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THE GEOLOGIC SETTING OF COAL AND CARBONACEOUS MATERIAL, NARRAGANSETT BASIN, SOUTHEASTERN NEW ENGLAND

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INTRODUCTION

The Narragansett Basin (Fig. 1) is a 1600 km^2 structural and topographic depression in southeastern Massachusetts and Rhode Island in which Pennsylvanian coal-bearing sediments have been variably metamorphosed and deformed, and intruded by the Permian-aged Narragansett Pier Granite. It supported intermittent and limited coal mining during the nineteenth and, to a lesser extent, twentieth century. The most successful mines were at Portsmouth (Stops 2 & 3) and Cranston (near Stop 5) Rhode Island, although current activity is limited to the Masslite Quarry area (Stop 4).

It is of interest for several reasons. First, the Narragansett Basin is a particularly appropriate place to study the response of organic material to progressive metamorphism, as through outcrop and drillcore one can sample carbonaceous material and associated sediments from sub-greenschist to upper amphibolite facies conditions, a situation rarely found in other metamorphic terranes. The topic has received surprisingly little attention, given: 1) the importance of this type of metamorphism in terms of the global recycling of carbon; 2) the control organic material exerts upon the chemical environment during metamorphism; and 3) the fact that coal cannot retrograde metamorphose, making it an ideal candidate to "remember" peak metamorphic conditions in polymetamorphic terranes. Second, it contains the most complete record of the Alleghanian orogeny, an event that represents a major episode of deformation, regional metamorphism, and plutonism that was the consequence of the final (and perhaps most important) stage in the evolution of the Appalachian orogen (described more fully in Mosher and others, this volume). Finally, with the possible exception of peat deposits, the coal deposits represent the only indigenous fossil fuel energy resource in New England, and as such merit consideration.

The purpose of this trip is to examine the field relationships of the major deposits of coal and carbonaceous materials in the basin, that occur over a range of metamorphic and deformational conditions. Part of the trip will also consist of examination of mesoscopic and microscopic features of the coal and associated rock, as seen in drillcore and under the microscope.

Much of the organic material in the Narragansett Basin does not qualify as coal in the strict sense, because either the rank is too high and/or the ash content is too great. We will use the term coal, however, to refer to all of the material, with additional description as appropriate.

* "The paleobotany section was written by P.C. Lyons".

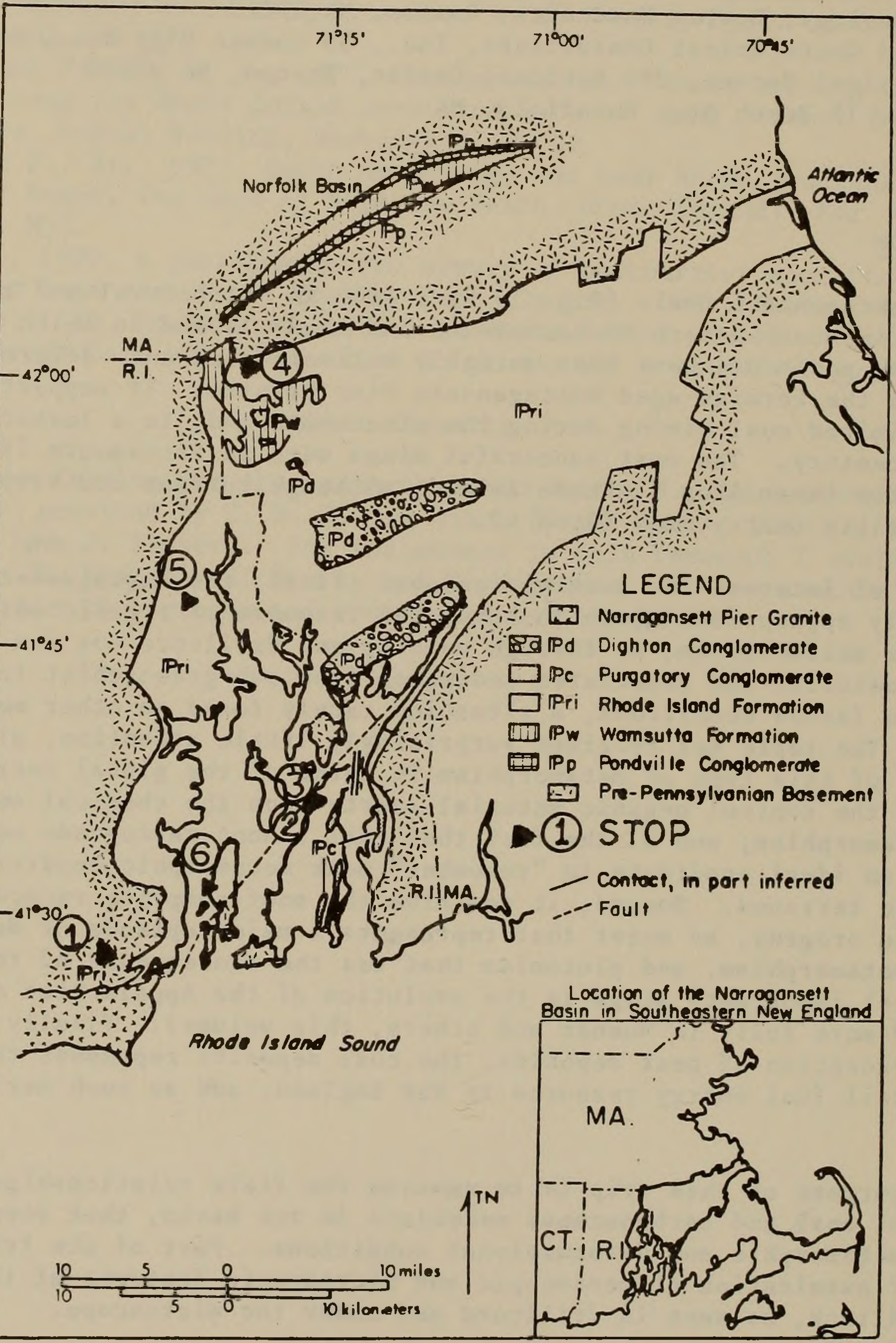


Figure 1. Geologic map of the Narragansett basin. Modified from Murray and Skehan, 1979.

GEOLOGIC SETTING

The non-marine clastic sediments of the basin rest at least in part unconformably upon an Avalonian (Rast and Skehan, this volume; Dreier and Mosher, this volume) terrane comprised primarily of Late Precambrian to Cambrian sediments, volcanics, and volcaniclastics. Although the basin/basement contact of the basin is largely unexposed, it appears to be mainly (entirely ?) faulted along its western margin, and for the other margins at least locally unconformable upon the basement. Several horsts of granitic basement occur within the basin, and recent offshore geophysics suggest that the Narragansett Basin plus several of these horst blocks extend at least 33 kilometers southward under Long Island Sound (McMaster and others, 1980). Gravity traverses across the basin (Appendix E in Skehan and Murray, eds., 1978) indicate an irregular surface, probably developed on faults, that in places is at least 3,000 meters deep. More detailed discussions of the geology are given in Quinn (1971), Quinn and Moore, (1968), Skehan and Murray (1980), and Murray and Skehan (1979).

Five formations, now referred to collectively as the Rhode Island Bay "Group" (Skehan and others, 1979) are recognized, and their stratigraphic relationships are shown in Figure 2. Of these, the Rhode Island Formation is by far the thickest (>3000m), contains all of the coal measures, and has an extensive and well documented megaflora (Lyons and Darrah, 1978). It consists (in order of decreasing abundance as seen in drillcore) of sandstone, siltstone, conglomerate, shale, and coal. The abundance of coarse grained material, together with a variety of primary sedimentary features (redbeds, recognizable channels, festoon cross bedding, absence of any limestones, etc.) indicate a non-marine, clastic origin for the entire "Group". The preferred depositional environment is that of humid alluvial fans and meandering streams in an intermontane basin, where coal swamps formed either along flood plains parallel to channels or behind alluvial fans. Deposition was probably rapid and at least locally synorogenic. The stratigraphic section may also have been relatively both younger and thinner in the southern Narragansett Basin. Additional information concerning the stratigraphic relationships and their interpretation may be found in Towe (1959), Mutch (1968), Skehan and others (1979), and Severson and Boothroyd (1981).

The northern half of the Narragansett Basin was slightly metamorphosed (anchizone, see Hepburn and Rehmer, this volume) and deformed into open, upright east-northeast trending, northwest verging folds). In contrast, the southern portion underwent multiple episodes of folding and faulting accompanied by a Barrovian metamorphism (see Burks and others, this volume). The earliest, most intense, and most widespread episode (D1) is characterized by northwest verging folds and thrusts that are synchronous to slightly older than the regional metamorphism. The next episode (D2) of folding was roughly coaxial, with westward dipping axial planes, and usually of a smaller scale relative to the first episode. A third episode of folding (D3) is about roughly east-west axes, and may be correlative with the single folding event in the northern half of the basin. A second, retrograde metamorphism was syn- to post-D3. The intensity as well as complexity of the structure of the southern part of the Narragansett Basin is greatest along the trace of the Beaverhead fault, and Stop 2 may be within this fault zone. The Narragansett Pier Granite intrudes the southwestern margin of the basin, and at least locally truncates the Barrovian facies series isograds. The granite is post-D2 fabric, although whether it post-dates all of the deformation and metamorphism is unclear. The age of the granite is precisely bracketed, as it contains Late Pennsylvanian plant fossils

TIME-STRATIGRAPHIC UNITS		FLORAL ZONES OF READ AND MAMAY (1964)	ROCK-STRATIGRAPHIC UNIT					NEW ENGLAND		
EPOCH	STAGE		CENTRAL APPALACHIANS				NEW ENGLAND			
NORTH AMERICA	EUROPE		CENTRAL AND WESTERN PENNSYLVANIA	EASTERN PENNSYLVANIA		WEST VIRGINIA	MASSACHUSETTS RHODE ISLAND	FLORAL LOCALITY	LOCALITY NUMBER	REFERENCE
LATE PENNSYLVANIAN	Stephanian B or C	11 or 12	Waynesburg Fm. (lower part)	No rocks at surface		Waynesburg Fm. (lower part)	Dighton Conglomerate			This report
			Monongahela Group			Monongahela Fm.	Rhode Island Formation (upper part)	Pawtucket, RI	10	Lesquereux (1889)
	Stephanian A or B	11	Conemaugh Group (upper part)	Llewellyn Formation		Conemaugh Formation (upper part)		Portsmouth, RI	42	Darrah (1969)
								Seekonk, MA	14	
	Cantabrian							Easton, MA	70	Lyons and Darrah (1978)
	Westphalian D (upper)	10	Conemaugh Group (lower part)			Conemaugh Formation (lower part)	Rhode Island Formation (middle part)	Plainville, MA	54	Hitchcock (1861)
MIDDLE PENNSYLVANIAN	Westphalian C (upper) and D (lower)	10	Allegheny Group (upper part)			Charleston Sandstone of Campbell and Mendenhall (1896)	Rhode Island Formation (lower part)	Foxboro, MA	24	Lyons (1969)
								Mansfield, MA	16	Lyons and Chase (1976)
								Worcester "coal mine", MA	—	Grew and others (1970)
	Westphalian C (late)		Allegheny Group (lower part)					Plainville, MA	20	Oleksyhyn (1976)
	Westphalian C (early)	9						Valley Falls, RI	1	—Round (1920)
		7,8	No rocks at surface	Sharp Mountain Member	Pottsville Formation	Kanawha Formation	Wamsutta Formation (upper part)	Attleboro, MA	56	Knox (1944)
EARLY PENNSYLVANIAN	Westphalian B or C	6		Schuylkill Member		New River Formation	Wamsutta Formation (lower part)	None	—	—
	Westphalian A and B	5					Pondville Conglomerate (upper member)	Canton, MA	139	Lyons and others (1976)
	Namurian C			Tumbling Run Member		Pocahontas Formation	Pondville Conglomerate (lower member)	None	—	Skehan, Murray, Hepburn, and others (1979)
	Namurian B	4								

Figure 2. Stratigraphic relationships in the Narragansett basin. Modified from Lyons (1981, in press). Locality numbers refer to Fig. 2 (Lyons, 1981, in press).

within pendents (Brown and others, 1978), and primary monazites that give a U/Pb age of 275 m.y. (Kocis and others, 1978). (The locale from which these radiometric and floral dates were obtained is a stop in both the Burks and others and Hermes and others trips in this volume.) The granite undergoes a variety of changes along its contact with the carbonaceous metasediments (color change, variations in mineral assemblage) that are probably the consequence of the interaction of contrasting fluid phases associated with the relatively oxidized granite and relatively reduced metasediments, respectively (Murray and Skehan, 1979).

Mineral assemblages (Grew and Day, 1972) and chemistry (Murray, unpub. data) imply peak metamorphic conditions of T=600°C & P=5-6 kbar for the southern part of the basin (Fig. 4). Based upon coal petrology (Gray and others, 1978; Raben and Gray, 1979; Murray and Raben, 1980) and illite crystallinity (Rehmer and others, 1978; Rehmer and Hepburn, this volume), temperatures of the order of 200+°C are believed to have been attained in the northern part of the basin. The distribution of isograds is given in Figure 2 of Burks and others (this volume) and in Murray and Raben (1980).

The Narragansett Basin is unusual in that it contains not only radiometric (Rb/Sr, U/Pb, K/Ar, and incremental argon) but also abundant megafloral dates in rocks from a wide range of metamorphic conditions, and this permits a precise definition of the duration of the Alleghanian orogeny in southern New England. The preferred interpretation consists of the following stages: 1. Rapid, synorogenic deposition of non-marine clastic sediments from Westphalian A (or older ?) times (310 m.y.) through Stephanian B or younger ($\leq$285 m.y.); with the stratigraphic section in the southern Narragansett Bay area possibly thinner and younger than that of the rest of the basin. 2. Several composite episodes of ductile and brittle deformation accompanied by regional metamorphism followed; emplacement of S-type Narragansett Pier granite occurred towards the end of this orogenic cycle. 3.Preliminary incremental argon ages (Dallmeyer, 1981) imply fairly rapid uplift. These events represent, essentially, a continuum that suggests that the Alleghanian orogeny was a relatively abrupt though intense event in southern New England.

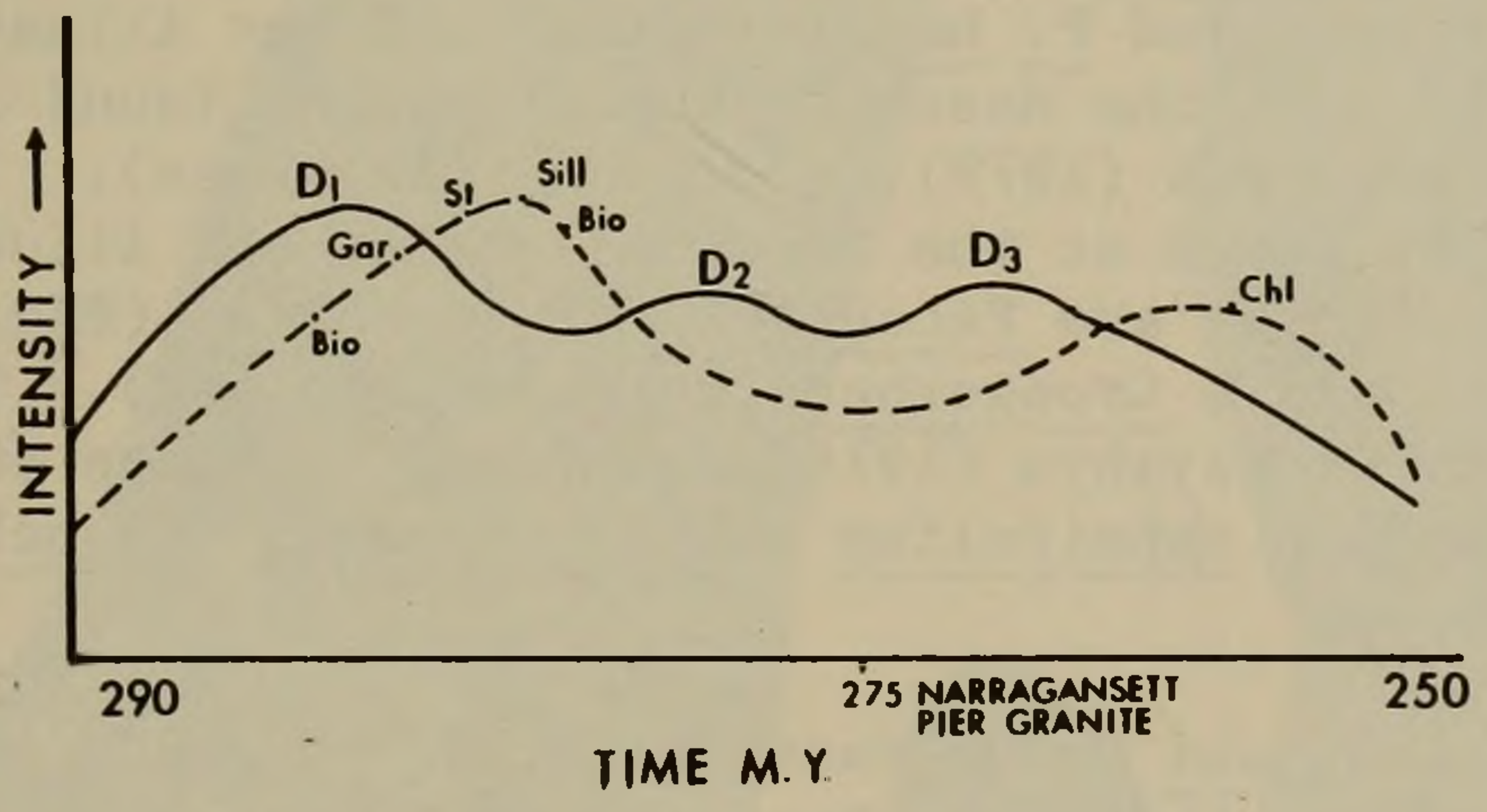


Figure 3. Variation of intensity of metamorphism and deformation with time, in the southern Narragansett Basin.

PALEOBOTANY

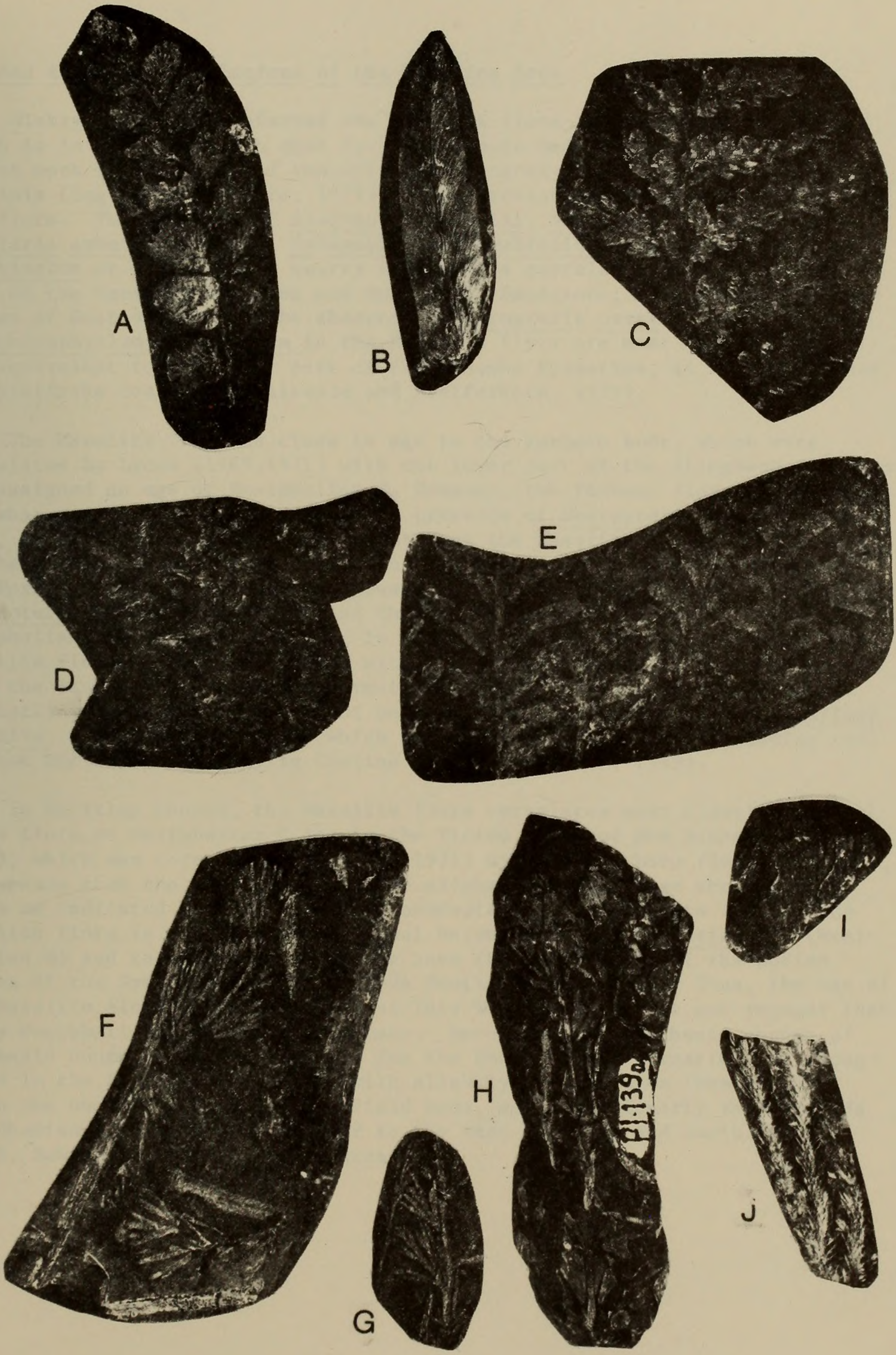
The Narragansett basin has a rich megaflora consisting of roughly 300 nominal species, nearly all of which are from the Rhode Island Formation, and a much smaller fauna dominated by cockroaches. The biostratigraphy has been described in a series of recent articles by P. Lyons and colleagues (listed in References Cited), and will not be repeated here. Rather, a summary of the biostratigraphy of the richest floral locale, the Masslite quarry (Stop 4), will be presented. This locale represents one of the oldest sections of the Rhode Island Formation yet identified. Continuous core drilling has shown that the section is approximately 300 meters above basement. The contact is an angular unconformity, which is directly overlain by 20 meters of arkosic conglomerate.

Paleobotany of Masslite Beds

Plant fossils have been used extensively to date and correlate the coal-bearing rocks of the Narragansett basin. These rocks range in age from Middle to Late Pennsylvanian, corresponding to Westphalian C to Stephanian B of Europe (Fig. 2). The coal beds of the Masslite quarry (Lyons and Chase, 1976) contain the oldest known beds in the Narragansett basin and have been dated as Westphalian C (Oleksyshyn, 1976). A summary of species found in the Masslite (and surrounding areas) flora is given in Lyons and Chase (1976, Table 1).

The earliest illustrations of plant fossils from the Masslite quarry (Lyons, 1969) are of *Annularia sphenophylloides*; *Alethopteris serlii*; *Eremopteris* species (Lyons, 1969, Pl. VIII, Fig. A), which may be *Eusphenopteris* cf. *neuropteroides* Van Ameron; and a *Sphenopteris* species (Lyons, 1969, Pl.XV, Fig. B), which is similar to *Mariopteris* cf. *paddocki* (Oleksyshyn, 1976, Fig. 11C). The most detailed description of fossils in the Masslite quarry is found in Oleksyshyn (1976), who illustrated and described 28 species including 10 sphenopsids; 2 new species, *Palmatopteris narragansettensis* and *Palmatopteris plainvillensis*; and 3 pecopterids referred to as *Pecopteris clarkii*, *P. miltoni*, and *P. hemitelioides*. Other illustrations of plant fossils constituting flora of the Masslite quarry can be found in Lyons and Chase (1976), Lyons and Darrah (1979), and Lyons (in press). Eight species of plant megafossils found at the Masslite quarry are illustrated in Figure 4. Newly illustrated species are *Pecopteris* cf. *dentata* (Fig. 4C), *Pecopteris* cf. *plumosa* (Fig. 4E), and a *Crossotheca* species (Fig. 4D). Two important species not reported by Oleksyshyn (1976) and found by Lyons at the Masslite quarry are *Sphenophyllum cuneifolium* and *Neuropteris scheuchzeri* (Fig. 4B).

Figure 4. A, *Neuropteris* cf. *loshi* Brongniart, Pl-6, HU-45759; B, *Neuropteris scheuchzeri* Hoffmann, Pl-33, HU-45753; C, *Pecopteris* cf. *dentata* (Brongniart), Pl-135, HU-45760; D, *Crossotheca* sp., Pl-6, HU-45759; E, *Pecopteris* cf. *plumosa* Artis, Pl-35, HU-45760; F, *Eremopteris lincolniana* D. White, *Sphenophyllum emarginatum* Brongnart, Pl-139a, HU-45762; I, *Sphenophyllum emarginatum* Brongnart, Pl-139a, HU-45762; J, *Lepidodendron* cf. *lanceolatum*, Pl-36, HU-45750; Pl- original field number; HU- Harvard University Paleobotanical Collections Specimen Number; Scales for figures: B, 1.4X; H, 1X; J, 0.65X; all others 3X.


A
B
C
D
E
F
G
H
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I
J

Age and Regional Correlations of the Masslite Beds

Oleksyshyn (1976) referred the Masslite flora to Westphalian C, an age which is in agreement with that for the Foxboro beds (Lyons, 1969, 1971). Recent work in the proposed Pennsylvanian Stratotype of West Virginia and Virginia (Englund and others, 1979) allow correlations on the basis of the megaflora. The presence of Alethopteris serlii, Neuropteris scheuchzeri, Annularia sphenophylloides, Sphenophyllum cuneifolium, and Sphenophyllum emarginatum at the Masslite quarry indicates a correlation with the upper part of the Kanawha Formation and Charleston Sandstone; both Middle Pennsylvanian of West Virginia. The absence of Neuropteris ovata and the presence of Sphenophyllum cuneifolium in the Masslite flora are most indicative of the equivalent to the upper part of the Kanawha Formation, an interval above the Winifrede coal bed (Gillespie and Pfefferkorn, 1979).

The Masslite flora is close in age to the Foxboro beds, which were correlated by Lyons (1969,1971) with the lower part of the Allegheny Formation and assigned an age of Westphalian C. However, the Foxboro flora is probably somewhat younger, as evidenced by the presence of Neuropteris ovata (Lyons, 1969, Pl.IX, Fig. A), which is absent from the Masslite flora. The flora of the Hardon Mine at Mansfield is interpreted to be somewhat younger than the Foxboro flora because of the presence of the larger pinnuled form of Neuropteris scheuchzeri (Lyons and Chase, 1976, Fig. 4C), which is found in Westphalian D equivalents (Lyons, in press). In western Pennsylvania, the Masslite flora correlates closely with the flora of the Clarion coal bed near the base of the Allegheny Formation (Darrah, 1969). This correlation is mostly indicated by the lack of pecopterids, such as Pecopteris lamuriana, P. unita, and P. candolleana, which are found in the Middle Kittanning coal bed but not in the underlying Clarion coal bed (Darrah, 1969).

In Maritime Canada, the Masslite flora correlates most closely with the Minto flora of Westphalian C Age in the Pictou Group of New Brunswick (Bell, 1962), which was correlated by Lyons (1971) with the Foxboro flora. However, it appears that the Minto flora may be slightly younger than the Masslite flora as indicated by the variety of neuropterids in the Minto flora. The Masslite flora is probably transitional between the Lonchopteris zone (Westphalian B) and the Linopteris obliqua zone (Westphalian C) of the Morien Series of the Sydney coalfield of Nova Scotia (Bell, 1938). Thus, the age of the Masslite flora could be as old as late Westphalian B but not younger than early Westphalian C in Maritime Canada. Moreover, the northwest corner of the basin contains the oldest ages for the Rhode Island Formation yet recognized in the Narragansett basin, with slightly younger ages (Westphalian C) in the nearby Foxboro and Mansfield beds, and significantly younger beds (Stephanian A/B) occurring further to the east (Easton) and south (Portsmouth, Newport, and surrounding areas).

Plainville, Seekonk, Taunton, and Worcester. There were about 23 Rhode Island mines and prospects, in Bristol, Cranston, Cumberland, East Providence, Jamestown, Little Compton, Newport, Portsmouth, Providence, South Kingstown, and Warwick. It should be noted that many of these Rhode Island sites were actually "graphite" mines, and lie within biotite or higher metamorphic zones, where the term "graphite" refers to carbonaceous material partly to completely recrystallized and well ordered.

Some of these mines were open cuts, although most were vertical or slope shafts ranging in depth from a few dozen feet to the 2,100 foot Portsmouth incline. The coal was used for heating and cooking; in stationary engines and locomotives; for making lime, glass, and bricks; and in forges, bake ovens, and greenhouses. In 11 of the mines the coal was so thermally altered it could be used not only for fuel, but also as natural carbon. If sold for fuel it was locally called "coal"; if for foundry facings or paint it was called "graphite".

Between 1860 and 1883 Portsmouth anthracite was used successfully for smelting imported copper ore. From 1940 to 1959 Cranston coal was sold widely as amorphous graphite. At the Masslite quarry in Plainville, at least since 1967, indigenous coal and carbonaceous shale have been mixed with Pennsylvania coal (and since 1979 with fuel oil) and used as a heat source in the manufacture of lightweight aggregate. In all, about 1.36 million tons of coal have been mined in the Narragansett Basin. At the Portsmouth mine (1808-1913) at least 1.06 million tons were removed. Mining was conducted down a 31° dip, 4,600 feet along strike. At the Cranston mine (1857-1959) about 180,000 tons were taken from an open pit plus a slope 450 feet deep on a 19° dip, 1,270 feet along strike. At Mansfield, about 7,000 tons were mined prior to 1923.

Many other mines and prospects were opened in the Narragansett Basin , but none were as profitable. The mines failed mainly because the cost of pumping water and of working the irregular coal lenses required the inferior coal, usually poorly cleaned and prepared, to be sold at prices too near those of competing coals, which gave more heat and were less troublesome to use.

Narragansett Basin Exploration Project (1976-1980)

In response to the energy embargo of 1974, renewed interest was generated in the possible coal resources of New England. The result was an exploration program, managed by Weston Observatory (of Boston College), that relied heavily upon continuous core drilling. The program lasted from 1976 to 1980, and was funded primarily by NSF (RANN), U.S. Bureau of Mines, and finally D.O.E. During this time approximately 10,000 meters of NX drillcore were obtained, along with related field and analytical studies. Because of the lack of outcrop and inaccessibility of mines, this core represents the best source of data on the coals--it is currently stored at Weston Observatory, and is available for research. Although drilling took place throughout the basin, the emphasis was upon Plainville (Stop 4), Mansfield, Bristol, Somerset (Brayton Point), and Portsmouth (Stop 2). At present, there are no firm plans to continue exploration or to resume mining in the area. The results of this five year exploration project are contained in a series of reports (Skehan and Gill, 1981--this contains references to earlier reports), which may be obtained from Weston Observatory.

COAL AND GRAPHITE

Analytical Technique

Of the approximately 42 reported coal and graphite occurrences (25 mines & 17 prospects), we have chosen five locales for discussion that may be considered representative of the coal deposits found in the basin. We also include analytical data from Pennsylvania anthracite and petrographic data from the graphite deposits. For each of the coal samples we obtained proximate and ultimate analyses, petrographic and vitrinoid reflectance data, and partial chemical analyses of mineral matter. Petrographic and mineral matter analysis were carried out at the U.S. Steel Research Laboratory under the direction of Ralph Gray, while the chemical analyses of coal were obtained from U.S. Steel as well as compiled from various sources (Lyons and Chase, 1981). Information (petrographic and microprobe analysis) is also available for associated metasediments (Murray, unpub. data), and to a lesser extent for the higher grade graphite deposits; and this data will also be discussed. A brief description of each sample locality is given below.

1 Pennsylvania anthracite. Samples were collected from the western part of the southern field, and are included here for comparison:

2 Mansfield, Mass. The samples analyzed come from a 1 meter seam of high ash coal obtained during drilling in the vicinity of several small mines. Metamorphic grade is subgreenschist.

3 Plainville, Mass. The sample was handpicked from the seam currently being quarried. Other than possibly being lower in ash than the bulk seam (a carbonaceous shale), it is representative of material being mined. This subgreenschist grade sample is the lowest metamorphic grade sampled to date.

4 Somerset, Mass. The sample was obtained from a 4 meter coal seam encountered in drillcore near a major fault in the southeastern part of the basin (i.e. directly underneath the Brayton Point fossil fuel power plant). Metamorphic grade = lowest greenschist.

5 Bristol, R.I. Samples are from a 1 meter thick seam encountered in drilling and possibly correlative with a nine meter seam, that was drilled 100 meters away. The coal occurs within a kilometer of a horst of basement granitic gneiss that may be the locus of a local metamorphic high in the basin, although the metamorphic grade for this region is also lowest greenschist.

6 Portsmouth, R.I. The samples come from a 1 meter seam from drillcore; other seams in the vicinity range to 4 meters thick. Drilling was in the vicinity of (and possibly correlative with) the coal seams of the largest mine in the Narragansett Basin. The metamorphic grade is lowest greenschist.

7 Cranston, R.I. The samples come from the 6 meter seam mined intermittently until 1959. The rocks are in the chloritoid zone.

9 Tower Hill, R.I. The samples come from a small nearly inaccesible graphite mine in the sillimanite-kspar zone. The well developed cataclastic fabric seen in the walls of the mine are typical of the shearing that appears to be localized in the vicinity of the coal and graphite deposits, and which is seen at Fenners Ledge (Stop 5).

Field Relationships

Seams are typically thick (to 10+ meters), laterally discontinuous, and occur in irregularly shaped bodies. Most of the variations in thickness apparently are structurally controlled, based upon our own observations, as well as old mine reports. The latter often refer to seams (i.e. at Mansfield, Portsmouth, and Cranston) as "pinching and swelling" or characterized by the presence of ellipsoidal "rolls" that have their long axis subparallel to the regional trend of folds. At the only place where coal is actually being quarried (Stop 4) the thickness varies from 10+ meters at the hinge of an anticline to zero meters along the limbs (<100 meters across strike). At Bristol R.I. detailed drilling suggests that again thickness varies from 10+ to <2 meters over very short distances (i.e. <70 meters), and that the coal may have broken loose from its stratigraphic position and migrated along fault surfaces. Extreme variations in seam thickness may also be sedimentologically controlled.

Megascopically, all coals are strongly deformed, and deformational style varies from isoclinally folded in high ash coals to relatively more brecciated and veined in low ash varieties. In many cases, the coal appears to have become decoupled from the enveloping rock, and thick veins of fibrous quartz and micas ("asbestiform quartz") often occur along the roof and floor contacts and within the coal. The presence of dragfolds within the coal and slickensided surfaces along faults subparallel to contacts also suggests that the coals have undergone shearing. Presumably this is at least in part a consequence of the strong contrasts in competency between the coal and the surrounding sediments (usually sandstones or conglomerates).

In hand specimens, the coals have a dull, graphitic to submetallic appearance, and due to a pervasive secondary depositional carbon and brecciated fabric, are often sooty when handled. The brecciated to friable nature of the coals and the presence of substantial amounts of primary and secondary mineral matter cause the coal to break with an irregular fracture. Conchoidal fracture, which is distinctive of most anthracites from Pennsylvania, can only be observed on small surfaces (if at all) in Narragansett Basin coals. Coals that are relatively low in syngenetic mineral matter tend to break up with a hackly fracture, whereas coals with high concentrations of syngenetic phyllosilicate mineral matter may break with a preferred orientation either along original bedding or slickensided surfaces (Fig. 5). The brecciated coal occasionally appears to have a closely spaced cleat, however, careful examination suggests that this "cleat" is in some cases a cubic cleavage characterized by the alignment of graphite and mica along surfaces roughly parallel to to the axial plane of regional folds. The cleats, as well as "polished" surfaces (i.e. ones characterized by smooth coatings of graphite) are concordant with regional tectonic fabric, and similar relationships have been reported from deformed high rank coals from Pennsylvania (Hower, 1980), Australia (Stone and Cook, 1980), and China (Fen and others, 1979). By chloritoid grade (Stop 5) the coal megascopically resembles a graphitic schist, although microscopically it is still recognizable as coal. At higher grades (Stop 6 & Tower Hill) the transformation to graphite is essentially complete, and all organic matter has recrystallized. The graphite in these amphibolite facies rocks occurs as finely disseminated matter, and as veinlets (< 0.1mm thick) that define schistosity. Larger masses of graphite (originally coal seams) are brecciated, with intense shearing along contacts and with a complex network of veins (Stop 5).

The coals are also often friable and hydroscopic, due to a combination of: 1) granular character, 2) secondary graphitic depositional carbon, 3) microbrecciation, 4) removal of mineral matter through leaching, and 5) softening and pore formation in thermally altered coals. The coals may hold more than 20 wt.% moisture if left out in damp air.

Table 1. Coal chemistry and vitrinoid reflectance of selected samples from the Narragansett basin, southeastern New England and the Pennsylvania anthracite basin. Analyses compliments of R.J. Gray, United States Steel.

	1 Pennsylvania anthracite southernfield		2 Mansfield, MA. drillhole # 8		3 Somerset, MA. drillhole # 33		4 Portsmouth, R.I. drillhole # 2		5 Bristol, R.I. drillhole # 51		6 Cranston, R.I. Budlong mine
	as rec'd	dry basis	as rec'd	dry basis	as rec'd	dry basis	as rec'd	dry basis	as rec'd	dry basis	dry basis
Ultimate analyses											
carbon	78.84	81.41	53.27	55.27	77.52	78.89	60.99	68.79	63.87	64.03	
hydrogen	3.05	2.89	.91	.51	.86	.68	1.40	.15	.53	.50	
nitrogen	.75	.76	.21	.22	.28	.28	.23	.26	.16	.16	
oxygen		1.17		.58		1.27		.00		.33	
sulphur	2.98	3.04	1.02	1.06	.30	.31	.050	.06	.05	.05	.002
ash	10.52	10.73	40.82	42.36	18.25	18.57	27.26	30.75	34.84	34.93	
moisture	1.93		3.64		1.74		11.34		.25		
Surphur forms											
FeS_2 as S			.78	.81	.25	.25	.022	.025	.06	.06	
SO_4 as S			.12	.12	.004	.004	.005	.006	.002	.002	
organic S				.13		.06		.03		.01	
Proximate analyses											
volatile matter				4.9		4.6		3.1		3.6	2.4
fixed carbon				51.8		77.7		64.1		61.8	78.1
ash				43.3		17.7		32.8		34.6	19.5
Vitrinoid reflectance											
mean maximum	3.52		6.48		7.19		4.47		5.98		
mean minimum	2.61		3.93		3.70		2.75		2.64		
mean bireflectance	.91		2.55		3.49		1.72		3.34		
HGI			94.5		50		47.5		38		

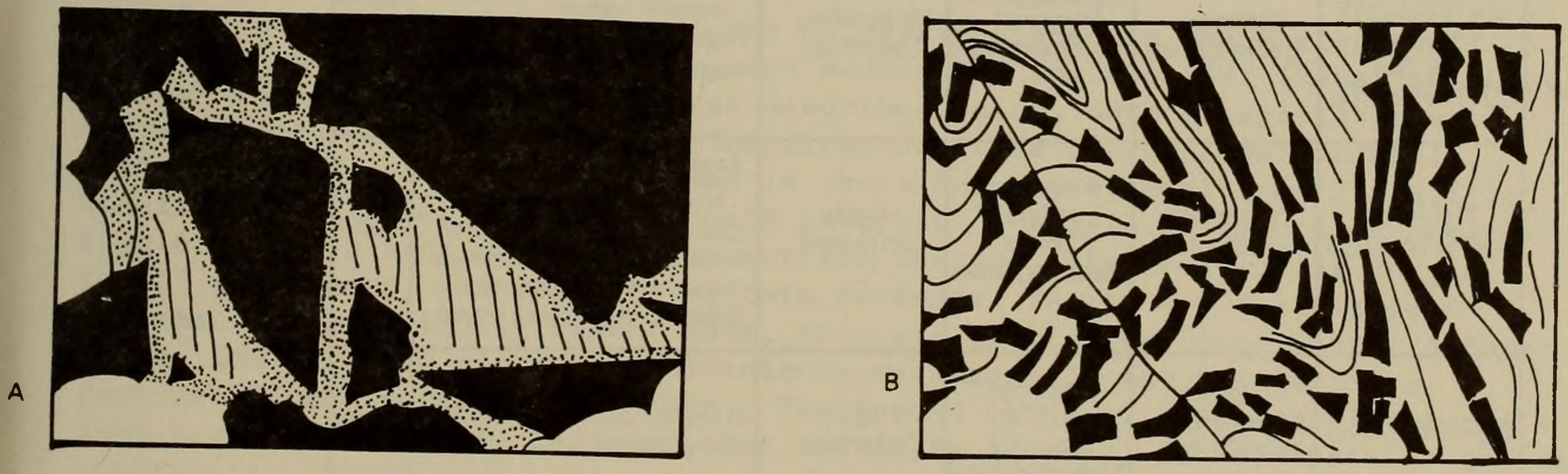

Figure 5. Sketch of deformational and metamorphic textures in coals. Both sketch are derived from reflected light sections viewed at 400X. Fig. 5A; Low primary ash coal (shaded pattern) that has been brecciated with displacement and rotation of fragments resulting in volume increase. Secondary depositional graphitic carbon (stippled pattern) coats the fragments and mineral matter (clear pattern) fills the voids. From Portsmouth, R.I. Figure 5B; High primary ash (clear pattern) and coal (shaded pattern) that has undergone folding accompanied by brecciation of coaly layers. Masslite quarry.

Table 2. Mineral matter in high rank coals. Analytical data courtesy of F.E. Huggins, Huffman, and G.P. Gray, Research Laboratory, United States Steel Corp. tr<4 particles or 0.3 wt. % found; *Principally mixtures of common mineral phases; + Manganese to 5% by weight of particles.

	Penn. Anthracites		Narragansett Bassin Anthracites				
	10348 Southern	*10349* Field	10398 Bristol, R.I.	10399 Portsmouth, R.I.	10400 Mansfield, MA.	10401 Somerset, MA.	4889 Cranston, R.I.
Quartz	8	8	28	60	18	32	25
Kaolinite	5	0.6	tr	tr	tr	tr	—
Illite/Muscovite	26	36	39	13	34	24	43
Chlorite/Chamosite	0.5	0.7	6	3	7	8	9
Montmorillonite	tr	tr	tr	1	—	tr	tr
Mixed Silicates	19	23	23	10	29	9	12
Pyrite	31	23	—	—	4	3	tr
Fe Carbonate/Oxide/)** Metal/Oxyhydroxide)	2	0.5	1	4	0.7	1.4	2
Calcite	1	0.5	0.3	3	0.3	7 +	tr
Ankerite	0.4	tr	—	1	—	9 +	—
Fe Sulfate	1	—	tr	—	0.3	tr	2
Ca Sulfate	—	0.4	—	—	—	—	—
Rutile	—	tr	0.7	tr	—	tr	tr
Apatite	—	tr	1	tr	—	tr	—
Unknown Others*	6	8	1	5	6	6	7

Simplified Classification and Optical Properties of Metamorphosed Coals and Carbonaceous Shales

Narragansett Basin, Massachusetts and Rhode Island

COAL CLASS	Coalification History	Metamorphic History	Intensity of Deformation	Distinguishing Petrographic Properties	Temp. C°
'NORMAL' ANTHRACITE and META-ANTHRACITE	'Normal' Coalification	Diagenetic(?) Regional Metamorphism	Moderately Deformed	High vitrinoid max. reflectance values resulting from glassy surface texture High reflecting 'organic inerts' Regular fracture surface	>180-200
'THERMAL ANTHRACITES'	'Abnormal' Coalification	Regional and/or Contact Metamorphism	Highly Deformed	Apparent low vitrinoid max. reflectance values resulting from granular texture Low reflecting 'organic inerts' Softening and pore formation Incipient mosaic texture Graphitic depositional carbon	>350
BURNT COAL	'Abnormal' Oxidizing Conditions Coalification	Regional and/or Contact Metamorphism	Highly Deformed	Irregular polishing surface Brownish hue	>350
NATURAL COKE	'Abnormal' Reducing Conditions Coalification	Regional and/or Contact Metamorphism	Highly Deformed	Mosaic anisotropic texture Coke pores High bireflectance	>350
GRAPHITE	(?)	Regional and/or Contact Metamorphism	(?)	High bireflectance	(?)

Figure 6. Optical properties of Narragansett basin coal. Compiled from Raben and Gray, 1979.

Petrographic Analysis

Petrographic studies of textural relationships have proven to be the single most useful parameter in terms of providing insight into the nature and history of the coals, and representative textures are shown in Figure 5.

The mean maximum reflectance of vitrinites (R_oV) was measured to determine rank (Table 1). The reflectance of vitrinite in normal anthracite ranges from 2.5% to 7.0%, and those above 7.0% are considered meta-anthracites. The mean maximum reflectance for vitrinites in samples of Narragansett Basin coals range to a high of 7.62% in green light in oil (Table 1).

Vitrinites observed include both textured and untextured varieties. In some instances (Bristol, Portsmouth, and Cranston) the coal has been thermally altered, as evidenced by the occurrence of incipient mosaic texture, limited softening and pore formation. Most of the coals show some degree of thermal as well as mechanical alteration. As a result of this alteration, there often has developed microstructural domains, on a submicron scale, that are revealed with SEM imagery. These domains are smaller than the sensing area used for ASTM standards for reflectance determinations, and thus make of questionable value standard reflectance measurements. In particular, the apparent decrease of R_oV in the coals found in areas of relatively high metamorphic grade (e.g. Cranston, Bristol, and Portsmouth) can be explained in terms of the preferential development of microstructural domains. The "organic inert" components (fusinite and semifusinite) are less reflecting than associated vitrinite, especially in those coals displaying alteration features. This is is in marked contrast to maceral reflectivity patterns observed elsewhere (Stach and others, 1975). In some samples of coals that display granular texture within vitrinitic portions, there are associated materials structurally similar to natural coke with mosaic anisotropic texture and "coke pores". Such features have been rather exhaustively studied (because of their economic importance), and their formation is believed to require temperatures $T \geq 400^{\circ}C$ in natural systems.

Two gross categories of coal may be distinguished in the Narragansett Basin, and together they are have been designated "meta-coals" (Raben and Gray, 1979). In addition to the features described below, both categories are variably deformed and annealed. The first consists of relatively normal anthracite and meta-anthracite, and is characterized by coal from Plainville, Mansfield, and Somerset. These coals have high R_oV values (generally greater than 6.0%) resulting from a glassy surface texture, high reflecting "organic inert" components, and regular fracture surfaces. Except for the degree of deformation and slightly higher rank, they are similar to Pennsylvania anthracites, and standard vitrinoid reflectance measurements are considered a reasonable rank parameter for them. The second category consists of all coals that have been not only deformed, but thermally altered, and it includes thermal anthracites, burnt coal, and natural coke (Figure 6). Thermal anthracites have low R_oV values resulting from a granular surface texture, low reflecting "organic inert" components, irregular fracture surfaces, incipient mosaic texture, variable softening and pore formation, and graphitic depositional carbon. Burnt coals show an irregular polishing surface and brownish hue. Natural cokes have high bireflectance, coke pores, and mosaic anisotropic texture. There is some indication that the material resembling natural coke may have had an origin that was at least in part tectonic and not entirely thermal (R. Gray, pers. comm. 1979). In this respect, the coals are similar to ones described from regionally metamorphosed terrane in New Zealand (Diessel and others, 1978).

The changes described above are essentially completed by the attainment of biotite zone metamorphism. With increasing metamorphism, the "coal" behaves as a chemically inert and mechanically brittle material, and only two changes are apparent in thin (or polished) section. The first is the evolution of vein fabric and assemblages. Through chloritoid grade (Stops 2 & 5), the veins consist primarily of fibrous quartz, and slightly lesser amounts of "asbestiform" white mica + chlorite (see Rutstein, 1979, for a discussion of this mica intergrowth from the Portsmouth area). With increasing metamorphism (Stop 6), the fibrous nature of the grains gives way to a more equidimensional fabric consisting of unstrained, equant grains. The vein assemblages also change, and at Tower Hill consist of sillimanite plus complex intergrowths of mica, garnet, and staurolite (Grew and Day, 1972). The other change consists of the appearance of graphite schistosities, which become increasingly well developed with increasing metamorphism. Moreover, they occur not only in pelites, but also in coarse sandstones. These graphitic "microveins" are considered to have formed by the precipitation of carbon out of a gas phase (exhumed from nearby coal ?).

Proximate And Ultimate Analyses

Table 1 presents representive chemical analyses of Narragansett Basin coals, and the reader is directed to Lyons and Chase (1981) for a compilation and discussion of proximate and ultimate analyses obtained through 1979. Figure 7 shows the relation between fixed carbon and ash. The rank patterns based upon these analyses are, in general, in conflict with that predicted from metamorphic grade and petrography (Raben and Gray, 1979; Murray and Raben, 1980; Lyons and Chase, 1981), and there are several explanations. All of the Narragansett Basin coals are high in ash, and this will skew Parr-formula corrected analyses towards misleadingly high rank values (Quinn and Glass, 1958; Lyons and Chase, 1981). Unlike other coals, the ash is mainly secondary, and occurs as a dense network of veins. Volatile matter in the Narragansett Basin coals is also misleading because it includes a) water absorbed on brecciated surfaces, b) water structurally bound in mineral matter, and c) the predominance of non-combustible gases such as CO_2. Hydrogen content may be the best indication of rank, as it best correlates with rank patterns expected from petrographic studies of coal and rock.

Taking both chemical and petrographic data into account, the coals most simply classify as; 1) variably deformed, high ash anthracites to meta-anthracites in the northern half (i.e. Plainville, Mansfield, & Somerset), and 2) deformed, moderate to high ash, meta-anthracites and thermally altered carbonaceous material in the southern part of the basin (i.e. Cranston, Bristol, & Portsmouth).

Mineral Matter

Table 2 presents modal abundance of minerals found in the coal, as determined by automated scanning electron microspcopy (i.e. SEM-AIA) at the Research Laboratory of U.S. Steel. Iron-bearing phases were further identified using Mossbauer spectroscopy (Murray & Raben, 1980), and the results indicate the presence of metallic iron. This is suprising, implies values of f_{O_2} well below the graphite buffer, and may be related to the reducing effect of a (methane-rich) gas phase released from the coal during deformation. Except for the initial degassing, the coal behaves as a relatively inert, brittle material during metamorphism. One consequence is the development of veins connecting fragments of coal, probably because the coal acts as a "sink" for silica and other components released into the fluid phase via pressure solution operating upon the surrounding quartz-rich sandstones. To a lesser extent, the veins also contain illite and chlorite as submicroscopic intergrowths (Rutstein, 1979) along microfractures, and this intergrowth has in the past been incorrectly classified as "asbestiform quartz" Because of the unusually complete sample base (outcrop and drillcore), one may examine the changes that occur in fabric and mineral chemistry of the veins through the entire metamorphic spectrum, and possibly chart the strain history as well.

Graphite Crystallinity Studies

Several X-ray analyses of organic material from the coals have been carried out (Quinn and Glass, 1958; Grew, 1974; Wintsch and others, 1980), and all have shown considerable scatter in graphite crystallinity values in samples from greenschist facies. One explanation for the variation may be that the analyses were performed on polygenetic carbon, as petrographic studies show that secondary depositional graphitic carbon coats fragments of coal (Raben and Gray, 1979) and grain boundaries in surrounding rocks. In fact, petrographic studies of Narragansett Basin coals suggest the presence of three distinct carbon-bearing materials: 1) original material still recognizable as coal macerals; 2) the depositional graphitic carbon that apparently precipitated out from a gas phase (that was probably generated by the release of methane from the coal) coats fragments of coal and mineral grains, and defines schistosities in adjoining rocks; and 3) new carbon nucleating directly within the surfaces of macerals as evidenced by the presence of mosaic anisotric textures. This range in structural states of carbon is maintained through the highest grades of metamorphism; and at Tower Hill a detailed study of one "homogeneous" fragment of graphite showed that the crystallinity decreased systematically from rim to core (R. Wintsch, pers. comm., 1980). This range of crystallinity occurs in a sample associated with metasediments that were metamorphosed to P=5kbar and T=600+°C (Grew and Day, 1972; Murray, unpub. data).

THE RESPONSE OF ORGANIC MATERIAL TO METAMORPHISM AND DEFORMATION

We have used the petrographic observations presented earlier plus geological considerations to construct the probable sequence of events that resulted in the coals as we now see them. Figure 8 shows a preliminary correlation of coal rank with various metamorphic parameters, and will provide a framework for the discussion of the evolution of the coals. The tentative model for the evolution of the Narragansett Basin coals holds that prior to the onset of regional metamorphism and deformation, coalification varied from low volatile bituminous to anthracite, with rank possibly increasing to the north. Folding and faulting were initiated throughout the basin, with pressure solution and degassing of the coals during brecciation important mechanisms. Depending upon the ash content, the coal responded to deformation primarily by disharmonious folding (high ash) or brecciation (low ash), as shown in Figure 5. Presumably the migration of brecciated coal fragments towards structurally favorable positions (fold hinges) began as well. With the onset of regional metamorphism and deformation the coals were altered to either high rank anthracites and meta-anthracites or thermally altered (i.e. they left normal coalification

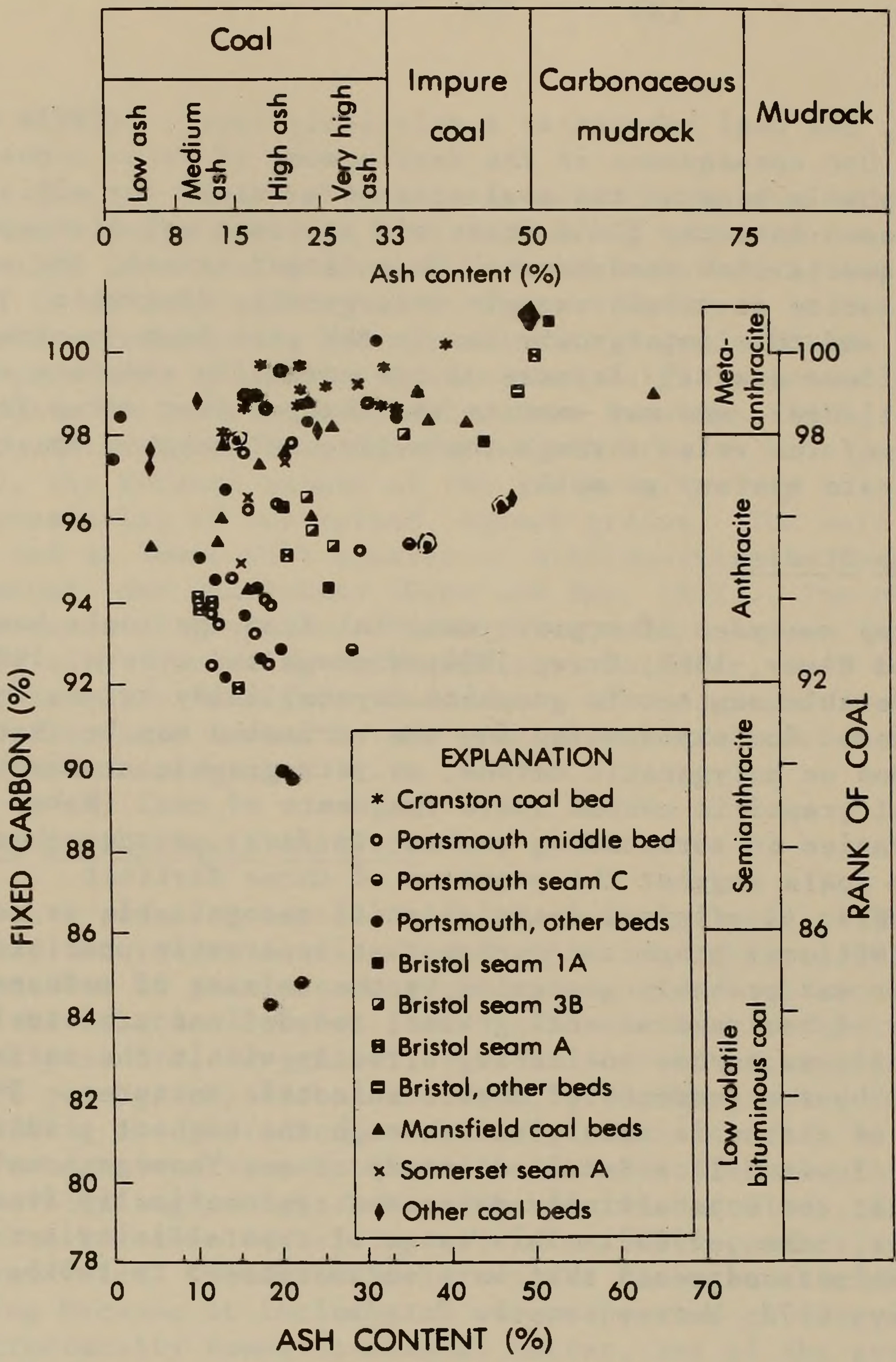

Figure 7. Relationship between fixed-carbon content (Parr-corrected) and as-received ash content of 90 coal samples from the Narragansett basin. Modified from Lyons and Chase (1981).

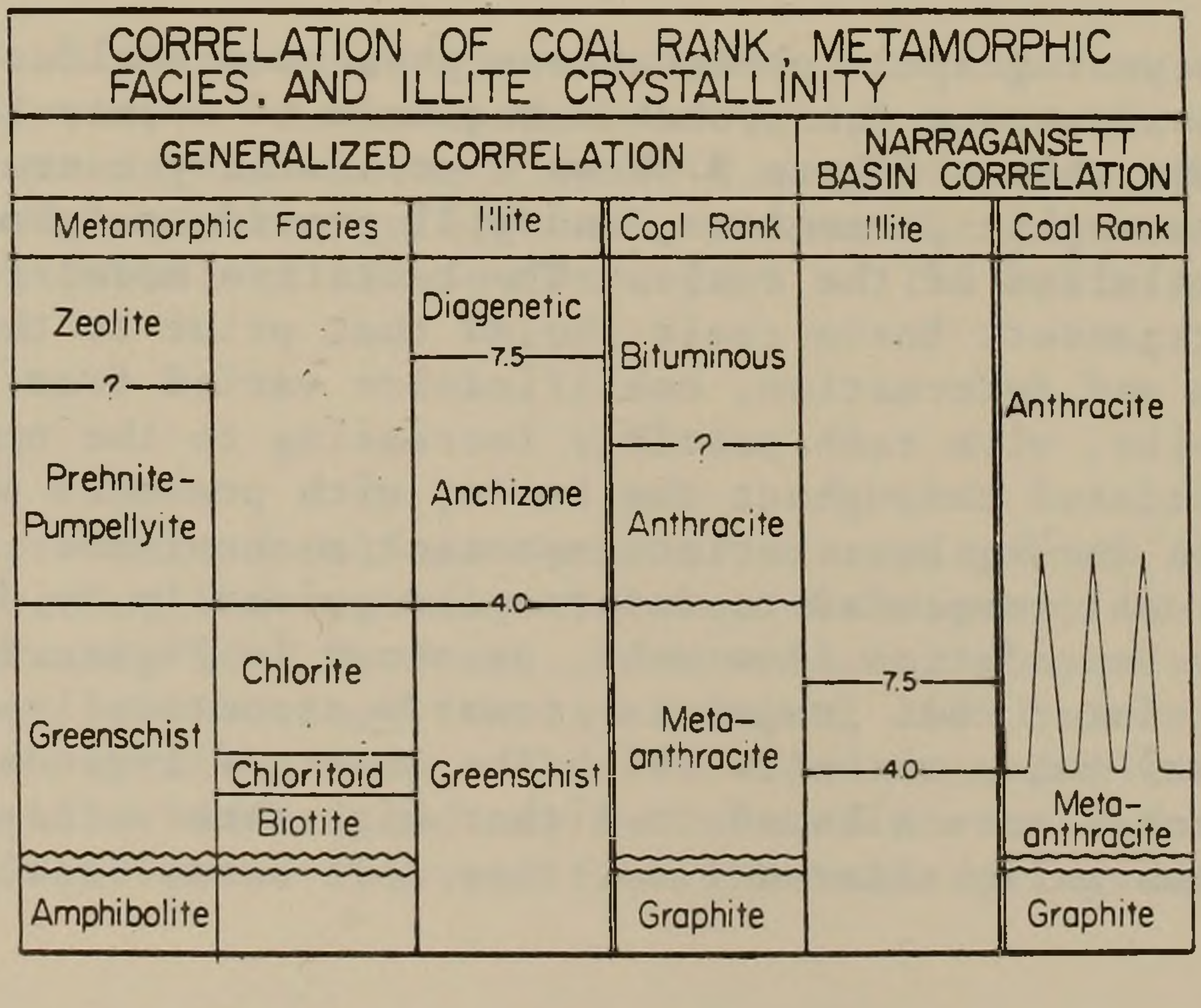

Figure 8. From Murray and Raben, 1980.

paths) coals; which type was attained being a function of the rank and/or kinetics.

With the onset of more rapid and intensive dynamothermal metamorphism, the coals developed incipient mosaic textures, granular texture, coke structures, and secondary graphitic depositional carbon. The above features were established by the chloritoid grade, and at higher metamorphic grades they become further accentuated, culminating in the development of graphitic schist. The presence of softening textures at Bristol and Cranston may mean that the metamorphism was rapid. There are also several details of the evolution of the coals that are germane to discussions of the overall metamorphic history of the area.

1. The secondary depositional graphitic carbon coats brecciated coal fragments and mineral grains in the surrounding sediments, in the latter case it may convert a sediment originally a shale into a carbonaceous shale. This carbon was precipitated out of a gas phase that was probably methane-rich and derived from gas released from the coal during brecciation. The reason it precipitated could be either increasing metamorphism or interaction with a more oxidized environment associated with the surrounding sediments.
2. SEM and Mossbauer spectroscopy studies of the iron bearing phases in the coals identified the presence of metallic iron and other highly reduced phases (Murray and Raben, 1980), suggesting that the fluid phase in coals and their immediate surroundings may well be buffered at values of f_{O2} well below the graphite buffer. The cause of such low values is presumably the abundance of CH_4 in the gases released from the coal with deformation. Regardless of the mechanism by which such highly reducing environments are maintained, their effect on mineral equilibria in adjacent pelitic rocks should be substantial. And, it is apparent that the degradation and homogenization of organic material with associated sediments during progressive metamorhism is a complex process, and one that needs to be much more completely evaluated before various meaningful correlations can be made between coal rank and mineral parageneses (Zen and Thompson, 1974; Murray and others, 1979; Murray and Raben, 1980) or illite crystallinity (Wolfe, 1976; Rehmer and others, 1978; Kisch, 1980).

Clearly, the duration and rate of metamorphism are important parameters in the evolution of the coal. In addition, the rank at the onset of regional metamorphism and structural setting of the coal exert strong controls on the end products. A complex interplay among metamorphism, strain history, and primary differences in coal character have resulted in unusually large variations in coal petrography and chemistry at a given locale, as well as throughout the basin. The classification and characterization of Narragansett Basin coals is made particularly difficult because of the ubiquitous presence of the following features; non-combustible gases, secondary depositional carbon, hydroscopic nature, and presence of thermally altered material. Thus, one must reevaluate the validity of classification systems based upon standard rank parameters when applied to very high rank and/or thermally altered coals. Moreover, as pointed out in Quinn and Glass (1962) and Lyons and Chase (1981), the very high ash concentrations (both primary and secondary) in these coals generate additional problems in the use of rank classifications based upon Parr-formula corrected chemical analyses, which are a standard criteria for coal classification.

ACKNOWLEDGMENTS

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STOPS

TOTAL
MILEAGE

STOP 1

Ranger Hall, U.R.I. The following topics will be covered.
20 minutes. A synopsis of the geologic history of the Narragansett Basin, with an emphasis upon the history of mining and related activities, and upon the evolution of organic material with progressive metamorphism and deformation.
2) 40 minutes. A "cram course" in coal (and graphite) petrology, with the focus being a discussion of the petrographic features that are unique to Narragansett Basin coals.
3) 30 minutes. Examination of drillcore and other samples of carbonaceous material from now inaccessible mines and prospects.

Leave Kingston on Rte. 138 East. Go 4 miles and turn north (left) onto Rte. 1. Go approximately 2.5 miles and take Exit for Rte. 138 East to Jamestown and Newport. Stay on Rte. 138, following signs for the Newport Bridge. Cross the Jamestown Bridge and follow Rte. 138 to the Newport Bridge (toll of $2). After crossing the bridge, take the Rte. 138 exit (the second one). The exit ramp ends at a stop sign across from Jai Lai (Hi Li). Turn right; log starts from this stop sign.

0.0	Hi Li parking lot.
0.6	Stop light for Rtes. 138 and 114; turn right and follow Rte. 114 through 3 stop lights.
7.3	Turn left onto Cory Lane (first left after flashing yellow light), following signs for Portsmouth Abbey School.
8.1	Bear right after the Portsmouth Abbey Hockey Rink, and continue into the school's parking lot. A path leads down to boathouse on shore.

STOP 2

Shoreline exposures of Rhode Island Formation, northwest Aquidneck Island. Nearly continuous outcrops of fossiliferous slate, siltstone, sandstone, and coal occur both north and south of the Abbey boathouse. (This is the same as STOP 3 of the trip lead by Burks and others, this volume.) Approximately a mile to the north can be seen the rectangular tower of the Kaiser Aluminum plant, which was built over the southern (of two) shafts of the Portsmouth coal mines (Stop 3).

During 1980 two holes were drilled on the grassy field at the northeast end of the outcrop, on the Portsmouth Abbey School property. The drillsites were chosen for the following reason. Since the strata along the shoreline were believed to be for the most part upright and of the same approximate orientation as the coal seams mined to the north (i.e. N30E 20-30SE), the drill sites would, hopefully, sample at least part of the "stratigraphic" section between the shoreline outcrops and the mined area. The first hole encountered a 2 meter thick seam petrographically similar to the coal mined at Portsmouth. An additional drillsite 100 meters away was designed to obtain another sample of the coal.

Sedimentologically, the rocks are finer grained than most of of the Rhode Island Formation seen elsewhere, and they may represent either lacrustrine or floodplain deposits. A well-developed floral assemblage from the middle of the strip of outcrop north of the boathouse indicates that the sediments are Westphalian D or Stephanian A in age. Coal petrography (Murray and others, this volume) coupled with routine petrography suggests temperatures T=400°C were attained during metamorphism.

Both strips of outcrops are characterized by N20E 30SE subparallel bedding and cleavage, with the cleavage being axial planar to tight F1 folds. Despite the presence of grade bedding, cross stratification, and flattened erosional contacts, it is suprisingly difficult to assign a general younging direction to the outcrop. If one accepts the "concensus" opinion that the beds are for the most part upright, then one can infer a position on the upright limb of a tight, NNE trending overturned syncline. The hinge may be along the eastern edge of the island, an orientation of bedding consistent with the presence of nearly flat (dip <15°) beds encountered during drilling there. Alternatively, folding may be on a substantially smaller scale, with a synformal hinge no further than a kilometer to the east (S. Mosher, pers. comm., 1981). Tight, parasitic D1 folds are best displayed at the northern end of the northern outcrop. Open, E-W trending folds (D3 ?) are cut by NE striking, NW directed thrusts at the southern outcrop. Pressure solution phenomena are well developed, and of particular interest are fibrous quartz-mica veins that formed in coal and carbonaceous slates seen in the southern strip of outcrop.

Turn to left when leaving the parking lot and retrace route to Rte. 114.
8.9 Intersection of Rte. 114 and Cory Lane
Proceed north on 114 to Willow Lane.
10.3 Intersection of Rte. 114 and Willow Lane; turn right onto Willow Lane and drive straight ahead, crossing railroad tracks and passing (to the left)
11.2 the Kaiser Aluminum plant.
At the pavement's end continue on the dirt road 0.2 miles to the gate on the left side of the road.

STOP 3
Mine dump at the site of the Portsmouth Coal Mine. Specimens of meta-anthracite may be collected here, the site of the largest coal mine in the basin.

The mines on northern Aquidneck Island were worked intermittently during the eighteenth through early twentieth century, and approximately 1.13 million tons of coal were removed from here between 1860 and 1913. Mining was mainly confined to the middle of three coal seams, and this seam was worked from two slopes, 1800 feet apart, that extended down dip. The seams averaged 36 inches, although lenses up to 12 feet were common. This is the location of samples collected for chemical analyses (Tables 2 & 3), isograd classification (Quinn, 1971), and crystallinity studies (Quinn and Glass, 1962; Grew, 1974).

13.5 Return to Rte. 114 by retracing the route to Cory Lane, and proceed north.; Rte. 114 becomes Rte. 24.
Take Rte. 24 north to I-195 (Fall River).
24.1 Go west on I-195 (towards Providence)
27.8 Rte. 103 exit. To your left (south) can be seen the smoke stacks of the Brayton Point Power Plant, the largest fossil fuel (coal now, previously oil) burning plant in New England. Three meter thick coal seams (the analyses labelled Somerset in Tables 1 & 2) were encountered during drilling here, approximately 270 meters under the plant.
Continue west in I-195.

30.2 Rte. 6 (Swansea) exit. The outcrops of Dighton Conglomerate seen along the southeast expressway ramps were described in STOP 2 of the 1976 NEIGC led by Skehan and others. They are part of the southernmost of the three synclines containing Dighton at the core (see Fig. 1).

41.2 Continue west on I-195 to intersection with I-95.; bear right, in order to take I-95 north.

52.0 Rte. 123/I-95 (Norton-Attleboro exit). Outcrops along the exit lane are of Dighton Conglomerate, in the northern most of three synclines that contain this unit.
Continue north on I-95.

56.3 Series of roadcuts in Wamsutta Formation.

59.5 Continue north to intersection with I-495.; take I-495 west.

64.0 Exit from I-495 onto Rte. 1A, and head south (left turn at end of exit ramp).

65.4 Turn right onto Cross Street, and follow signs to Masslite Broken Stone Quarry.

66.0 Park in visitor's parking lot, and check in at the front office. This stop is on private property, and never accessible without permission. At the time of preparation of this article, the coal seam could be best seen by taking the dirt road to the right-hand excavation. This is also the best place to find good examples of plant fossils and primary sedimentological features. In contrast, faulting and folding is best observed in the other pit, to the left. This is also a stop in the Hepburn and Rehmer article in this volume, and is STOP 3 of a previous NEIGC (Lyons and Chase, 1976).

STOP 4

Masslite quarry, Plainville, Mass. This quarry (Fig. 9; also see Fig. 3 of Lyons and Chase, 1976) represents the best exposure of coal stratigraphy in the basin, and consists of a generally fining up sequence below the coal and coarsening up sequence above it, with a total stratigraphic thickness of 150 meters (in terms of present exposure). Large boulders have broken away from the quarry wall, and they conveniently display all of the pertinent sedimentological textures and plant fossils found in the quarry.

The coal seam is tectonically thickened, as evidenced by the presence of isoclinal folds in the coal, and quartz- and mica-rich veins occur along numerous shear zones. In contrast, folding and faulting in the surrounding clastic sediments is less intense. Apparently, differential movement has taken place along both the upper and lower contacts of the coal seam, and one of the results has been to tectonically thicken the coal. The coal seams were probably originally quite lenticular in shape (i.e. they were distinctly non-tabular) as well as significantly weaker than the surrounding coarse grained clastic sediments, and this may be at least in part responsible for the structural complexity observed in the vicinity of the seam.

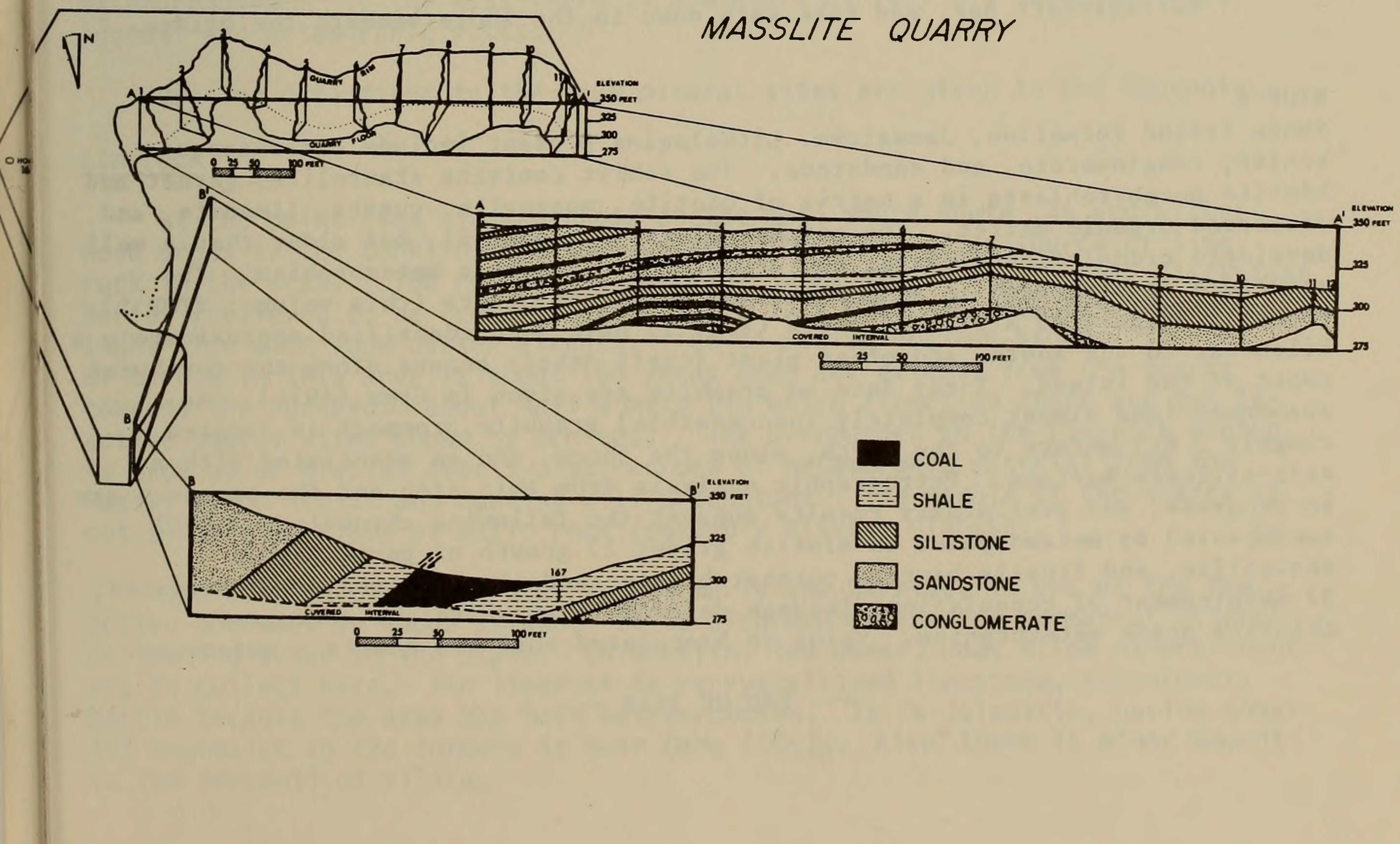
The shale below the coal has rooted horizons, and the siltstone below the shale is extremely fossiliferous. Coarser grained lithologies contain branches, stems, and rip clasts of finer grained lithologies. A detailed sedimentologic and stratigraphic study of the drillcore and outcrop in the quarry has recently been completed (Severson, 1981; Severson and Boothroyd, 1981). They concluded that the Rhode Island Formation represents medial to distal humid alluvial fan environments and the overlying Dighton conglomerate repesents proximal alluvial fans. The coal deposits are presumed to have developed on abandoned bar and with another recent study of the sedimentology of the basin by Cable (1981). This quarry has also provided the greatest number of plant fossils of any locale of the basin, as shown in (Fig. 4).

The rocks exposed here represent the least metamorphosed part of the basin studied to date. Illite crystallinity data (Hepburn and Rehmer, this volume), coal petrology (Raben and Gray, 1979) and petrography (Murray, unpub. data) indicates that the rocks are in the anchimetamorphic zone.

The coal and carbonaceous shale seam is being actively quarried and mixed with the adjacent shales and carbonaceous shales, and used in the production of lightweight aggregate. Lightweight aggregate is a "popcorn"-like substance that is produced by the ignition of the coal and shale. If anthracite from Pennsylvania were to be used instead of the indigenous material, the Masslite quarry operation would not be profitable. We will tour the proccessing plant.

73.5 Return to the intersection of I-95 and I-495, and take I-95 south.
94.7 Take Rte. 10 north (Exit 16; Cranston, R.I.).
95.6 Turn left (south) on Reservoir Ave.
96.3 Turn right (west) on Park Ave.
96.8 Turn right (north) on Gansetts Ave; this becomes Cranston Ave.
Turn left into the NHD Hardware lot; if you run into Rte. 10 again, you have gone too far.
The outcrops are to the left and rear of the hardware store.

Figure 9. Geologic relationships in the northern part of the Masslite quarry.



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Continue north on I-95.

56.3 Series of roadcuts in Wamsutta Formation.

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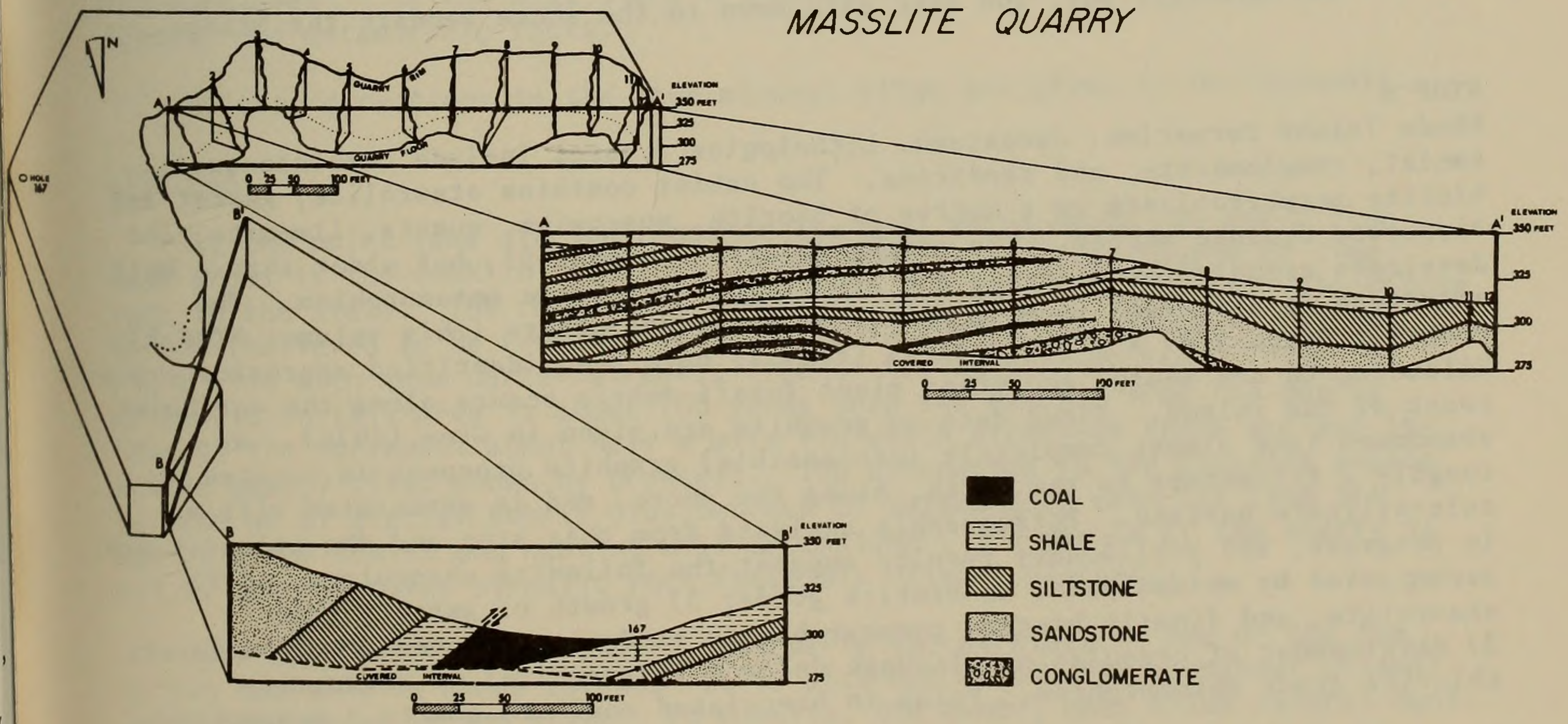

STOP 5
Fenners Ledge, Cranston, R.I. The stop consists of the series of small cliffs and outcrops south and west of the NHD Hardware store. The rock types consist of sandstone, siltstone, slate, and graphite lenses, with the latter largely covered up. Chloritoid, white mica, chlorite, quartz, and ilmenite are the main metamorphic minerals, and X-ray data on micas and graphite from this site may be found in Quinn and Glass (1962) and Grew (1974).

The structure is unusually complex for this part of the basin, perhaps because of its proximity ot the basin's margin or the presence of faults. The general trend of bedding and S1 is N35E 65SE, with variations in strike from N0E to N50E due to later gentle folding. Fine rods developed on S1 trend N32E HORIZONTAL, and are folded about N65E 42NE axes. A crenulation cleavage is also present. A series of faults subparallel to S1 have both dip-slip and strike-slip movement, based upon the orientation of coarse quartz fibers. Along these fault surfaces, S1 is folded and crenulated along primarily NE trending axes.

101.3 Return to I95, reversing the directions used to get here.
Head south on I-95.
110.3 Take Rte. 4 south (get in the left lanes for exit).
Rte. 2 joins Rte. 4, and the road changes to a four lane undivided highway; continue south to rotary
Stay on Rte. 4, heading towards beaches.
120.3 Rte. 1 joins Rte. 4.
Take Rte. 138 east, towards Newport.
Cross over the Jamestown Bridge to Conanicut Island.
124.7 Park at the east end of the Jamestown Bridge, (near Jamestown Shores Motel), which connnects Conanicut Island with the western shore of Narragansett Bay, and take path down to the shore beneath the bridge.

STOP 6
Rhode Island Formation, Jamestown. Lithologies present include carbonaceous schist, conglomerate, and sandstone. The schist contains staurolite, garnet and biotite porphyroblasts in a matrix of biotite, muscovite, quartz, ilmenite, and dispersed organic matter. The porphyroblasts are post-S1, but older than a well developed crenulation cleavage and associated retrograde metamorphism. The structure is discussed in more detail in Burks and others (this volume; STOP 5). Probable Stephanian A plant fossils (Fig. 2) have been identified approximately a kilometer to the south, and other plant fossil debris occurs along the northwest coast of the island. X-ray data on graphite are given in Grew (1974). An abandoned (and almost completely inaccessible) graphite prospect is located roughly 2 kilometers to the north, along the shore, and is associated with a calc-silicate horizon. Petrographic analysis from this stop and the prospect are in progress, and preliminary results suggest the following chronology: 1)D1 accompanied by metamorphism to biotite grade; 2) growth of garnet, then staurolite, and finally biotite porphyroblasts randomly oriented on S1 surfaces; 3) development of crenulation cleavage defined by graphite; 4) retrograde chlorite grade metamorphism. Veins in brecciated coal are quartz + muscovite.

--- END OF TRIP ---