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THE DIAGENETIC TO METAMORPHIC TRANSITION IN THE NARRAGANSETT AND NORFOLK BASINS, MASSACHUSETTS AND RHODE ISLAND

by

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Purpose

The Narragansett-Norfolk Basin Complex records the best example of Alleghenian metamorphism in New England and includes a complete sequence of metamorphic zones from unmetamorphosed sediments to the amphibolite facies (sillimanite zone). Today we will observe the changes that occur in argillaceous and arenaceous rocks at the lower end of this sequence as we proceed generally upgrade. Using metamorphic subzones determined on the basis of illite crystallinity as a guide, we will traverse from the zone of diagenesis through incipient metamorphism into the lower greenschist facies. Illite-muscovite, chlorite, quartz and feldspar dominate the mineralogical suite at these metamorphic grades. Thus, most of the mineralogical changes that occur (i.e., the improvement of mica crystallinity and magnesium enrichment of chlorites) are not visually discernable. We will, however, be able to observe the other changes that take place during incipient metamorphism such as the transition shale-slate-phyllite in argillaceous rocks, and changes in cleavage development and structural style with different lithologies. Characteristic minerals of low-grade metamorphism will be able to be seen at some stops.

Introduction

The Narragansett and Norfolk Basins (Figure 1) are erosional remnants of a late orogenic, structural and topographic depression. The basin complex contains Late Pennsylvanian non-marine clastic sedimentary rocks in association with penecontemporaneous volcanics and granitic intrusions. The thickest and most extensive unit in the Narragansett Basin is the Rhode Island Formation, mostly made up of gray and black fluvial sandstones and argillaceous rocks with minor conglomerate. These rocks grade into red-colored fluvial sediments, the Wamsutta Formation, in the northern part of the Narragansett Basin and in the Norfolk Basin. Well-preserved plant fossils are widespread in both these units and establish their partial temporal equivalence. Coal has been mined in the Rhode Island Formation intermittently from 1736 to 1959. The current energy situation has restimulated an interest in the basin and in evaluating the economic potential of the coals.

Prior to our work on illite crystallinity, sub-biotite zone rocks, which occupy approximately 2/3 of the basin complex, have been subject to little further subdivision. Quinn and Moore (1968) broadly separated this region into a chlorite zone and a zone of still lower grade rocks ("firmly indurated but essentially not metamorphosed") in the northwest part of the basin. In the southern part of the basin and along the basin margins, the metamorphic grade increases rapidly over short distances and reaches a maximum (upper amphibolite facies; sillimanite

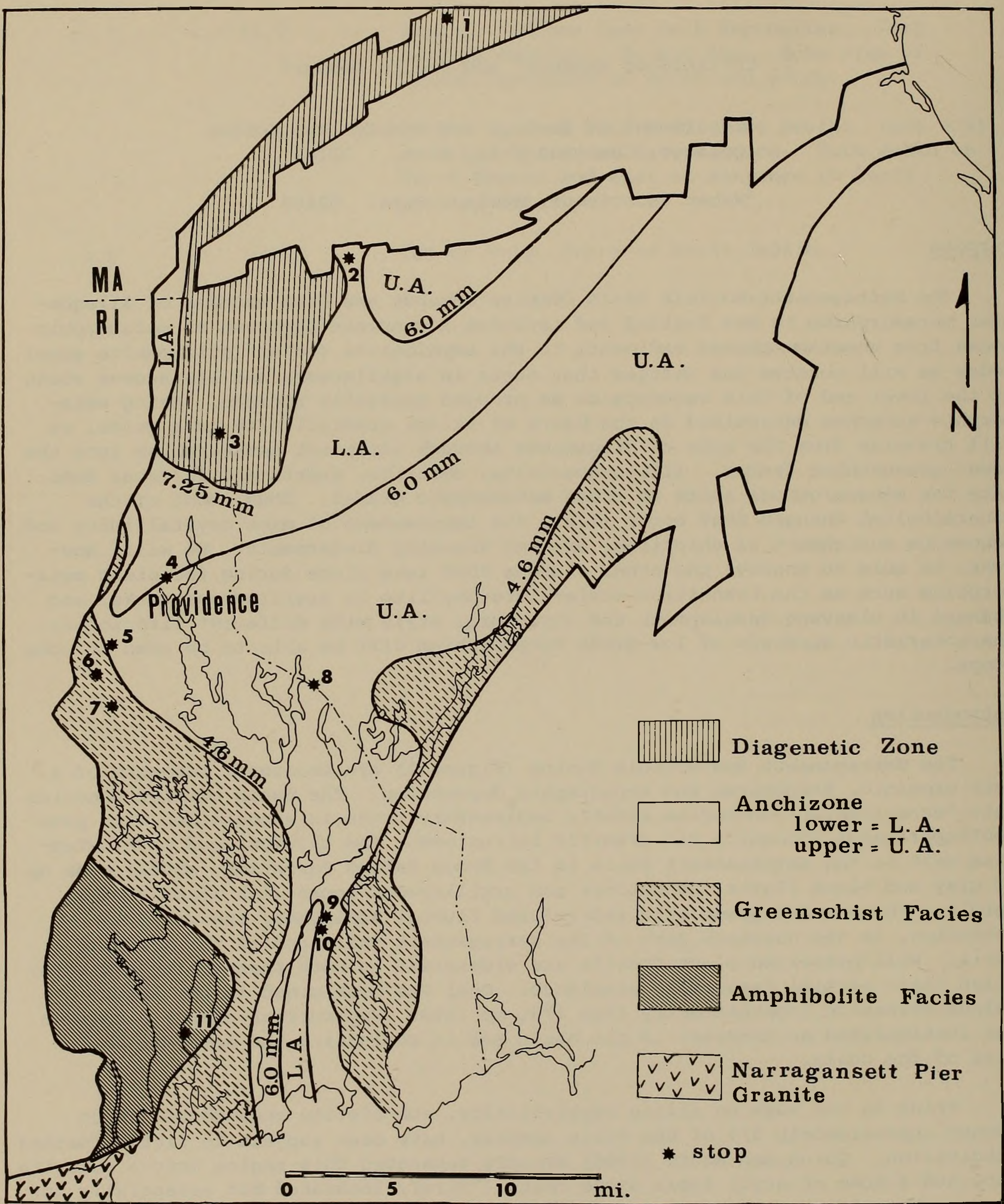

Figure 1. Map of illite isocrystallinity contours and metamorphic facies of the Narragansett-Norfolk Basin Complex, Mass. and R.I. Amphibolite facies boundary from Quinn (1971).

zone) in the southwest corner of the basin, near the Narragansett Pier Granite (Figure 1).

In the past coal from the Narragansett Basin has been variously ranked as anthracite and meta-anthracite, with somewhat ambiguous and conflicting results (Ashley, 1915; Toengas and others, 1948; Quinn and Glass, 1958; Grew, 1974). Most of the coals on which there is useful chemical data come from the areas of low-grade, sub-biotite zone rocks that comprise the bulk of the basin. According to most recent compilations, these have an apparent rank of anthracite with minor amounts of semi-anthracite and meta-anthracite (Lyons and Chase, 1979; Skehan and others, 1979). However, petrographic analysis shows that the Narragansett Basin coals have undergone a very complex thermal and structural history that can explain many of the previously confusing chemical and physical analyses of the coal (Gray and others, 1978; Raben and Gray, 1979). As a result of these studies, only the coals in the northwest corner of the basin may be considered normal anthracites. The bulk of the coal deposits of the Narragansett Basin are primarily the products of thermal alteration and coking of coals that were already at least of bituminous rank prior to coking.

Illite Crystallinity, Coal Rank and Metamorphic Mineralization

We have applied illite crystallinity techniques and measurements to the sub-biotite portions of the basin complex in an effort to refine the subdivision of this zone and to better understand the thermal history of the coals. In diagenesis and incipient metamorphism (anchimetamorphism), the 10 Å clay mineral illite gradually alters to muscovite through minor chemical and structural changes. In this process, the crystal structure becomes more regular, as 14 Å and 17 Å layers interstratified within the 10 Å illite crystal structure are lost with increases in temperature. This change is reflected in the shape of the 10 Å (001) basal X-ray diffraction peak, which becomes both sharper and more symmetrical as the grade increases and as illite becomes muscovite (Figure 2). A common measure of this change is the Kubler Index (K.I.), which records the peak width at half-height and gives particularly sensitive results in the range of high-grade diagenesis to low-grade metamorphism. Kubler (1964) by comparison of his data to other metamorphic effects has established standard ranges of illite crystallinity

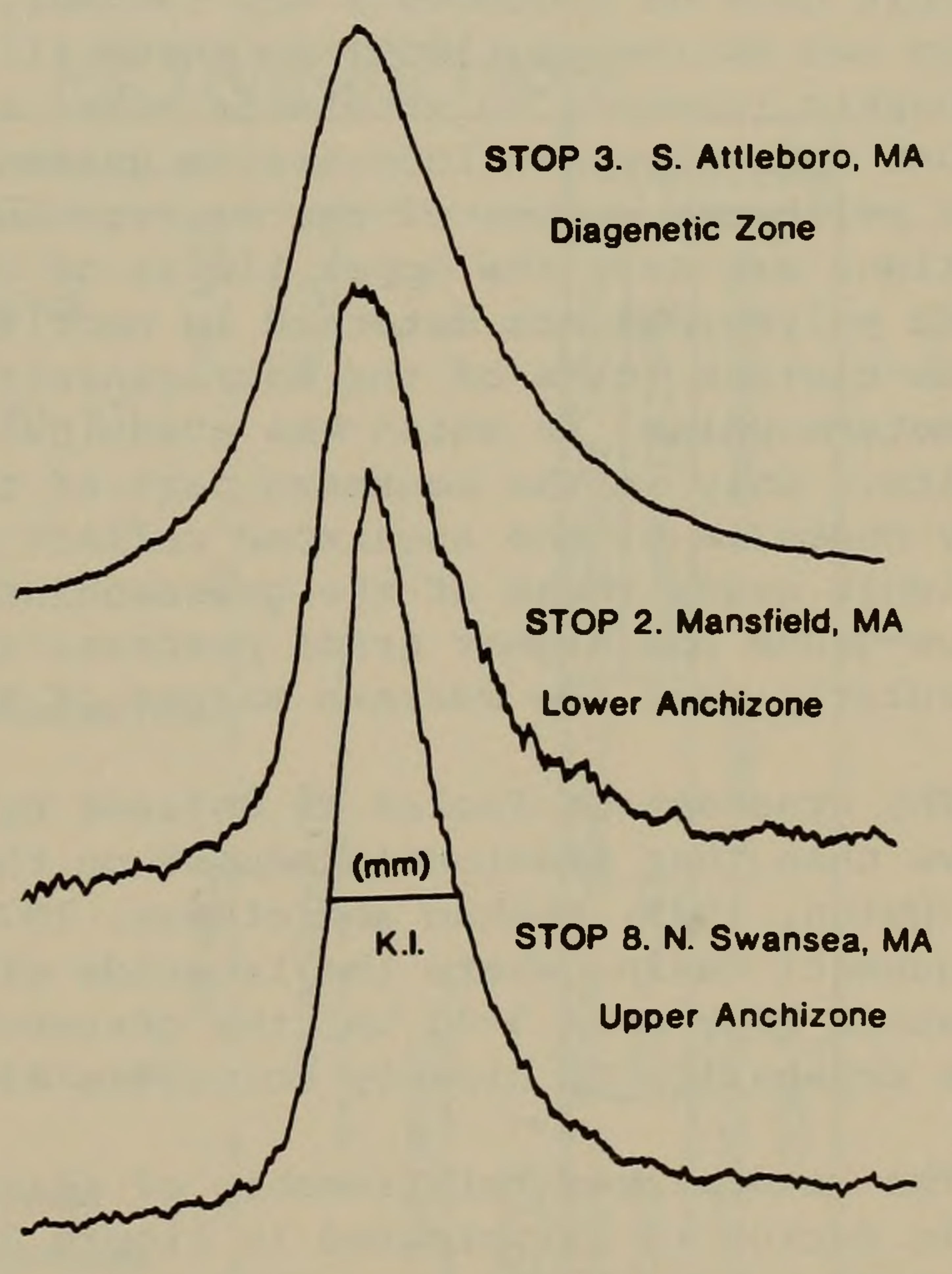

Figure 2. From top to bottom, 10 Å mica peaks becoming sharper and more symmetrical with increasing metamorphic grade. The crystallinity is measured as the peak width at half-height (Kubler index or K.I.) in millimeters.

for the zone of diagenesis, the zone of anchimetamorphism (anchizone), and the onset of the greenschist facies of regional metamorphism. The absolute values of peak width measurements are dependent upon the experimental X-ray diffraction conditions (e.g., widths of the divergence, scatter and receiving slits used; time constants; kind of radiation used; instrument differences). Thus, the use of standards that have been matched to Kubler's standards is required to define these three zones in a like manner. For Kubler's standards and conditions used in the Narragansett Basin study these values are:

Diagenetic zone = peak width greater than 7.25 mm (= Kubler's 7.5)
Anchizone = peak width between 7.25 mm and 4.6 mm
Sub-biotite greenschist facies = peak width less than 4.6 mm (= Kubler's 4.0)

We further separated out an upper and lower anchizone, with a boundary at 6.0 mm. Illite peak widths less than 6.0 mm correspond approximately with the place at which chlorite growth is accelerated and unstable clastics replaced. Thus, it can be used as an approximate boundary for the chlorite isograd.

We collected illite crystallinity data from the carefully disaggregated <2 micron fraction of fine-grained rocks of the Rhode Island and Wamsutta Formations (i.e., slates and phyllites, coals, thin shale partings, and argillaceous rip-up clasts). This minimized the problem of admixed coarse detrital muscovite, which would cause illite basal peaks to appear anomalously sharp and well-crystallized. From this data we produced a map (Rehmer, Hepburn and Schulman, 1978; Rehmer, Hepburn and Ostrowski, 1979) in which illite isocrystallinity contours act like metamorphic isograds to subdivide zones of increasing thermal alteration (Figure 1). Our data shows an increase in grade toward the south and center of the basin. In the northwest corner of the Narragansett Basin and adjoining Norfolk Basin, conditions are near the upper limits of diagenesis; coals are anthracitic and only 2M mica polymorphs are detected in unoriented X-ray diffraction patterns. Most of the sub-biotite rocks of the Narragansett Basin complex belong within the zone of anchimetamorphism, in which the principal phyllosilicate phases are illite and chlorite. Only in the southern part of the Narragansett Basin do the isocrystallinity contours of the anchizone reflect the same regional pattern found within the higher grade rocks of the greenschist and amphibolite facies. In the north, the low-grade and higher grade patterns appear to intersect at a high angle, particularly near the western margin of the basin near Providence, R.I.

The greenschist facies as defined by illite crystallinity is more areally extensive than that previously mapped on the basis of the first appearance of biotite (Quinn, 1971; Skehan and others, 1979). However, in the southern part of the Narragansett Basin, where the isograds rise rapidly in intensity from sub-biotite to kyanite zone over 3-10 km, the greenschist facies boundary as determined by illite crystallinity closely coincides with the biotite isograd.

The generalized relationship of illite crystallinity to coal rank and metamorphic facies is illustrated in Figure 3. While diagnostic metamorphic minerals are rare megascopically in pelitic rocks of the diagenetic and anchizones, paragonite and pyrophyllite are readily detected by X-ray diffraction and chloritoid may be seen in thin section. Paragonite, considered a diagnostic mineral for the upper anchizone and greenschist facies (e.g., Frey, 1970) was detected in X-ray diffraction patterns of samples from the vicinity of Pawtucket and Providence, R.I. In our work and that of Quinn and Glass (1958) paragonite has only been found in the Narragansett Basin in the upper anchizone and lowermost greenschist facies. Chloritoid also appears in this part of the basin. Although formerly considered to be a mineral of the anchizone (Kubler, 1968), chloritoid typically makes its appearance only in the greenschist facies proper (Frey, 1970, 1978; Kisch, 1974). In the Narragansett Basin, the greenschist facies boundary as mapped by illite crystallinity closely coincides with the chloritoid isograd of Skehan and others (1979). Chloritoid can thus be regarded as a diagnostic mineral for the onset of the greenschist facies in the Narragansett Basin. Pyrophyllite also occurs in the upper anchizone in the Narragansett Basin (e.g., Stop 9). Frey (1978) considers pyrophyllite to be a characteristic mineral of the anchizone in the Central Alps, formed at the expense of kaolinite. Ostrowski (1980, 1981) has studied the chlorites of the Narragansett Basin pelitic rocks in conjunction with our study. Her work demonstrates that the trend toward magnesium enrichment of chlorite with increasing metamorphic grade is part of a continuum that can be extended downward into the diagenetic and anchimetamorphic zones.

The relationship of illite crystallinity to standard coal ranks has been examined in many previous studies, particularly in the Carboniferous tectonic basins of Europe (Frey and Niggli, 1971; Kisch, 1974a,b, 1978; Wolf, 1975; Gill and others, 1977). This correlation is generalized in Figure 3. Increasingly however, as more such studies are done, it is becoming clear that although the generalized correlation holds, there is not a precise one-to-one relationship between illite crystallinity, coal rank and other metamorphic mineral growth. In other words, for different coal basins, there will be some differences in where the

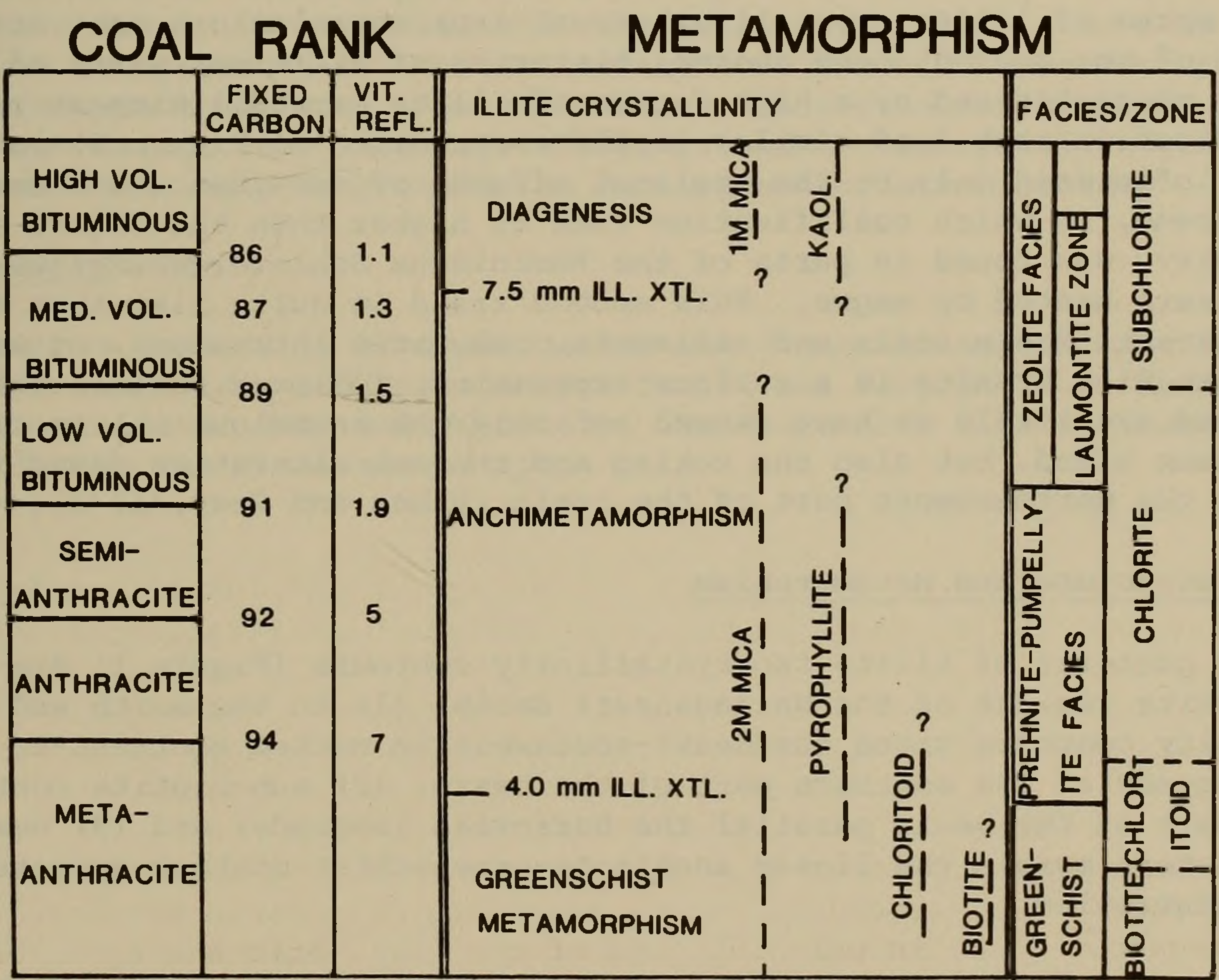

Figure 3. Schematic diagram showing typical relationships of coal rank, illite crystallinity, other mineral paragenesis and standard metamorphic facies and zones. Assembled from several sources. The values for illite crystallinity at zone boundaries given here are those of Kubler (1964). Kubler's 4.0 mm equals our 4.6 mm (Fig. 1) and Kubler's 7.5 mm equals our 7.25 mm. See text for details.

lines are drawn on Figure 3. This is only to be expected; factors leading to clay mineral transformations are somewhat different than for coal. Organic matter is transformed predominantly as a function of temperature and to a lesser extent time. With clay mineral alterations such additional factors as total pressure, various partial pressures (P_{H2O}, P_{CO2}, P_{CH4}, etc.) and composition of pore waters must be considered along with temperature and time.

Correlation of our illite crystallinity data to coal rank has been somewhat hampered by a lack of chemical data for Narragansett coals that conforms to ASTM rules for standard determination of rank using the ASTM classification scheme (see Lyons and Chase, 1979, for a complete discussion of this problem). As expected, the trends in increasing illite crystallinity and increasing coal rank lie in parallel directions. Our data, however, clearly differs from the "standard correlation" shown in Figure 3. In the Narragansett Basin, pelitic rocks with quite high values of illite crystallinity (i.e., poorly crystallized illite) can be found in association with anthracitic coals. For instance, in the northern part of the basin (Mansfield and Plainville, Mass. area) shales whose illite crystallinity values suggest that only diagenetic thermal conditions were attained are found with coals whose mean maximum vitrinite reflectance values (aver. 6.4 and 5.6, respectively, from Raben and Gray, 1979) are more typical of the anchizone.

Wolf (1975) in her work on the Rheinische Schiefergebirge has found two differing paths of illite crystallinity/coal rank correlations that are primarily a function of the geologic and thermal histories of different parts of that basin. One trend, characterized by a high degree of illite crystallinity at relatively low coalification rank (and similar to the correlation of Figure 3) is found in sediments influenced only by the regional effects of subsidence and deep burial. A second trend, in which coalification rank is higher than the degree of illite crystallinity, was found in parts of the Rheinische Schiefergebirge where the sediments were heated by magma. This second trend is quite like that found for the Narragansett Basin coals and sediments. Magmatic intrusions, of which the Narragansett Pier Granite is a surface expression, followed sedimentation in the Permian, and are likely to have caused not only the anomalous illite crystallinity vs. coal rank trend, but also the coking and thermal alteration found in the coals in all but the northernmost part of the basin (Raben and Gray, 1979).

Timing of Structure and Metamorphism

Three patterns of illite isocrystallinity contours (Figure 1) are found within sub-biotite regions of the Narragansett Basin: (1) in the north and west isocrystallinity contours trend northeast-southwest in marked contrast to the Barrovian isograds of the southern part of the basin; (2) sub-biotite contours in the southern part of the basin parallel the Barrovian isograds; and (3) near the basin's eastern margin the linear anchizone-greenschist contour appears likely to be fault-controlled.

The isograd discordance between low-grade terrains of the north and the high-grade terrain of the south may reflect the overprint of two distinct thermal events. In such a model, a low-grade burial metamorphism increases to the southeast but has a higher-grade thermal event, centered near the southwestern corner of the basin, superimposed over it. The intrusion of the Narragansett Pier Granite (276 m.y.; Kocis and others, 1978) has been suggested as at least a partial cause of the highest isograds (Quinn and Moore, 1968; Grew and Day, 1972).

Although their models differ considerably in detail, both Grew and Day (1972) and Murray and others (1979) have found evidence in the southern part of the basin to suggest a two-stage high-grade metamorphism, with the Narragansett Pier Granite intruded at or just after the peak of metamorphism, followed by a late low-grade metamorphism. Thus, a second possibility is that the low-grade burial metamorphism best displayed in the northern part of the basin has been superimposed on the higher grade rocks centered around the Narragansett Pier Granite and has caused retrograde reactions. In support of this model, the rocks of the Narragansett Basin, even the low-grade phyllites, yield uniform apparent K-Ar ages (from biotite and muscovite) of 230-260 m.y. (Zartman and others, 1970; Dallmeyer, 1981). This would suggest that argon retention at the close of Permian metamorphism occurred at approximately the same time in both the northern and southern parts of the basin.

Structure

Slaty cleavage and schistosity is generally well-developed in the argillaceous rocks of the sub-biotite zone Narragansett Basin; many of the coarser clastic rocks of the anchizone have also developed a spaced fracture cleavage. Although we will observe a general increase in cleavage and deformation with rising isocrystallinity isograds, attempts to directly correlate these two features has always proven futile (Kubler, 1967). Dynamic factors, which are important in the formation of schistosity, have no perceptible effect on illite crystallinity. We have found, for example, that the illite crystallinities from slickenside surfaces are essentially identical with those from juxtaposed samples that do not have movement surfaces. On the other hand, increasing temperature, the most important factor in illite crystallinity, and the recrystallization of the phyllosilicates can help to promote the development of a schistosity.

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THE DIAGENETIC TO METAMORPHIC TRANSITION IN THE NARRAGANSETT AND NORFOLK BASINS, MASSACHUSETTS AND RHODE ISLAND

Road Log

The trip will start in the unmetamorphosed Pennsylvanian rocks of the Norfolk Basin in Norwood, Massachusetts and proceed southward across the Narragansett Basin, ending at the Jamestown Bridge in the staurolite zone. The last stop is a 15 minute drive from the NEIGC headquarters at the University of Rhode Island, Kingston.

Meeting Place: The trip will assemble in the parking lot adjacent to Rt. 1 of the Holiday Inn, Dedham, Mass. at 9 A.M. The Dedham Holiday Inn is on Route 1 just North of exit #60 from I-95 (Rt. 128). Turn left into the parking lot of the Holiday Inn at the 1st traffic light after leaving the exit ramp North of I-95. Participants traveling from Kingston should allow an hour to an hour and a quarter to reach this meeting place.

MILEAGE

Cum.	S/S	
0.0	0.0	Road log begins at exit from parking lot of the Dedham Holiday Inn onto Route 1; TURN RIGHT (south).
0.2	0.2	Enter Rt. I-95 (Rt. 128) SOUTH. Continue on I-95 to Exit #62.
2.4	2.2	Exit #62 (University Avenue). Bear Right.
2.5	0.1	Turn LEFT at end of ramp.
2.6	0.1	Turn RIGHT onto University Avenue.
3.6	1.0	Turn LEFT at stop sign (by W.W. Grainger, Inc.).
4.3	0.7	Turn RIGHT beyond interstate overpass into Shawmut Industrial Park.
4.8	0.5	Turn RIGHT into parking lot of Walworth Marine Co.; outcrop is behind the buildings by the railroad tracks.

STOP 1. (45 minutes) Norwood Quad. Wamsutta Formation; Shawmut Industrial Park. Diagenetic Zone (K.I. = 9.0-11.6 mm)

This outcrop consists of four fining upward alluvial cycles in the Wamsutta Fm., here mostly sandstone and conglomerate with lesser amounts of reddish and green siltstone and slate. An abundance of sedimentary features can be seen here including cross-bedding, scour-and-fill, pelitic rip-up clasts, and root mottling. The prevailing dip direction of the cross-beds is southwest (Chute, 1966).

Bedding is somewhat variable, averaging N65°E, and is overturned dipping 80°NW. A well-developed fracture cleavage occurs within argillaceous rocks, is weaker in siltstones and absent from the coarser clastics.

In pelitic units this cleavage is particularly well developed adjacent to shear zones. Cleavage generally intercepts bedding at a low angle and dips less steeply than the bedding (approx. N75°E, 60-65°NW). Several shear zones are evident, with slickensided surfaces developed in the pelites. Tension gashes, filled with carbonate, quartz and chlorite, are developed adjacent to shear zones.

The Wamsutta Formation has been mapped both here in the Norfolk Basin and in the northern part of the Narragansett Basin, and it is likely that these two basins were fully merged at the time of sedimentation (Quinn and Oliver, 1962).

Cum.	S/S	
7.3	2.5	Retrace Route to I-95. Enter I-95 (Rt. 128) SOUTH. Stay in right lane and be prepared to exit onto I-95 South.
7.8	0.5	Enter Route I-95 South.
9.7	1.9	Outcrop on left is similar to Stop #1.
21.6	11.9	Leave I-95 at Exit #7A (Rt. 140 South). BE PREPARED TO STOP SUDDENLY.
21.7	0.1	Park with caution on right shoulder adjacent to the exit ramp.

STOP 2. (30 minutes) Mansfield Quad. Rhode Island Formation; cloverleaf of Interstate 95 & Rt. 140, Foxboro, Mass. Lower Anchizone (K.I. = 6.7 mm).

A large section of Rhode Island Formation with complex folding, faulting and possible facies changes is exposed here. A detailed map of this area has been presented in Lyons and Chase (1976).

The lithologies are mostly fluvial graywacke sandstone and dark gray slate and siltstone, with lesser polymict conglomerate. The sandstone is laminated to cross-bedded, and in places contains large pelitic rip-up clasts. Approximately 30 plant species have been described from this locality, and high-ash coal beds were originally exposed along I-95 during its construction (Lyons and Chase, 1976). Mean max. vitrinite reflectance from 11 samples of these coals ranges from 4.8-7.5 (ave. 6.4), dominantly anthracite with minor meta-anthracite (Raben and Gray, 1979).

Bedding is less distinct than STOP #1; and although higher grade, the cleavage is less regular. Cleavage varies greatly with lithology. Fine sandstones and siltstones have a well-developed close-spaced "slaty" cleavage, although massive sands and conglomerates are little affected. Pelitic beds have a wavy, pervasive foliation and have developed a phyllitic sheen, particularly in the dark graphitic rocks. The foliation surfaces in fine-grained rocks show extensive slickensides. Lyons and Chase (1976) have mapped over a dozen faults in this outcrop.

Continue on Rt. 140 until you can turn around.

22.3 0.6 Re-enter I-95 SOUTH.

30.9 8.6 Exit onto Rt. 123 West (Exit #3B).

31.4 0.5 Base of exit ramp, proceed west on Rt. 123.

33.1 1.7 Turn RIGHT onto May St.

33.3 0.2 Junction May St. and Rt. 1. Park with care. Outcrop is on the east side of Rt. 1.

STOP 3. (30 minutes) Attleboro Quad. Wamsutta Formation; Rt. 1 and May St., South Attleboro, Mass. Diagenetic Zone (K.I. = 9.4-10.8 mm).

Fluvial sequences of red shale, siltstone and sandstone, lithologically similar to Stop #1 can be seen in this outcrop of the Wamsutta Formation, now in the Narragansett Basin. The rocks locally are in a simple dipping sequence (N50^{o}E, 40^{o}NW) with cleavage subparallel to bedding. Only a weak, irregular, wide-spaced fracture cleavage is present in the shale and none is evident in the siltstones and sandstones.

Fine-grained beds are brick red with some green mottling that is irregular and laterally discontinuous. Lidback and Gheith (1980) attribute the red coloration of the Wamsutta to the secondary formation of hematite, and the mottling to the fluctuating Eh-Ph of groundwater during diagenesis.

The transition zone between Wamsutta (red) and Rhode Island (gray) beds is best seen in the vicinity of Attleboro, Mass., where red and gray beds are commonly interlayered. Gray "Rhode Island" shales outcropping on the grounds of the Fuller Memorial Hospital (on the opposite side of Rt. 1 from this stop) have similar diagenetic illite crystallinities (K.I. = 10.2-12.4 mm) despite the pigmentation difference.

Turn around, head SOUTH on Rt. 1.

33.3 --- Junct. May St. and Rt. 1; proceed SOUTH on Rt. 1.

33.5 0.2 Turn LEFT onto Rt. 1A SOUTH. Continue on Rt. 1A to I-95.

34.8 1.3 Turn RIGHT onto I-95 SOUTH.

36.8 2.0 Large outcrops of Rhode Island Formation on left.

40.1 3.3 Leave I-95 at Exit #24 (Branch Ave.).

40.3 0.2 At end of ramp, turn LEFT onto Branch Ave.

40.6 0.3 Turn RIGHT onto North Main St.

41.0 0.4 Turn LEFT into University Heights Shopping Center.

41.2 0.2 Proceed around the Rhode Island Hospital Trust Bank building to outcrops at the rear of the shopping mall.

STOP 4. (30 minutes) Providence Quad. Rhode Island Formation; University Heights Shopping Center, Providence, Rhode Island. Lower-Upper Anchizone boundary (K.I. - 6.0 mm).

Interbedded graphitic phyllite, siltstone, sandstone, and minor small-pebble conglomerate outcrop along the ledge at the rear of the shopping center. The primary cleavage is generally along bedding, but both are irregular in orientation. Cleavage is developed in all lithologies except the conglomerates. Phyllites have a prominent fissility; secondary slip-cleavage producing a prominent, near horizontal crinkle lineation is found in the graphitic phyllites.

A faulted asymmetrical anticlinal fold is evident near the south end of the outcrop. Slickenside surfaces on graphitic phyllites, and the wrapping of the cleavage in phyllites around more resistant sandstone layers indicate an abundance of differential movement surfaces.

Coarse detrital mica is very evident in the sandstones here. Because of the prevalence of coarse detrital muscovites in sediments of non-marine, intermontane basins, extra care must be taken to avoid the admixture of this well-crystallized material into the 10 A fraction when undertaking illite crystallinity studies. We sampled no lithologies coarser than siltstone for the study and always used the most fine-grained rock available. Disaggregation of the samples, by oxidation of organics and ultrasoneration, avoided grinding of coarse detrital grains into the fine fractions. Finally, analysis of illite crystallinity was only performed on the less than 2 micron fractions of the disaggregated samples.

41.1 0.2 Return to North Main St. Turn RIGHT (North).

41.6 0.2 Turn LEFT onto Branch Ave. again.

42.0 0.4 Turn LEFT onto I-95 SOUTH.

42.1 0.1 Bottom of ramp, re-enter I-95 SOUTH.

44.1 2.0 Junct. I-95 and I-195. STAY on I-95 SOUTH.

47.0 2.9 Leave I-95 at Exit #16, Rt. 10, Cranston, (Also marked, "To Reservoir Ave.").

47.4 0.4 Enter Rt. 10 NORTH.

48.8 1.4 Exit at Cranston St. (also marked "Industrial Park"). Stay in left lane of exit ramp.

49.0 0.2 Turn LEFT at bottom of ramp.

49.1 0.1 Turn LEFT onto Cranston St.

49.8 0.7 Branch of the Cranston Public Library on left.

50.0 0.2 Turn RIGHT onto Chestnut Hill Ave.

50.1 0.1 Outcrop on right in yard.

STOP 5. (30 minutes) Providence Quad. Rhode Island Formation, Cranston, Rhode Island. Upper Anchizone - Greenschist Facies boundary.

Private Property. Please be careful of lawns and gardens.

The ledge behind the house consists of homogeneous, organic-rich, dark gray siltstone and fine-sandstone with thin pelitic partings. Although bedding is indistinct, it is parallel to cleavage, as indicated by the orientation of large, abundantly preserved plant fossils found in this outcrop. Cleavage occurs throughout, but is a somewhat irregular fracture cleavage in the arenaceous beds. A secondary crinkle lineation occurs within the phyllites. Traces of chloritoid, an index mineral to the anchizone-greenschist boundary (Frey 1978), are found microscopically in the phyllites here. Ilmenite megacrysts, commonly sheathed in thin layers of "pressure shadow" quartz and chlorite, are prominent in the phyllites.

Some of the white mica detectable in x-ray diffraction patterns from this and other localities in the Providence area (Quinn and Glass, 1958) is paragonite, which is not optically distinct from muscovite. Paragonite, with a basal (001) peak of 9.7 Å, creates a double-peak or high-angle shoulder on the 10 Å muscovite peak. Thus illite crystallinity measures are anomalously broad (K.I. = 5.5 at this locality) compared to what data would be from paragonite-free samples, and supplementary petrographic information must be used to aid in the construction of isocrystallinity contours.

50.2 0.1 Return to Cranston St. Turn RIGHT and proceed south.

50.4 0.2 At light, turn RIGHT; STAY on Cranston St.

50.6 0.2 Turn LEFT onto Dyer St.

51.1 0.5 Continue straight at light (Budlong Rd.).

52.6 1.5 Turn LEFT (Marked "To Rt. 2, Reservoir Ave.").

52.7 0.1 IMMEDIATELY turn RIGHT into Chateau Sur Crest Apartments and park.

STOP 6. (15 minutes) Providence Quad. Lowermost greenschist facies (incipient biotite growth).

A very small outcrop, no hammers please. (You may collect very similar material during our lunch stop). Very well cleaved, gray phyllite with prominent ilmenite porphyroblasts. This outcrop is essentially on the upper anchizone-greenschist boundary. Small incipient biotites are seen in thin section, forming from chlorite. The ilmenite porphyroblasts are commonly rimmed by chlorite, thus giving them a duller luster in hand sample than is typical for ilmenite.

This is about the upper limit at which illite crystallinity data can be effectively used to interpret low-grade conditions, because (1) the mica is no longer interlayered with other phyllosilicates, and thus muscovite peak widths no longer change with increasing grade; and (2) Biotite with an (001) spacing of 10.1 Å produces a low-angle broadening on the 10 Å muscovite peak.

52.7	---	From Chateau Sur Crest Apartments, turn RIGHT onto Reservoir Avenue.
52.9	0.2	At light, cross Route 2.
53.0	0.1	Turn LEFT into Garden City Shopping Center. Proceed to Newport Creamery. LUNCH and REST STOP. For those who wish to collect phyllite with ilmenite porphyroblasts similar to Stop 5, proceed to the small scattered outcrops on the hill behind the Old Colony Bank.
53.0	---	Exit from Garden City Shopping Center. Turn LEFT onto Route 2 South (Reservoir Avenue).
53.5	0.5	Turn RIGHT. Entrance to Rt. 37 EAST (marked "To Air Terminal and 95").
53.8	0.3	Top of ramp; proceed east on Rt. 37.
54.3	0.5	Exit onto Pontiac Avenue.
54.5	0.2	At bottom of exit ramp, turn RIGHT onto Pontiac Avenue, toward Howard Industrial Park.
55.2	0.7	Turn LEFT (Stay on Pontiac Avenue).
55.3	0.1	Turn LEFT into the industrial park.
55.6	0.3	Proceed to RR tracks at bottom of hill and park.

STOP 7. (45 minutes) East Greenwich Quad. Rhode Island Formation. Lower Greenschist Facies.

Large glacially polished outcrops on both sides of the road. Meta-sandstone, siltstone, and conglomerate predominate here with minor amounts of phyllite to schist. Muscovite regrowth can now be seen megascopically. Ilmenite porphyroblasts are common in the more pelitic layers. Bedding strikes generally northward and dips 25° to the east. The principal cleavage approximately parallels bedding, but is not prominent in the massive sandstone and conglomerate beds. A secondary cleavage is seen cutting all the rock types and causing a crinkle lineation in the more pelitic layers. Excellent sedimentary features are prominent even at this grade of metamorphism and include cross-bedding, scour-and-fill, argillite rip-up clasts, and sandstone dikes. Tectonic injection of pelite into sandstone and conglomerate beds is also seen, particularly on the polished outcrop east of the road.

55.6 --- Continue straight.

55.8 0.2 Turn LEFT at T-intersection.

56.0 0.2 Turn RIGHT onto Pontiac Avenue.

56.5 0.5 Bear RIGHT onto Rt. 37 EAST (toward Warwick and I-95).

57.0 0.5 Exit from Rt. 37. Take I-95 North toward Providence; proceed north on I-95.

62.7 5.7 Bear RIGHT; take I-195 East.

66.9 4.2 Mass.-Rhode Island border, entering Massachusetts. Continue east on I-195.

71.2 4.3 Leave I-195 at exit #2, Rt. 136 South toward Newport, Rhode Island.

71.5 0.3 At bottom of ramp, turn RIGHT onto Rt. 136 South.

72.6 1.1 At state line, park by outcrop on right.

STOP 8. (15 minutes) East Providence Quad. Rhode Island Fm. Upper Anchizone (K.I. = 5.3 mm).

The rock is a well-cleaved, homogeneous light gray-green siliceous and feldspathic siltstone to siliceous slate with small irregular chlorite knots. Bedding is at a high angle to the cleavage and is seen by color differences and chlorite concentrations along bedding surfaces. The bedding strikes N30°E and dips 20°SE. The cleavage is variable, striking N50°W to N65°W and dipping 30° to 40°NE. The homogeneous siliceous/feldspathic nature of the siltstone here is unusual in this area of the Narragansett Basin and may represent a volcanogenic sediment.

72.6	---	Continue South on Rt. 136 into Rhode Island. Stay on Rt. 136 to Mt. Hope Bridge.
80.4	7.8	Toll booth, Mt. Hope Bridge (30¢ toll). Cross bridge.
81.4	1.0	At south end of bridge, bear LEFT on Boyd St. (marked "138 and to 24 North").
81.8	0.4	Turn LEFT onto Common Fence Point Rd.
82.8	1.0	Turn RIGHT onto Rt. 24 SOUTH.
84.8	2.0	Park by large outcrop on both sides of Rt. 24; Butts Hill.

STOP 9. (15 minutes) Prudence Island Quad. Rhode Island Fm.; Butts Hill.
Upper Anchizone (K.I. = 5.7 mm).
WATCH FOR POISON IVY.

The rocks are homogeneous, well cleaved to fissile, very dark-gray, organic-rich slates and siltstones with minor amounts of sandstone. Small knots of recrystallized chlorite give a fleckshiefer appearance. Bedding and cleavage both dip to the south at a shallow angle, although cleavage forms at a low angle to the bedding. The cut appears to be a simple dipping sequence without apparent major structural complexity. All the units are very well cleaved, with the exception of thin sandstone beds that have only a more widely spaced cleavage.

Note that we have come back down grade metamorphically from the last several stops. The rocks here are typical of those in the center of the low-grade metamorphic trough in the southern Narragansett Basin, both metamorphically and sedimentologically. The rocks are much more homogeneous on the scale of an outcrop here, than in the northern part of the basin (e.g., Stop 3). Fine-grained lithologies are widespread in this part of the basin, and some of the thickest coal seams are found in the Portsmouth, R.I. area (J. Skehan, pers. comm.).

84.8	---	Continue south on Rt. 24, which merges with and becomes Rt. 114.
86.2	1.4	Turn RIGHT into small lane parallel to the main road.
86.4	0.2	Proceed along lane until opposite the large roadcut on the east side of Rt. 114. Park; walk across highway to the outcrop. Watch carefully for traffic!

STOP 10. (15 minutes) Prudence Island Quad. Rhode Island Fm. Turkey Hill.
Upper Anchizone (K.I. = 5.5 mm).
WATCH FOR POISON IVY.

The rocks are well-cleaved, homogeneous gray-green, chloritic siltstone to argillaceous siltstone with scattered large pyrite porphyroblasts and small secondary knots of chlorite. Minor ankerite is present and phyrophyllite occurs as a fine-grained silky sheen on some foliation surfaces (confirmed by x-ray). The bedding here is obscure, only easily observed where thin pelitic beds occur within the siltstones. It dips at a shallow angle to the southwest and is itself transected by the prominent cleavage at a low angle.

The notable differences between this outcrop and that seen at Stop 9 is its coarser grain-size and its depositional environment; they are at approximately the same metamorphic grade.

86.4 --- Rejoin Rt. 114 and continue south.

92.1 5.7 Turn RIGHT. Follow signs to the Newport Bridge.

93.8 1.7 Rotary; go around 270° onto Rt. 138 West (marked "To Jamestown and New York").

94.5 0.7 Cross Newport Bridge.

97.1 2.6 Toll booth at west end of bridge (toll $2.00); continue west on Rt. 138.

98.0 0.9 Turn LEFT; continue on Rt. 138 West.

99.3 1.3 Pull off on right and park just before the Jamestown Bridge (at Mr. Pipe's Restaurant). Walk down dirt path at right to the shore.

STOP 11. (45 minutes) Wickford Quad. Rhode Island Formation. Amphibolite Facies; Staurolite Zone.

Along the shore here are beautiful exposures of interbedded mica schist, metasandstone and stretched pebble metaconglomerate that strike generally north with a moderate dip to the east. The mica schist is fine-grained, well foliated and varies from silvery-gray to dark-gray depending on the carbon content. Abundant porphyroblasts of garnet and "turkey track" staurolite to several cms. in length occur in the schist and on pelitic partings in the sandstone and conglomerate. The staurolite has locally been retrograded to chlorite. Grew and Day (1972) present a detailed discussion of the metamorphic textures and mineralogy for the rocks at this locality. Plant fossils occur in graphitic mica schist, interbedded with the garnet-staurolite mica schist, along the shore 1500 feet south of this exposure (Quinn, 1971, p. 50). The fluvial sequences of conglomerate-sandstone-shale seen at low grade outcrops earlier today (e.g., Stops #1, #3) can still be recognized in spite of the changes brought about by increased metamorphism and tectonic thinning.

END OF TRIP

Proceed to the N.E.I.G.C. headquarters at the University of Rhode Island in Kingston by continuing on Rt. 138 West for approximately 12 miles. Rt. 138 joins Rt. 1 South for 3 miles of this route, then proceeds westward to Kingston.

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