of the metarhyolitic Willimantic gneiss (Stop 2) is very similar to the Hope Valley alaskite of Day et al (]980) and may be equivalent to it.

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1. Present address: Exxon Co., USA, 2000 Classen Center, Oklahoma City, OK 73106

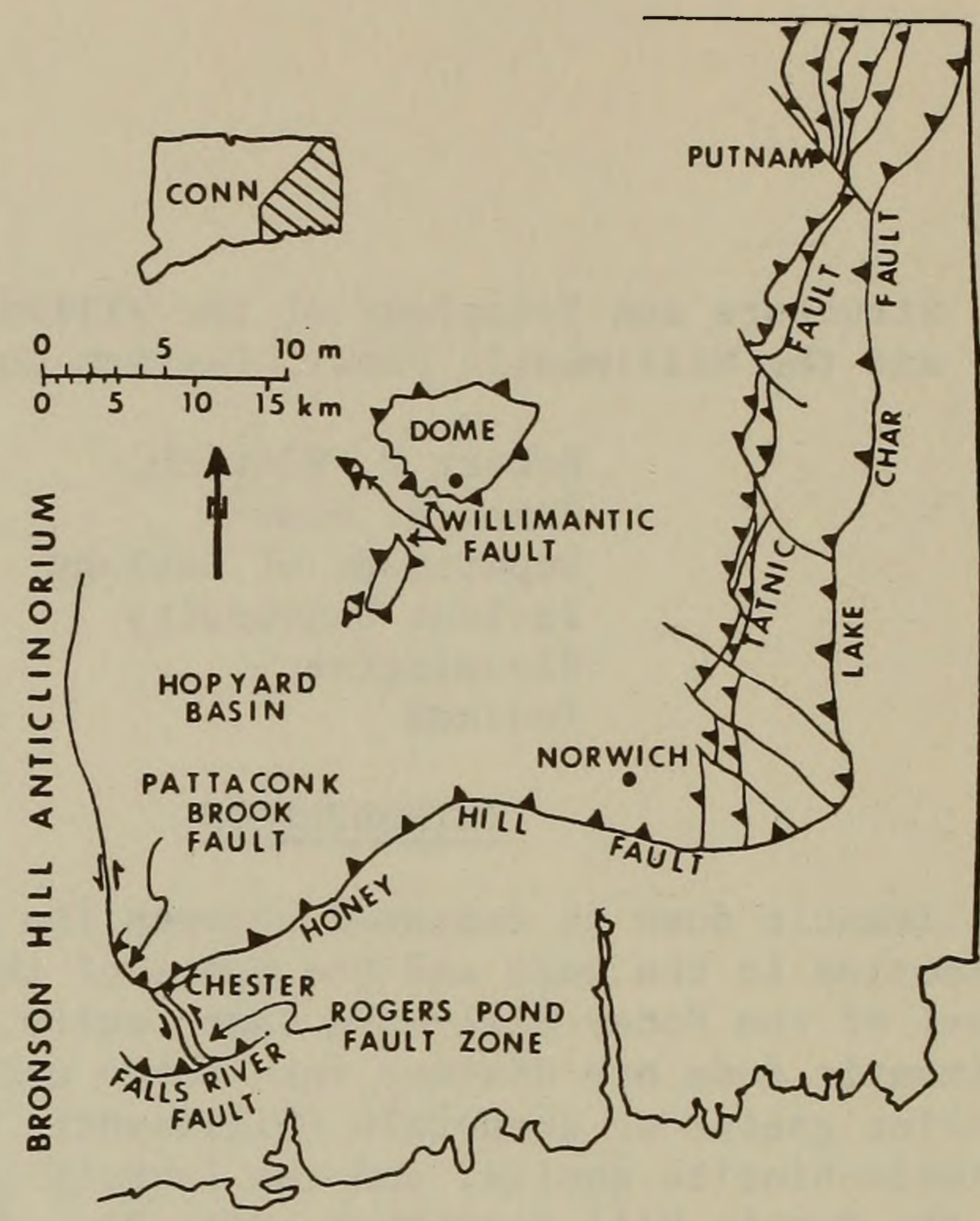


Fig. 1. Map showing the distribution of selected features around the Willimantic dome, eastern Connecticut. The Willimantic, Tatnic and Honey Hill faults probably define a single thrust fault the movement of which was to the southeast. The four areas of exposure of the Willimantic fault constitute windows through the fault and outline the areas extent of the Willimantic dome.

The mineralogy and composition of the plagioclase gneiss unit is indistinguishable from the gneiss at Hadlyme, immediately south of the Honey Hill fault near Chester (Fig. 1) but does not coincide with the Monson gneiss of the Bronson Hill anticlinorium (Wintsch and Grant, 1980; Wintsch and Pease, this volume). The Tatnic Hill formation, with its distinctive internal stratigraphy is well represented around the Willimantic dome, which is 15 km west of the type area in Danielson (Dixon, 1964). However, the Tatnic Hill formation has not been identified west of Chester in the Bronson Hill anticlinorium. We thus believe that the Willimantic dome is part of the Avalonian terrane to the east, and should not be related to the Bronson Hill anticlinorium.

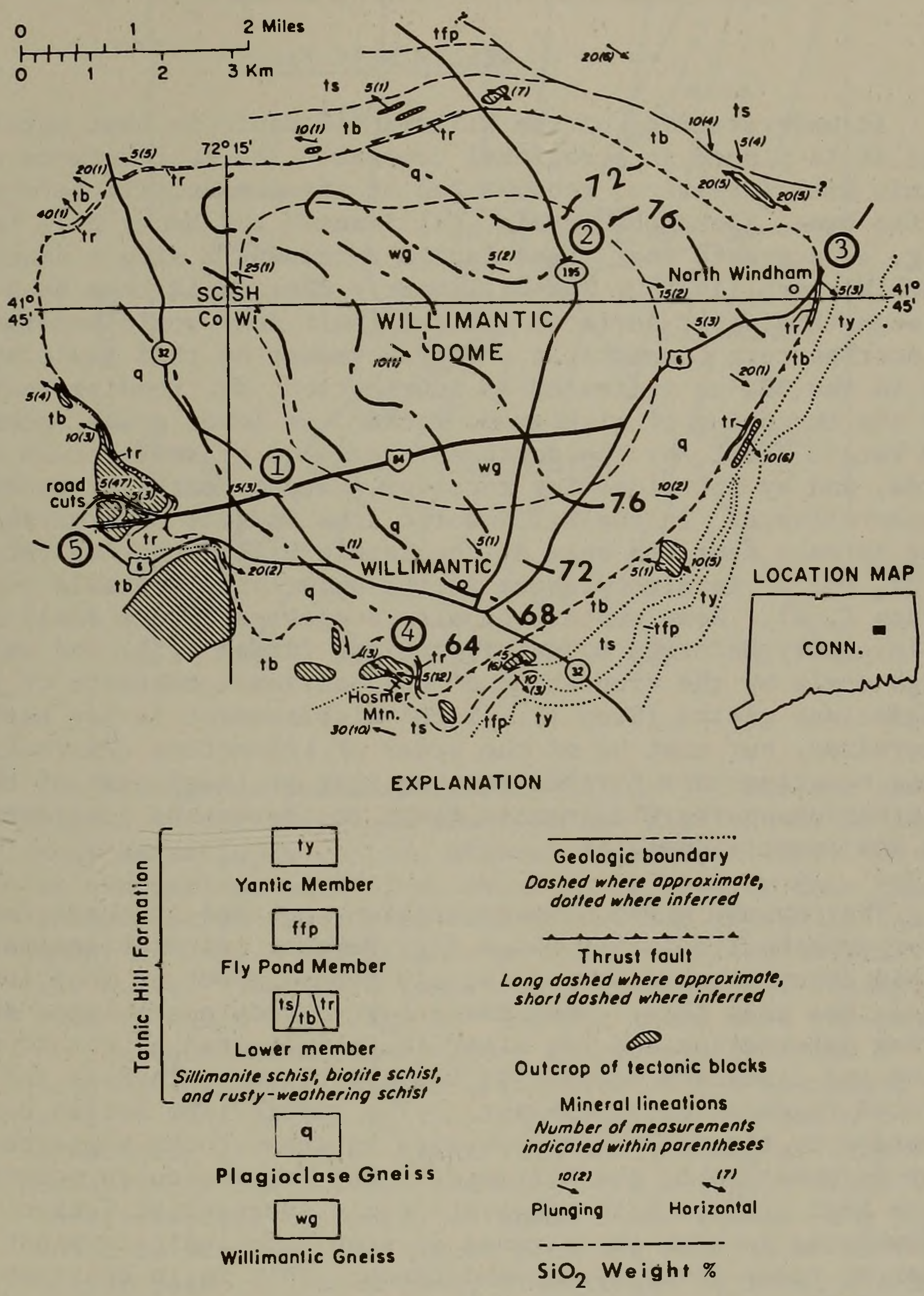


Fig. 2. Geologic map of the Willimantic dome, after Wintsch (1979). The dashed line separates rocks of the Brimfield Group structural trend (to the northeast) from rocks containing fabrics of the Willimantic fault. The concentration of SiO_2 (in wt %) in these rocks is given by the dot-dashed contours. A similar NW bearing trend is established by most major and trace elements, and the termination of these contours by the Willimantic fault suggests that the fault has cut out some of the plagioclase gneiss especially in the NW and SE. [Field trip stops are given by the circled numbers, and the University of Connecticut campus is 1 mile north of the map on State Route 195.]

WILLIMANTIC FAULT

An understanding of the Willimantic fault is best obtained when it is placed in a regional context. The reoccurrence of the Tatnic Hill formation, accompanied by intense ductile deformation at its base, along the Tatnic, Willimantic and Honey Hill faults (Fig. 1) suggests that these faults represent a single ductile fault zone (Wintsch, 1979). The Willimantic dome would then be a window through this fault surface, and the fault zone would underlie much of northeastern Connecticut. Most movement on this fault system was to the SE, as indicated by imbrication, NW trending tear faults, and the thrusting of high grade rocks over lower grade rocks along the Tatnic fault, by the southwest vergence of small scale open folds, and by the clockwise rotation (facing north) of boudins and porphyroblasts. In the Willimantic area ductile deformation is most intense near the base of the Tatnic Hill formation (Stops 3, 4, 5), but it is also present in the underlying gneissic rocks (Stops 1, 2). Some rupture is also suggested on the small scale by intensely deformed mylonitic schists (Stops 4, 5) and on the large scale by the truncation of compositional contours of the plagioclase gneiss (Stop 1). Total displacement is not easily determined, but must be of the order of kilometers (Wintsch, 1979). These relationships further suggest that at least some of the deformation on the Willimantic fault postdates the development of the Willimantic dome.

The maximum grade of metamorphism recorded in these rocks is upper amphibolite facies (Stop 5). However, mineral assemblages within discrete shear zones locally record lower or much lower grade conditions than this. That these lower grade assemblages developed during deformation and not after it is indicated by the strong foliation and lineation defined by the constituent minerals and by rotated feldspar porphyroblasts. The amphibolite facies conditions recorded by the mineral assemblages in these rocks suggests that most deformation on the Willimantic and Tatnic faults occurred at these high grades, although syntectonic greenschist facies assemblages in some shear zones at stop 5 do indicate minor deformation at these lower grade conditions. This is in contrast to the Honey Hill fault, which was more thoroughly reactivated under greenschist facies conditions, especially along the Pattaconk Brook fault in the east, and south of Norwich to the west (Fig. 1).

One particularly useful way of deciphering the deformation history along the Willimantic fault is through mineral lineations. These lineations share a strong northwest bearing, and may be defined by hornblende as sillimanite needles, biotite streaks, kyanite blades (rare) feldspar (+ quartz) rods, muscovite-chlorite streaks, quartz rods and slickensides. Together these lineations define a retrograde metamorphic path, along which sequential deformation events caused progressively lower grade assemblages to develop in different shear zones. The occurrence of andalusite at stop 4 establishes a very important upper pressure limit to this path, and allows semi-quantitative construction of this path as shown in Fig. 3.

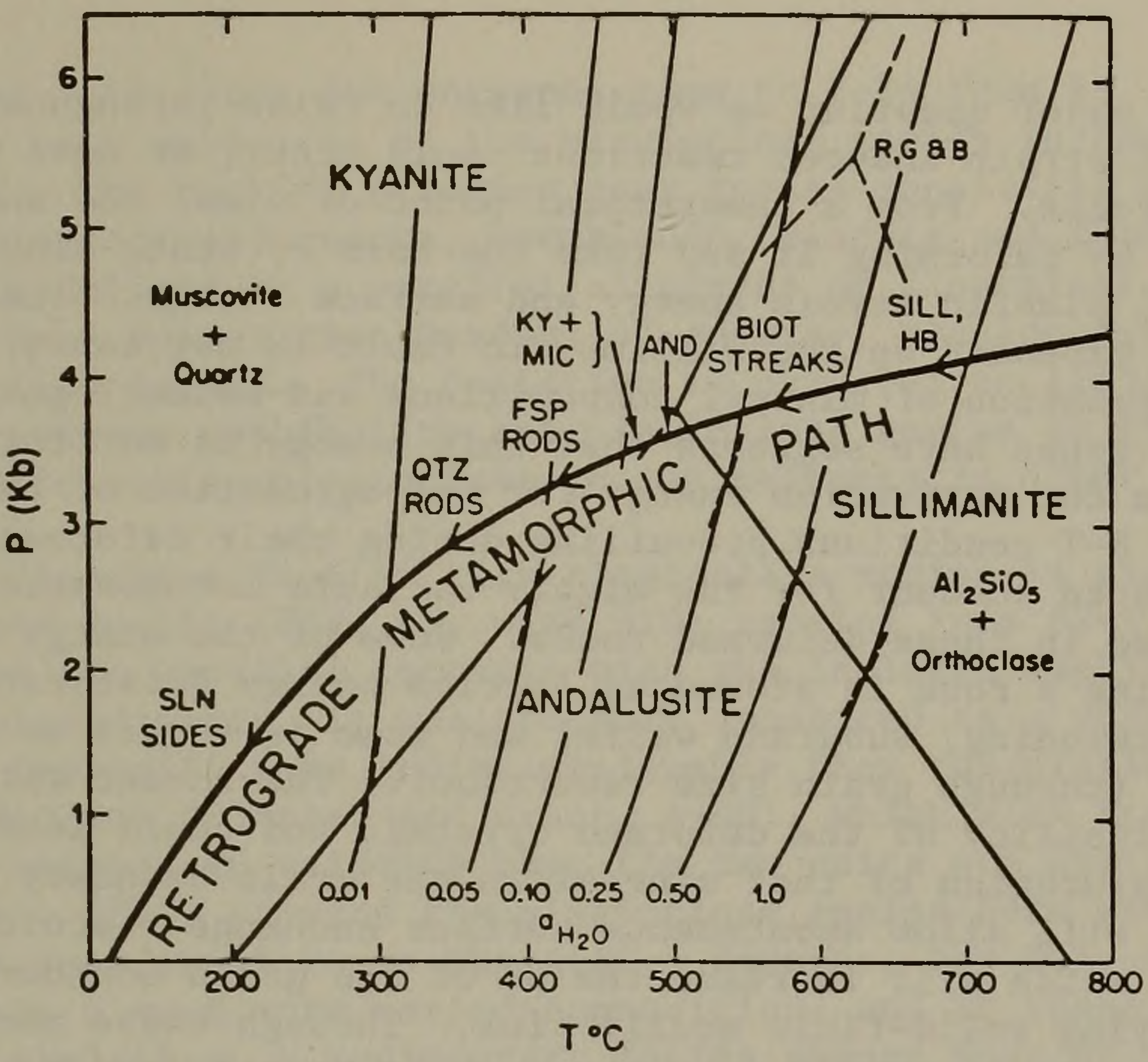


Fig. 3. The retrograde metamorphic path defined by mineral assemblages in ductile shear zones in the Willimantic fault. Many assemblages contain mineral lineations which developed at the various conditions equal to or greater than those indicated on the curve. The occurrence of andalusite (AND) at Stop 4 establishes an upper temperature limit to the curve. The 400°C temperature estimate for feldspar rods is taken from Fig. 5. Contour lines show the position of the equilibrium:muscovite + quartz = microcline + Al_2SiO_5 + H_2O for various activities of H_2O (standard state = real gas at P, T). The occurrence kyanite + microcline (KY + MIC) in ductile shear zones at Stop 5 establishes the maximum activity of H_2O (a_{H_2O}) of 0.10 (near-vertical contours) in these shear zones. The curve would be displaced to higher pressure conditions if the triple point of Richardson, Gilbert and Bell (R, G & B) (1969) were used instead of the Holdaway (1971) point.

The average bearing of these lineations in the Willimantic area is strongly NW-SE, but in the Putnam area (Hudson, 1982) and along the Honey Hill fault (Wintsch, unpub. data) bearing changes from NW to NS with decreasing metamorphic grade. The small (10°) counter clockwise rotation of transport direction suggested by Wintsch (1979) for the Willimantic area is probably not significant, and in view of the clockwise rotation of lineation bearing in the other areas, is probably not real (see also Stop 5). All the data taken together now suggest a clockwise rotation of lineation bearing at least 60° during the retrograde interval 700°-300°C (Fig. 3). In view of the recent radiometric uplift curves of Dallmeyer (written comm.) and Sutter and Wintsch (in prep) this deformation was active by 290 my and ceased by 230 my, making it Hercynian in age.

A major question we would like to raise throughout this trip is what strain induced reactions could occur, or have occurred in these rocks. From a theoretical point of view, the work done on a rock by deforming it may take the form of heat, elastic strain energy, plastic strain energy and surface energy. The amount of energy expended on the Willimantic fault is not known, but the retrogradation of mineral compositions and assemblages in high strain zones here suggests that this energy is sufficient to provide the activation energy for retrogradation of the shear zones to the P-T conditions prevailing during their deformation. This appears to account for the highly variable metamorphic grade recorded in these deformed rocks. Some of the energy expended by deforming a rock is stored as lattice energy (dislocations, deformation twinning, subgrain walls) and some is stored as surface energy (through grain size reduction). The former will increase the solubility of the deformed crystal, and could lead to the supersaturation of that mineral in the grain boundary fluid. The latter will allow spontaneous surface exchange reactions to take place, which will increase the pH of the grain boundary fluid thus destroying solid-fluid equilibrium. Through these mechanisms the mechanical energy added to the rock is transformed to chemical energy in the fluid, which causes overstepping of high variance mineral reactions. These processes should lead to the development of syntectonic porphyroblasts of hornblende (Stop 1) and feldspar (Stop 1, 3, 4, 5) and to the oxidation of iron (Wintsch, 1975; 1981). The progress of such reactions should correlate positively with strain, and this relationship may be assessed at most stops on this trip.

ROAD LOG

Assemble at the west end of the Willimantic Plaza parking lot at the west edge of Willimantic on Rt. 32, 0.5 mi east of the Rt. 32 exit off I-84 at 8:30 AM. From the University of Connecticut in Storrs, take Rt. 195 south 7 mi to I-84 at the Willimantic town line, proceed west on Frontage road following I-84 west signs. Exit at Rt. 32 and proceed left, 0.5 mi on Rt. 32 to assembly point. Breakfast is available from 7 AM at fast food drive-in, 0.4 mi east on Rt. 32.

This trip follows narrow roads and parking space is in short supply at some stops. Please help reduce the number of cars on the trip to the absolute minimum by sharing rides and filling each car to capacity. The last stop is just 2 mi from the assembly point so that drivers need not go far out of their way to return riders.

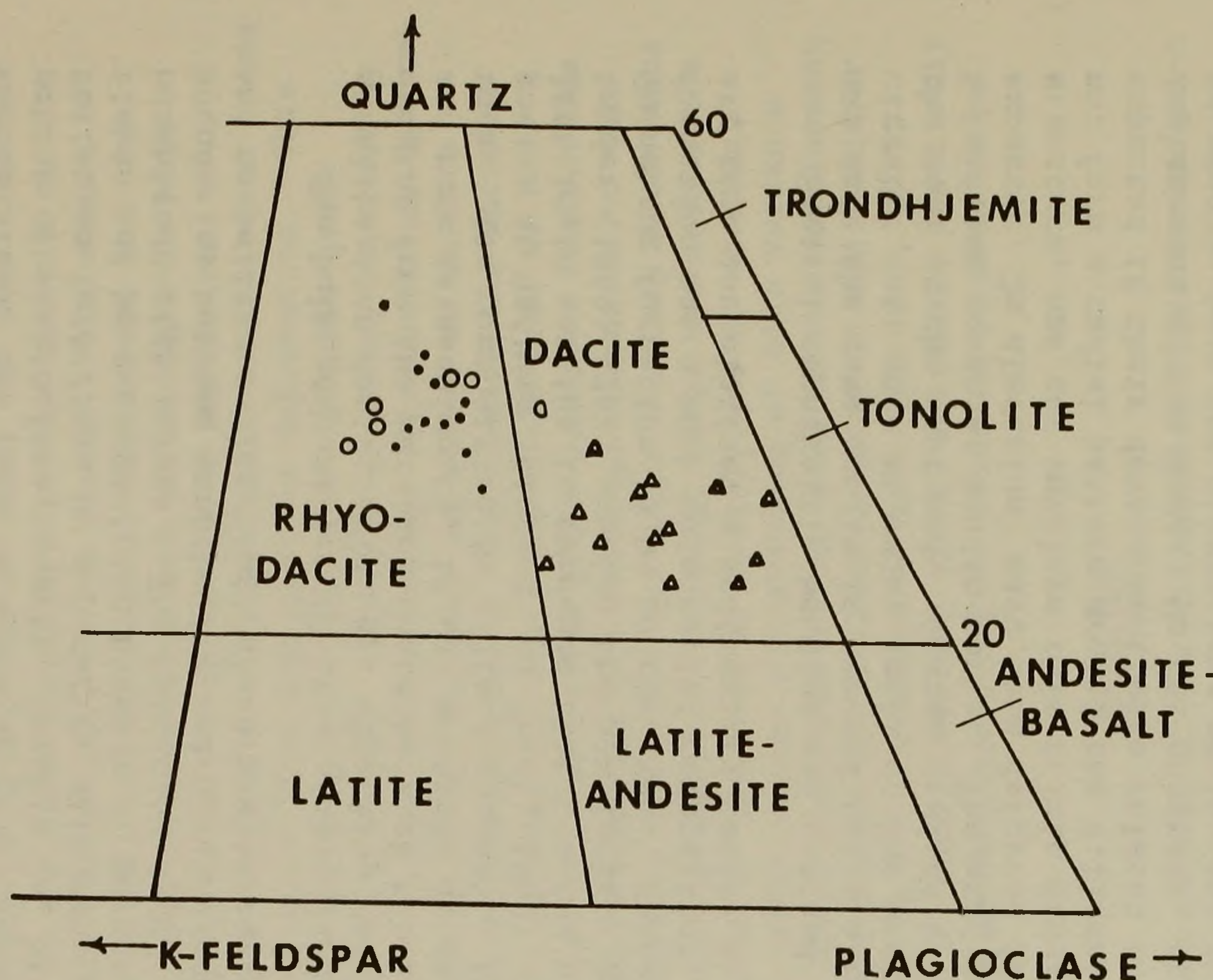
Proceed on foot, 0.4 mi west on Rt. 32 to roadcuts on the westbound (Hartford) on ramp to I-84.

<u>Stop 1</u>, road cuts along the entrance ramp to I-84 from Rt. 32, is some of the best exposures of the plagioclase gneiss in the Willimantic area. The rock is a medium gray gneiss consisting of 1mm grains of plagioclase, quartz, hornblende, biotite and magnetite. Foliation is defined by a parallel alignment of disseminated biotite flakes and by a composition banding of quartz-, plagioclase- and hornblende-rich layers. The foliation is parallel to lithologic boundaries between amphibolite and plagioclase gneiss in these rocks, and to pelitic schist-plagioclase-gneiss contacts in other outcrops.

The bulk composition of this plagioclase gneiss is similar to a silica-poor dacite (Fig. 4), with SiO_2 varying from 62-72 wt %. Judging from the parallel contacts with the included amphibolites and rare metasediments, it was probably deposited as a volcanoclastic rock. Its composition is indistinguishable from the plagioclase gneiss at Hadlyme (Wintsch and Grant, 1980), which with its similar lithologic setting is evidence that the two units are equivalent. Snyder (1964; 1967) equated the plagioclase gneiss here with the Quinebaug formation 15 km to the east. However, the Quinebaug formation has a much more varied composition, and if these two units are time correlative, a sedimentary facies change must be involved.

Several amphibolite boudins are exposed in this outcrop. In one case the same boudin is exposed twice along the southern semicircular cut: once at waist level at the west end once 6m above the road at the east end. Coarse grained quartz, plagioclase and K-feldspar occur at boudin necks. The margin of one boudin (southern exposure, 2m elevation) have been deformed into a fold like structure, and now envelope this felsic mineral. The boudins do not form a radial pattern around the Willimantic dome, as would be expected if their development were related to extension during the emplacement of the dome. On the contrary, their general NW-SE bearing in both the plagioclase gneiss and the Tatnic Hill formation is more easily explained by a boudin axis rotation during thrusting (Wintsch, 1979). Several undeformed pegmatites cut the gneiss. They tend to be mineralogically and texturally zoned, with very coarse grained quartz cores, K-feldspar-rich intermediate zones, and plagioclase-rich rims: a classic zoning pattern. They are clearly younger than the plagioclase gneiss, and thus do not offer a source for the deformed concordant, feldspar-rich veins which are common on both sides of the road.

The metamorphic petrology of these rocks reflects more its uplift history than the maximum P-T conditions of the metamorphism. This gneiss must have been metamorphosed to the upper amphibolite facies conditions of the overlying Tatnic Hill formation. The 650-700°C temperatures calculated from the compositions of coexisting biotite and (rare, unzoned) garnet probably represent minimum estimates of these conditions. The growth of rotated porphyroblasts of hornblende, plagioclase and K-feldspar probably occurred at these conditions. However, the equigranular mosaic of crystals with large interfacial angles typical of these conditions is not found. Quartz



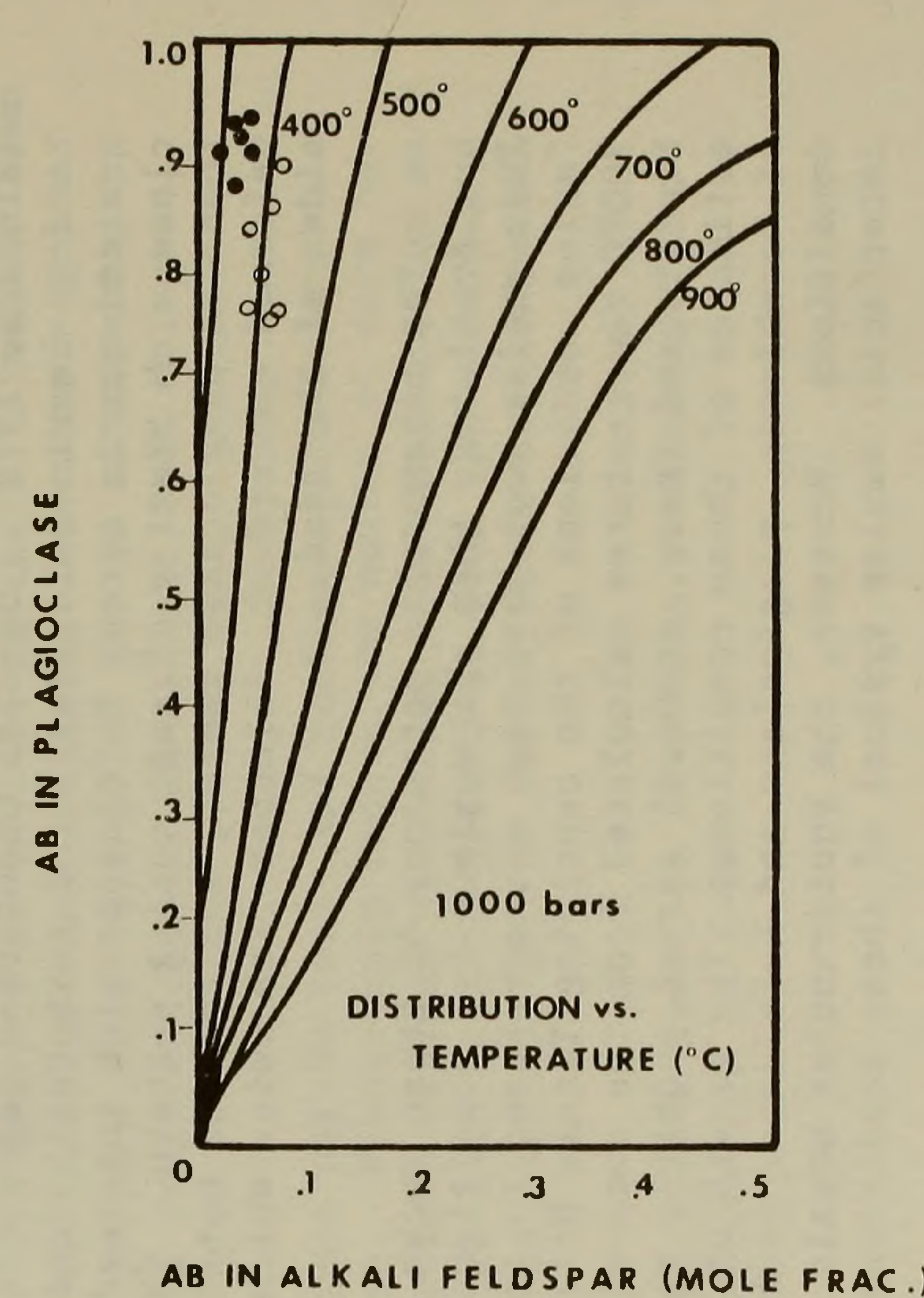


Fig. 4. The normative classification of gneisses from the Willimantic dome. Triangles represent plagioclase gneiss, closed circles represent Willimantic gneiss. The composition of the Hope Valley alaskite (open circles) from Day et al (1980) is included for comparison.

Fig. 5. The compositions of coexisting plagioclase and microcline from the Willimantic gneiss (filled circles) and the plagioclase gneiss (open circles). The calculated isotherms are from Whitney and Stormer (1977). The data suggest that the feldspars from the plagioclase gneiss equilibrated between 390-430°C, and that those in the Willimantic gneiss equilibrated between 310-360°C. The feldspars and quartz in the plagioclase gneiss form rod-shaped grains, whereas in the Willimantic gneiss only the quartz is rodded. The temperature at which rod-shaped feldspars disappear in these rocks is about 375°C, a temperature used to help in the construction of Fig. 3.

and feldspar crystals up to 3mm long are set in a matrix of crystals 1/10th this size. Lower amphibolite to upper greenschist facies conditions are reflected in the low structural state of the K-feldspar in the matrix, and in the alterations of amphibole to biotite and or epidote, of biotite to chlorite, and of plagioclase and microcline to white mica. These highly metasomatic replacement reactions indicate at least a local redistribution of K, Na, and Ca (among others), which could lead to the resetting of alkali exchange equilibria to the temperatures of this alteration. The 390-430^{o}C temperatures calculated from the compositions of coexisting microcline and plagioclase (Fig. 5) are compatible with the above alteration reactions, and suggest that this exchange equilibrium could be part of this lower grade reequilibration. The pervasive occurrence of chlorite with microcline in the plagioclase gneiss establishes lower greenschist facies conditions by the reaction:

muscovite + biotite = microcline + chlorie,

and confirms the implication above that some of this alteration occurred at relatively low grade metamorphic conditions.

It is possible that deformation contributed to the partial readjustment of this assemblage to these lower grade conditions. The lineations defined by rod-shaped crystals of quartz and feldspar, by biotite streaks, and by hornblende needles indicate a penetrative tectonic influence on this assemblage. This strain apparently caused undulose extinction in the larger crystals, and reduced the grain size of others to produce the present bimodal distribution of grain size. This increased lattice and surface energy may have provided the activation energy for some of these retrograde modifications. The strong preferred orientation of the above linear structures at N 55^{o} W is identical to the orientation of lineations in the Willimantic fault zone. This suggests that this ductile deformation occurred during deformation in the Willimantic fault. Return to cars at assembly point.

00.0 Begin road log at main entrance to parking lot of Willimantic Plaza. Cumulative distance is in miles. Turn right onto Rt. 32 at signal.

00.2 Turn right at signal onto eastbound (Providence) ramp for I-84.

01.4 Leave I-84 at exit marked University of Connecticut, Rt. 195.

01.6 Left turn at signal at bottom of ramp, through underpass.

01.8 Right turn onto frontage road.

02.6 Left turn onto Rt. 195 at signal. Proceed north on 195. Hills to west of road underlain by Willimantic Gneiss. Road runs on kame terrace.

04.0 Right turn onto Mansfield Hollow Road. Easy to miss this turn, just past a curve to left. (You get a second chance at Bassetts Bridge Road about 1 mile ahead where you turn right at signal and follow signs to Mansfield Hollow Dam.)

04.5 Turn right at stop sign on Mansfield Hollow Extension.

04.6 Park in Mansfield Hollow Dam parking area. The falls on the Natchaug River have powered mills in the Hollow since c1730. The Kirby Mill, just west of the falls, was built in 1882 of Willimantic Gneiss quarried nearby. Mansfield Hollow Dam, completed by the Corps of Engineers in 1952, was built to prevent recurrence of flooding in Willimantic, which was devastated in the hurricane of 1938. The dam is built at the confluence of the Fenton, Mount Hope and Natchaug Rivers, about 3 miles upstream of the point where the Natchaug joins the Willimantic. The dam proved its worth in August 1955 when heavy rains associated with Hurricane Diane produced a peak discharge in the Willimantic river upstream of the city that was 1.6 times that recorded in the '38 hurricane. Release of water stored in the reservoir after passage of the flood crest held maximum water-levels in the city to just below that of the mean annual flood. It was estimated that losses of $3,200,000 were prevented, equal in amount to one half the cost of the dam.

Walk down grassy slope to outcrops at base of dam to stop 2.

Stop 2, at the spillway of Mansfield Hollow Dam is to one of the freshest exposures of the Willimantic gneiss. It is a massive, gray to buff weathering, quartz, microcline, oligoclase granofels, with an average grain size of 1/2 - 2mm. Biotite, magnitite and retrograde muscovite, chlorite and sphene are accessory minerals. Foliation in this rock is defined by the parallel alignment of the minor phyllosilicates, and includes a lineation defined primarily by quartz-rods with aspect ratios up to 1:5. These lineations are difficult to recognize in the field, and can only be seen on surfaces parallel to the plane which contains them.

The composition of this gneiss is rhyodacitic (Fig. 4) and is rather uniform throughout its exposure. The upper contact of this gneiss appears to be sharp, although the small lenses of this gneiss present within the plagioclase gneiss suggest that the contact is inerlayered. The composition of the Hope Valley alaksite is very similar to the Willimantic gneiss (Fig. 4), and also underlies a plagioclase gneiss and the Tatnic Hill formation in extreme eastern Connecticut. These features are compatible with the suggestion of Day et al (1980) that this gneiss was deposited as a volcanic rock, and if true, it would suggest a very wide area of deposition of the rhyodacitic protolith.

The metamorphism of this granofels, like the plagioclase gneiss at stop 1 must have reached upper amphibolite facies conditions, but K_D's between coexisting oligoclase and K-feldspar (maximum microcline, according to unit cell refinements) suggests equilibration to temperatures as low as 350°C (Fig. 5). Some of these feldspars are rod-shaped, but aspect ratios rarely exceed 1:3. The orientation of the quartz and feldspar rods is strongly N 55°W, again compatible with strain associated with the Willimantic fault. The distribution of feldspar compositions shows a surprising decrease in apparent equilibration temperature with decreasing depth in the structure. This drop in apparent temperature is accompanied by an increase in the proportion of quartz rods to feldspar rods. Our working hypothesis is that plastic strain (dislocation creep) was responsible for the rod shaped crystals as well as for inducing the exchange equilibrium between the feldspars. If this is correct, then the temperatures recorded would reflect the temperature at which plastic deformation in the feldspars ceased. The data would also suggest that feldspars become significantly stronger than quartz below 350°C, in agreement with the experiments of Tullis and Yund (1980). Assessment of this hypothesis requires TEM and microfabric work, not yet undertaken. One conclusion which we can make with confidence, however, is that neither the exchange equilibria nor the mineralogy of the Willimantic gneiss reflect in any way the upper amphibolite facies metamorphic conditions which it must have experienced. Return to cars.

04.6 Leave parking lot by Mansfield Hollow Ext.

04.8 Continue straight past stop sign onto Mansfield Hollow Road, climbing out of the Hollow onto kame terrace.

05.0 Turn right at stop sign onto Bassetts Bridge Road. Kettles on both sides of road.

05.4 Crossing dike for Mansfield Hollow Dam.

07.0 Road curves to right at "Y" intersection with Bedlam Road. Outcrops of plagioclase gneiss in woods to east of road.

07.8 Turn left across bridge over Natchaug River.

07.9 Turn left at stop sign onto Old Rt. 6.

08.2 Pull off and park at side of road just before intersection of Old Rt. 6 with Rt. 6. Cross Rt. 6 to roadcuts of stop 3.

Stop 3, at road cuts on Rt. 6 near North Windham is included to illustrate some of the ductile deformation in the Tatnic Hill formation on the east side of the Willimantic dome. A sub-pelitic biotite-quartz-plagioclase schist with amphibolite layers (now boudinaged) representing the lower part of the biotite schist unit of the lower member of the Tatnic Hill formation is exposed here. The rock contains less garnet and sillimanite and is finer grained than most of this unit (compare with Stop 4, 5). It nevertheless contains isoclinal folds, amphibolite boudins and small scale tectonic blocks which are part of the evidence for high strain in the Willimantic fault zone. Return to cars.

08.2 Turn right on Rt. 6 and proceed south.

08.8 Signal at junction with Rt. 203.

09.1 Crossing E- end of Mansfield Hollow Dam.

10.6 Crossing I-84.

11.8 Crossing Natchaug River, entering Willimantic. Continue on Rt. 6.

12.7 Left on Rt. 32 at traffic circle. Pass through mill building and cross Willimantic River.

12.8 Hard right beneath railroad bridge and up steep ramp onto Pleasant Street. If you get to the signal, you went too far.
The mill complex of the American Thread Company is built largely of plagioclase gneiss quarried in the hill section of the city. Willimantic, the "Thread City", grew up around mills built to take advantage of "The Seven Falls of the Willimantic River", cut into plagioclase gneiss.

13.5 Turn left onto Rt. 289, Mountain Street, driving along the east flank of Hosmer Mountain.

14.1 Park off pavement just before reaching intersection with South-ridge Road.

<u>Stop 4</u>, at several road cuts on the east side of Hosmer Mountain shows the best profile across the contact between the plagioclase gneiss and the Tatnic Hill Formation. The plagioclase gneiss is similar to that at Stop 1. The rusty weathering base of the Tatnic Hill Formation is well exposed along the road section, and the overlying biotite schist unit crops out in natural exposures SW of Hosmer Mt.

Of particular interest in this outcrop is the apparent strain gradient across the contact. Strain is difficult to quantify in these rocks, because of the lack of strain indicators, but an increase in the development of boudinage (of the plagioclase gneiss and included amphibolites), of small scale folding, and of plagioclase and horn-blende porphyroblasts can be seen as the contact is approached. Across the contact into the Tatnic Hill Formation evidence of strain continues to be abundant until the zone of tectonic blocks is reached, where strain becomes very heterogenous.

The contact itself is exposed some 20m above the road surface near the southern end of the outcrop. Please do not sample the outcrop! Textures present on weathered surfaces should be left of all to see! The Tatnic Hill Formation here is a mylonitic schist, and relative to the precursor rock has undergone a 10-50 X grain size reduction. This schist contains a lower grade assemblage, and probably has experienced a higher strain than any of the surrounding rocks. The apparent discordance of this schist with the rocks both above and below suggests that some of the later strain in these rocks cut across both units. Farther south along the road upper amphibolite facies assemblages and structures dominate. These include intra-folial folds, boudinage, tectonic blocks, and feldspathinzation - evidence of the earlier, completely ductile deformation.

The first several meters of the Tatnic Hill Formation provide outstanding examples of strain induced reactions. These rocks contain both kyanite and andalusite rather than the expected sillimanite. Both aluminosilicates embay, and andalusite also includes biotite, and both are associated with magnetite, suggesting the oxidation reaction (Wintsch, 1981):

biotite = Al_2SiO_5 + magnetite + quartz + ions.

Hematite is also present in these rocks as thin blades intergrown with biotite. As grain size is reduced in these rocks, there is a decrease in SiO_2, Na_2O and CaO relative to Al_2SiO_5, and an increase in the Fe_2O_3/FeO ratio. This correlation of oxidized assemblage with small grain size supports the proposal of Wintsch (1981) that a pH increase caused by surface exchange could have been responsible for this oxidation. Thus the mineralogy and even the composition of these rocks do not reflect the upper amphibolite facies conditions which the rocks once experienced. Rather, they reflect a complex set of metasomatic reactions which by some path were probably strain induced at conditions near the Al_2SiO_5 triple point. Return to cars.

14.1 Turn left onto Southridge Road.

14.6 Left at stop onto South Street.

15.0 Left at stop onto Pleasant Street.

15.5 Right at stop, follow signs for Rt. 32 down hill and across Willimantic River.

15.8 Turn left onto Rt. 6, Rt. 32 west at signal.

16.5 Veer right at signal at "Y" intersection onto Rt. 32.

17.5 Turn right onto I-84 west (Hartford) ramp, passing Stop 1.

18.8 Enter road cuts in lower member of Tatnic Hill Formation. The spectacular tectonic blocks, obvious in the road cuts, are not readily apparent in surface exposures. Cost of these roadcuts was greatly in excess of the annual budget for the NSF Earth Science Section.

19.8 Cross Rt. 6 at signal and turn right into Commuter Parking Lot. Get out and walk.

As a compact group, cross Rt. 6 and Rt. 66 at the signal and proceed up the median of I-84 staying well away from traffic. These road cuts are among the most important exposures in Eastern Connecticut. Please do nothing to jeopardize their use by future geologists.

Stop 5, is to the road cuts along the unfinished interchange between I-84 and State Rt. 6. These truly spectacular exposures are made even more enjoyable by the fact that I-84 has not been completed, and we will not be distracted by menacing traffic. A sketchmap (Fig. 6) of these cuts is provided for reference to specific locations.

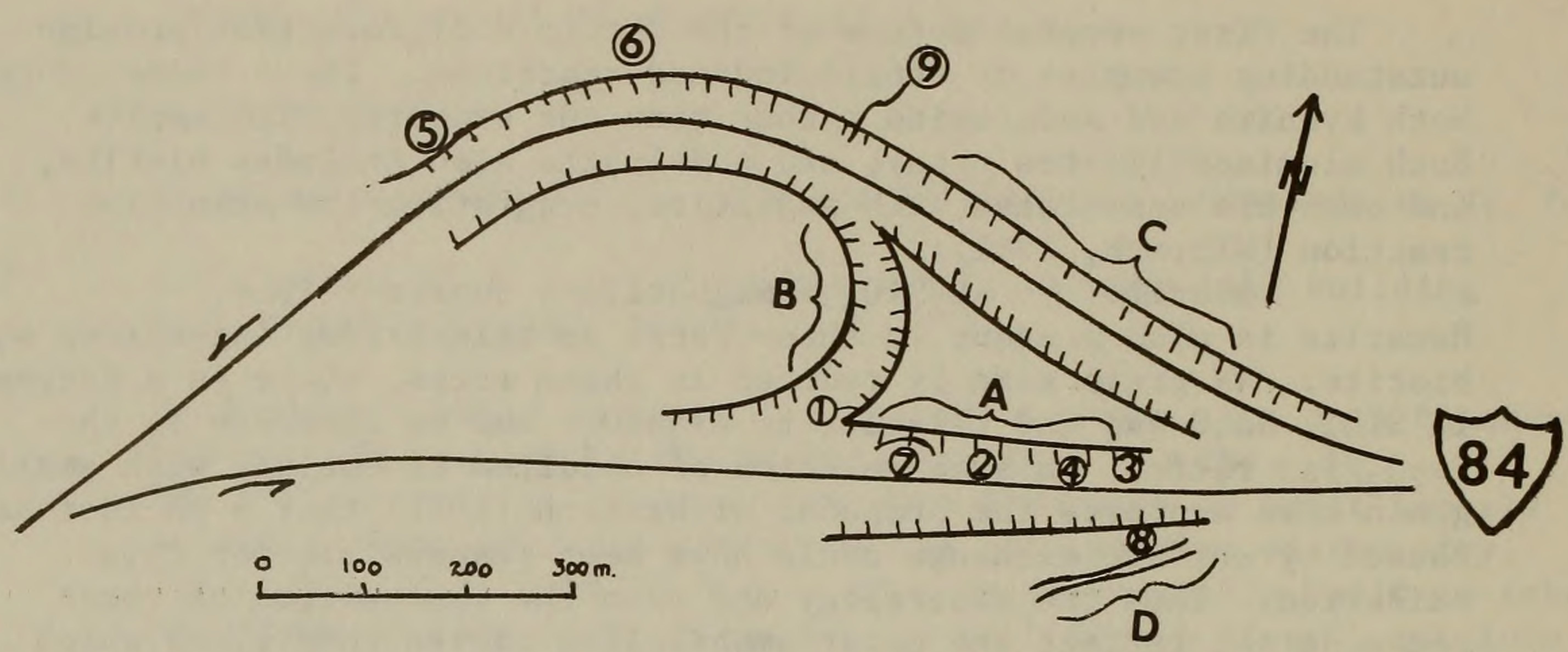


Fig. 6. A sketch map of the road cuts along the interchange of I-84 and U.S. Rt. 6 5km east of Willimantic showing the approximate locations of features described in the text of Stop 5.

The most stunning feature exposed in these outcrops are the large and very large tectonic blocks. They are best viewed from a distance of 30m or more, particularly on face A (Fig. 6). For those especially interested in these structures, a walk through all the cuts is imperative. Note particularly the lack of correlation of structures on either side of the road at C (Fig. 6). These blocks may have developed first as large drag folds, eventually evolving into these discrete blocks as strain is concentrated on the long limbs (Fig. 7). However, many blocks do not show these rotation features, and some degree of mega-boudinage caused by extension during thrusting was probably also involved.

Augen gneiss, blastomylonitic gneiss, mylonitic schist and mylonite are present in order of decreasing abundance in these rocks. The highest grade assemblages are best preserved in the augen gneisses inside the tectonic blocks (e.g. eastend, face A, Fig. 6). In the shear zones surrounding and cutting these blocks kyanite-bearing lower grade assemblages occur as blastomylonitic schist and gneiss (face B and locality 1, if not collected out) Still lower grade slabby mylonitic schists are well exposed on the natural cliff face at D, south of the road. True mylonites are rare, but late, fine grained, middle to lower greenschist facies mylonite 2 cm thick is present in the steeply west dipping shear zone which cuts the entire exposure at 2. This shear zone demonstrates that macroscopicly ductile deformation persisted to these low grade conditions. A brittle fracture zone occurs at 3, where the K-feldspar-chlorite-epidote bearing assemblage reflects very shallow, alteration of this zone. Finally chlorite-rich slickensided joint surfaces dipping steeply N-NW commonly cut all these rocks.

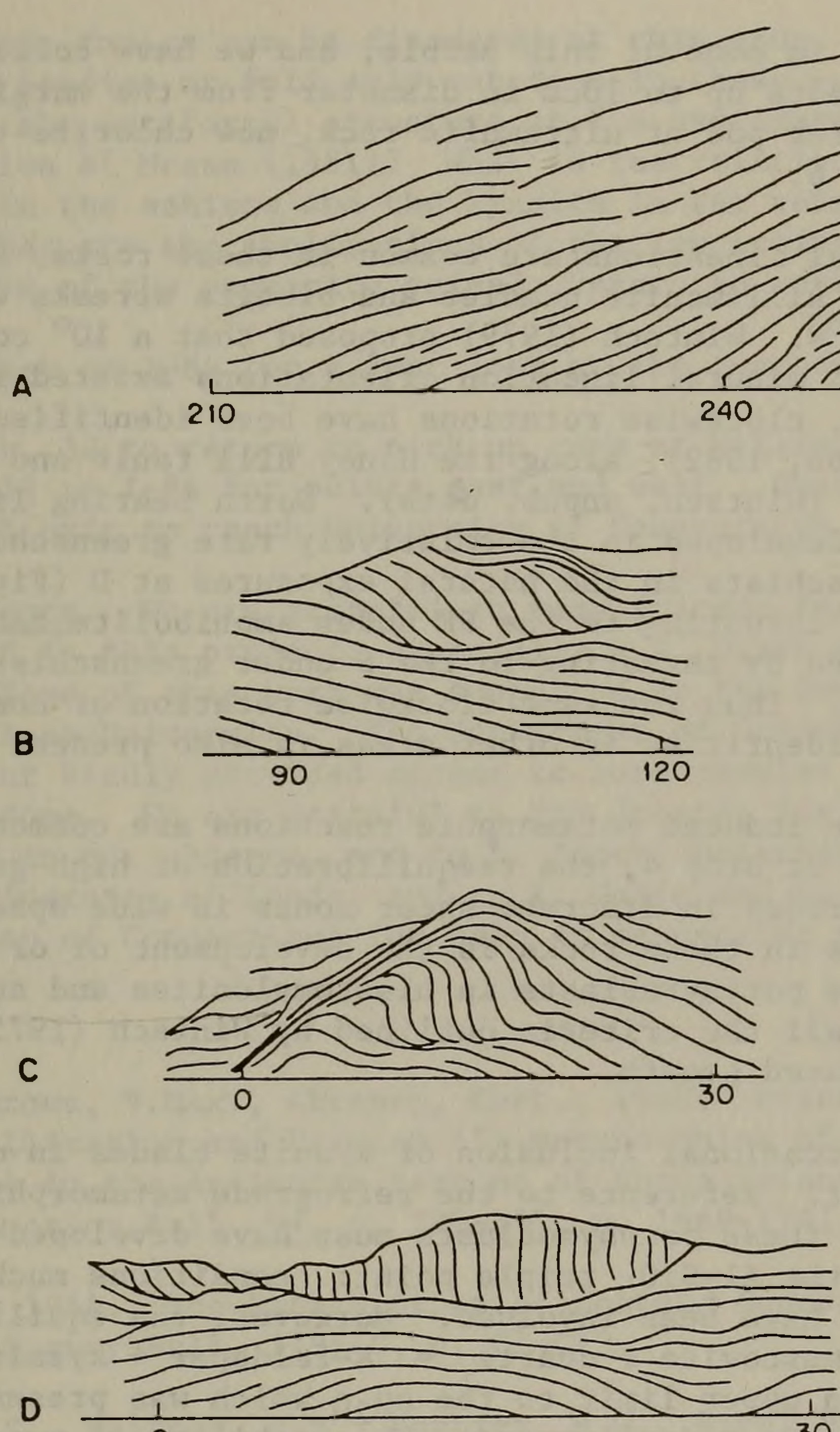


Fig. 7. Possible stages of evolution of a tectonic block from Wintsch (1979): a structure characteristic of the Willimantic fault. Figs. A through D were traced from north facing photographs and can be seen at localities 4, 2, 9 and 6 respectively of Fig. 6. The sequence suggests that these blocks develop as drag folds during thrusting from west to east. Other structures (face a, Fig. 6) suggest that boudinage may also be important.

Several other rock types are present in these cuts. Interlayered in the blastomylonite are at least 28 distinct amphibolite layers, all boudinaged (east end, face A). Successive boudinage of a large amphibolite boudin at its tapering neck can be seen at 4 (Fig. 6). Several 30-50cm thick layers of marble are present at 5. Diopside is present in some of this marble, and we have collected hornblende porphyroblasts up to 10cm in diameter from the margins of one of these. A 2m diameter pod of ultramafic rock, now chlorite-talc schist is present at 6.

Mineral lineations are common in these rocks, and are usually defined by sillimanite needles and biotite streaks which plunge gently N50°W. Wintsch (1979) proposed that a 10° counterclockwise rotation of mineral lineation orientations existed in these rocks. Since then, clockwise rotations have been identified in the Putnam area (Hudson, 1982), along the Honey Hill fault and in the Deep River area (Wintsch, unpub. data). North bearing lineations are very well developed in the relatively rare greenschist facies mylomitic schists in the natural exposures at D (Fig. 4). This shows that thrusting to the SE under amphibolite facies conditions was followed by thrusting to the S under greenschist facies conditions. Thus the same clockwise rotation of compression direction identified in other areas is also present here.

Strain induced metamorphic reactions are common in these rocks. As at stop 4, the reequilibration of high grade assemblages to lower grades in discrete shear zones is wide spread. Most conspicuous in these rocks is the development of orthoclase and plagioclase porphyroblasts in blastomylonites and augen gneiss. These fit all the criteria outlined by Wintsch (1975) for syntectonic, strain induced growth.

The occasional inclusion of kyanite blades in microcline is significant. Reference to the retrograde metamorphic path of Fig. 2 shows that these porphyroblasts must have developed at conditions less than the Al_2SiO_5 triple point: conditions much too low for melting to have been involved. Moreover, the equilibrium:

$$\text{muscovite} + \text{quartz} = \text{K-feldspar} + \text{kyanite} + H_2O$$

provides an upper limit to the a_{H_2O} which was present at the time of porphyroblast development. The stability of muscovite + quartz (calculated from the data in Helgeson et al 1978) is contoured for a_{H_2O} (standard state = P, T of the real gas). If the triple point of Holdaway (1971) is adopted, the maximum a_{H_2O} in these shear zones is seen to be 0.10, reflecting a fugacity of 80 b out of the possible 800 b of pure H_2O at these P-T conditions. It is not likely that an aqueous fluid was diluted by CO_2 because carbonates are rare in these shear zones, and fluids of a low oxygen fugacity may be ruled out by the presence of hematite in some of these shear zones. We cannot conceive of any other gases which could have been present in the necessary amounts and leave no trace on the assemblage. We are thus forced to the conclusion that a fluid 'phase' as such was not present during the retrogression of these shear zones - only an aqueous intergranular film. Because of this significance of the occurrence of kyanite + K-feldspar, we would be grateful if all discoveries of this assemblage on this trip would be brought to our attention.

Many other topics can be discussed at this stop. Is there evidence for boudins or fold axis rotation in these rocks? Is the rock forming the antiformal structure at 7 a candidate for the steady state foliation of Means (1981)? What is the relationship between the kyanite in the schists and the kyanite in the veins at 1 and 8 (Fig. 6)? What are the implications of the low activity of H_2O on the generation of the pegmatite veins? Return to cars.

19.8 Proceed east on I-84 for a last look at the tectonic blocks.

21.7 Exit at Rt. 32 to return to pick up cars at Willimantic Plaza. Take Rt. 32 to I-86 for points east and west. Continue on I-84 to Rt. 195 exit to reach University of Connecticut.

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REFERENCES

Day, H.W., Brown, V.Max., Abraham, Kurt., 1980. Precambrian (?) crystallization and Permian (?) metamorphism of hypersolvus granite in the Avalonian terrane of Rhode Island. Geol. Soc. America Bull. 91, p. 389-391; p. 1669-1741.

Dixon, H.R., 1964. The Putnam Group of eastern Connecticut. U.S. Geol. Survey Bull. 1194-C, p. C1-C12.

Helgeson, H.C., Delaney, J.M., Nesbitt, H.W., Bird, D.K. 1978. Summary and critique of the thermodynamic properties of rock-forming minerals. Am. Jour. Sci., 278A, 229p.

Holdaway, M.J., 1971. Stability of andalusite and sillimanite and the aluminium silicate phase diagram. Am. Jour. Sci. 271, 97-131.

Hudson, M.R. Ms., 1982. Mineralogy, petrology and structure of the Tatnic Hill Formation, Putnam, Connecticut. M.A. Thesis, Indiana Univ. 301p.

Means, W.D. 1981. The concept of steady state foliation. Tectonophysics, 78, p. 179-200.

Richardson, S.W., Gilbert, M.C., and Bell, P.M., 1969. Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria; the aluminium silicate triple point. Am. Jour. Sci. 267, p. 259-272.

Snyder, G.L., 1964. Bedrock Geology of the Willimantic Quadrangle, Connecticut. U.S. Geol. Survey, Geol. Quad. Map G Q 335, Scale 1:24,000.

Snyder, G.L., 1967. Bedrock Geologic map of the Columbia Quadrangle, east-central Connecticut. U.S. Geol. Survey, Geol. Quad. Map G Q 592, Scale 1:24,000.

Tullis, J.A., and Yund, R.A., 1980. Hydrolytic weakening of experimentally deformed Westerly granite and Hale albite rock. J. Structural Geol. 2, 439-451.

Whitney, J.A., Stormer, J.C. Jr., 1977. The distribution of $NaAlSi_3O_8$ between coexisting microcline and plagioclase and its effect on geothermometric calculations. Am. Min. 62, 687-691.

Wintsch, R.P. 1975. Feldspathization as a result of deformation. Geol. Soc. America Bull. 85, p. 35-38.

Wintsch, R.P. 1979. The Willimantic fault: a ductile fault in eastern Connecticut. Am. Jour. Sci., v. 279, p. 367-393.

Wintsch, R.P. 1981. Syntectonic Oxidation. Am. Jour. Sci. 281, p. 1223-1239.

Wintsch, R.P., and Grant, N.K., 1980. Major element, rare earth element and Sr isotope geochemistry of "Monson gneisses", eastern Connecticut (abstr.). Geol. Soc. Am. Abstr. Programs. v. 12, p. 89.