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Pennsylvanian Rocks of East-Central Massachusetts

Grew, Edward S.

Trip A-12

PENNSYLVANIAN ROCKS OF EAST-CENTRAL MASSACHUSETTS

by
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"that besides our satisfaction as to the Nature of Vegetation, some further Light, to divers parts of Knowledge, may likewise hence arise."
Nehemiah Grew (1682)

INTRODUCTION

Meta-anthracite, conglomerates, and arkose crop out in isolated exposures along a belt extending northeast from Worcester to Harvard, Massachusetts (Figures 1 and 2). Of considerable historical and geological interest is the meta-anthracite outcrop at the Worcester coal mine, which has yielded plant fossils, that, together with other evidence, have indicated that these rock units are Pennsylvanian in age. The purpose of this field trip is to visit some of these exposures, including the coal mine, and to consider the relations between these rocks and older metamorphic and plutonic rocks in this part of Massachusetts.

The dominant rock types in the exposures that have been assigned a Pennsylvanian age are phyllite and conglomerate containing pebbles of sedimentary rocks. The outcrops in Harvard and Bolton (Figure 2) consist entirely of these two rock types, whereas in Worcester, these rock types crop out only near the railroad near Shrewsbury Street (Figure 1). These rocks are generally resistant to erosion and form hills, such as Pin Hill in Harvard (Stop 4). Arkose and granite-pebble conglomerate, on the other hand, have only been found in Worcester, where they were exposed during recent construction (Stop 1). These rocks are deeply weathered. Meta-anthracite has been found at only one locality in Worcester (Stop 3).

The phyllite and conglomerate in Harvard and Bolton are generally referred to as the Harvard conglomerate (or Harvard conglomerate lentil); the meta-anthracite is included in the Worcester phyllite (Perry and Emerson, 1903). Hansen (1956, p. 20) proposed the term Worcester formation to include the Worcester phyllite, Harvard conglomerate lentil, and Emerson's (1917) Brimfield schist in the Hudson quadrangle and adjoining areas. Hansen (1956) regarded the Harvard as a basal conglomerate to the Worcester formation, as Crosby (1876) suggested much earlier. (For a more detailed review of the geology of the Harvard conglomerate, see Thompson and Robinson, this guidebook.)

On his map of Massachusetts, Emerson (1917) shows a band of Harvard conglomerate in Auburn (the next town south of Worcester) in addition to the bands in Harvard and Bolton. Although I made

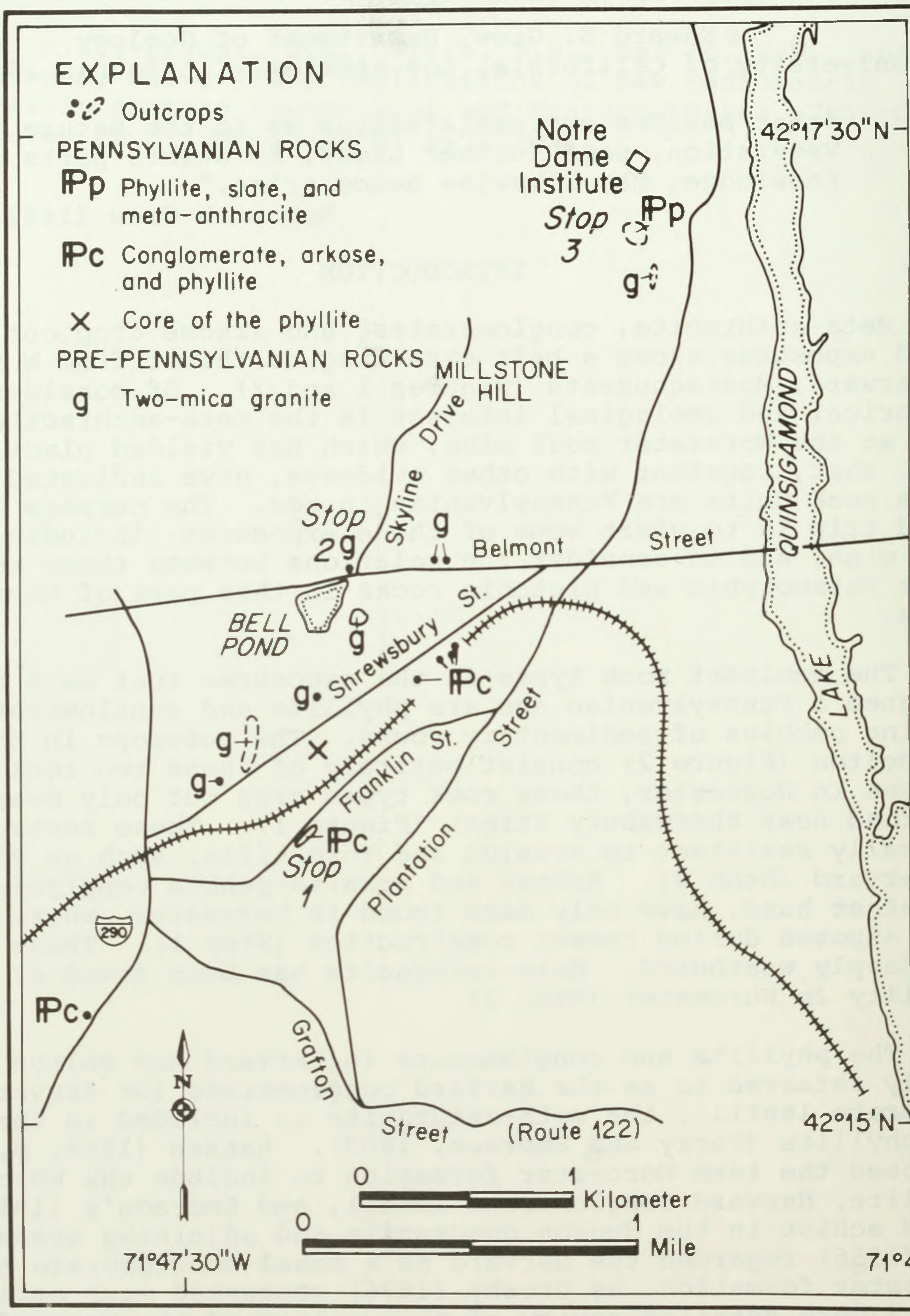

Figure 1. Sketch map of Worcester, Massachusetts, showing outcrops of Pennsylvanian rocks, outcrops of two-mica granite closest to the Pennsylvanian rocks, and the location of Stops 1, 2, and 3.

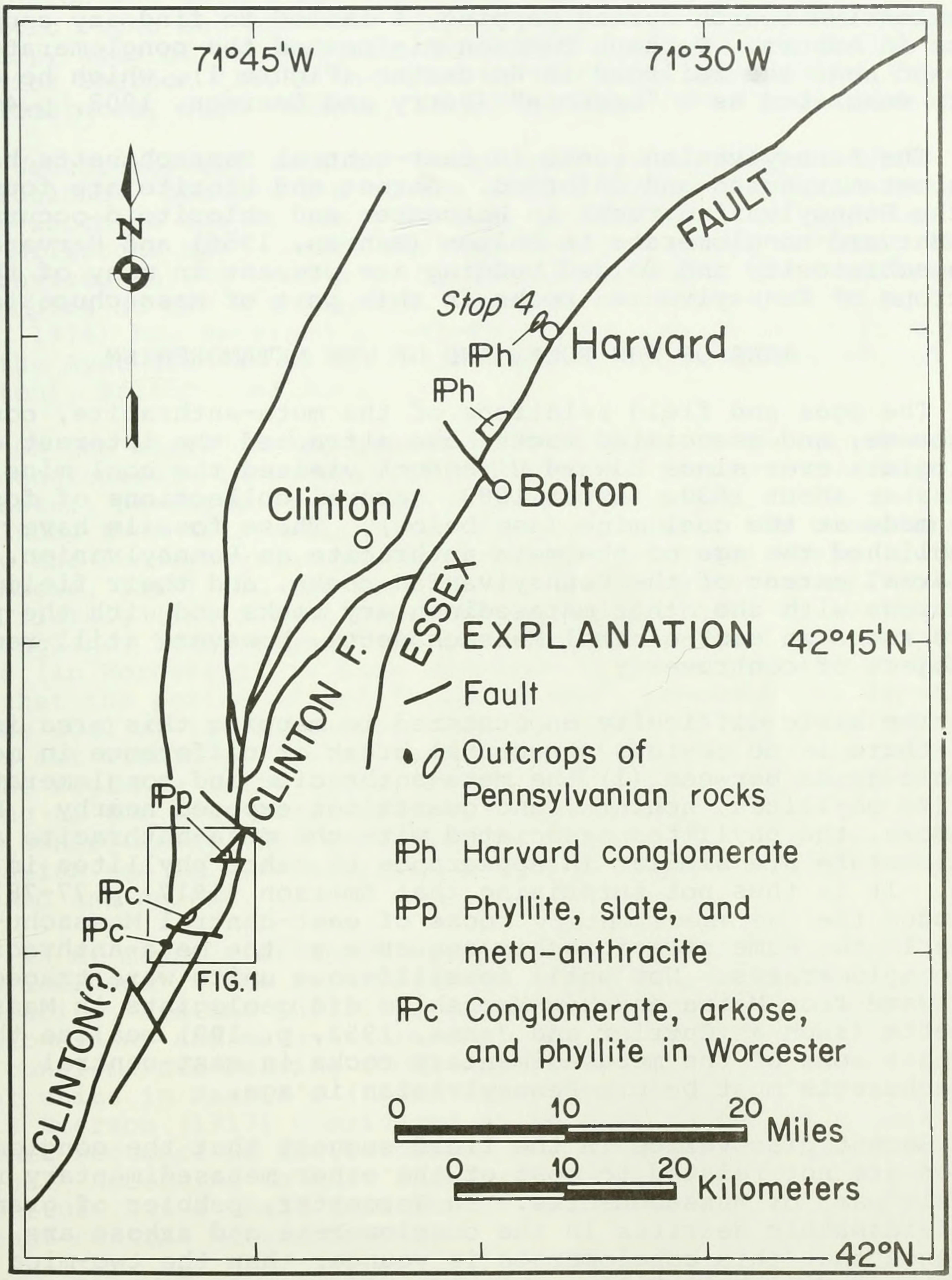

Figure 2. Sketch map of east-central Massachusetts, showing location of major faults and outcrops of Pennsylvanian rocks, including Stop 4. Faults are sketched from Castle and others (1976, plate 1).

an extensive search during mapping, I failed to find any conglomerate in Auburn. Perhaps Emerson mislocated the conglomerate exposed near the railroad in Worcester (Figure 1), which he and Perry described as a "breccia" (Perry and Emerson, 1903, p.40-41).

The Pennsylvanian rocks in east-central Massachusetts have been metamorphosed and deformed. Garnet and biotite are found in the Pennsylvanian rocks in Worcester and chloritoid occurs in the Harvard conglomerate in Bolton (Hansen, 1956) and Harvard. Mica schistosity and folded bedding are present in many of the outcrops of Pennsylvanian rocks in this part of Massachusetts.

AGES OF THE ROCKS AND OF THE METAMORPHISM

The ages and field relations of the meta-anthracite, conglomerate, and associated rocks have attracted the interest of geologists ever since Edward Hitchcock visited the coal mine in Worcester about 1830. After 1883, several collections of fossils were made at the coal mine (see below). These fossils have established the age of the meta-anthracite as Pennsylvanian. The areal extent of the Pennsylvanian rocks, and their field relations with the other metasedimentary rocks and with the plutonic rocks in east-central Massachusetts, however, still remain a subject of controversy.

The basic difficulty encountered in mapping this area is that there is no obvious structural break or difference in metamorphic grade between (1) the meta-anthracite and conglomerates and (2) phyllites, schists, and quartzites exposed nearby. Furthermore, the phyllites associated with the meta-anthracite and conglomerate are similar in appearance to other phyllites in this area. It is thus not surprising that Emerson (1917, p.77-78) included the metasedimentary rocks of east-central Massachusetts in the same stratigraphic sequence as the meta-anthracite and conglomerates. Not until fossiliferous units were traced southward from Maine and New Hampshire did geologists in Massachusetts (such as Currier and Jahns, 1952, p. 109) realize that at least some of the metasedimentary rocks in east-central Massachusetts must be pre-Pennsylvanian in age.

Recent discoveries in the field suggest that the conglomerates are not related to most of the other metasedimentary rocks in this part of Massachusetts. In Worcester, pebbles of granite and feldspathic detritus in the conglomerate and arkose are evidence that this conglomerate is younger than the two-mica granite on Millstone Hill. This two-mica granite intrudes the Oakdale quartzite, which conformably underlies the Worcester phyllite (Emerson, 1917, p.77). In Harvard, the unconformable relation between the conglomerate and Ayer granite is clearly shown in a single outcrop (Thompson and Robinson, this guidebook, fig. 1). The Ayer granite intrudes the Worcester phyllite and the Boylston schist, which grades into the Worcester (Emerson, 1917, p. 68). These relations imply, moreover, that a period of erosion and uplift followed the emplacement of these granitic rocks and preceded the deposition of the conglomerates. Clearly, some of the Oakdale, Worcester, and related units, all of which Emerson (1917) included in the same sequence as the conglomerates, must actually be much older than the conglomerates.

Geochronologic data on the granitic rocks support these conclusions. Zartman and others (1965) obtained a total rock Rb-Sr isochron age of 345 ± 15 m.y. on the two-mica granite from Millstone Hill, which Zartman (written communication, 1976) has revised to 380 ± 15 m.y. by including more recent analyses on samples he and I collected. Zartman (written communication, 1976) has obtained a U-Th-Pb zircon age of 425 ± 10 m.y. for the Ayer granite in Bolyston (town between Worcester and Clinton), Bolton, and Ayer.

On the basis of the geochronologic ages on the granites, the conglomerate in Harvard is Silurian or younger, and that in Worcester, Devonian or younger. Grew and others (1970, p. 123) concluded that "circumstantial evidence, namely the unconformity below the Pennsylvanian rocks of the Narragansett Basin (Quinn and Moore, 1968) and the lack of any proven post-Pennsylvanian, pre-Triassic (the oldest non-metamorphosed) rocks in southern New England, lends support to the suggestion that the conglomerate [in Worcester] is Late Devonian to Pennsylvanian in age, and that the period of uplift and erosion preceded the deposition of the coal at the Worcester mine." Moreover, the conglomerate crops out within 2.3 km of the coal mine in a direction parallel to the regional trend (Grew, 1973). Thus the conglomerate may belong to the same stratigraphic sequence as the meta-anthracite and, consequently, be Pennsylvanian in age. By analogy, a Pennsylvanian age is also assigned to the Harvard conglomerate in Harvard and Bolton.

In my mapping of the Worcester area (Grew, 1970, 1973), I have included in the Pennsylvanian only the conglomerates, meta-anthracite, and the phyllites immediately associated with the conglomerates and meta-anthracite. In Harvard and Bolton, only the conglomerate-bearing rocks appear to be Pennsylvanian. The other units in Hansen's (1956) Worcester formation and the other units Emerson (1917) considered to be part of the same stratigraphic sequence as the Worcester phyllite are pre-Pennsylvanian in age. According to this interpretation, Pennsylvanian rocks constitute but a small fraction of the metasedimentary rocks of east-central Massachusetts.

The metamorphism of the Pennsylvanian rocks implies that these rocks were at one time deeply buried, suggesting that a thick, and probably extensive, cover of Pennsylvanian sediments was deposited and subsequently removed by erosion after the metamorphism. The present exposures may thus be mere remnants of the deposits in a single basin extending from the area that is now Worcester to Harvard, or beyond, and comparable in size to the Narragansett basin.

The areal extent of rocks affected by the Pennsylvanian or younger metamorphism, on the other hand, may not be significantly larger than the narrow northeast-trending belt in which the Pennsylvanian rocks are presently found. In the Worcester and neighboring areas, metamorphic rocks containing sillimanite and andalusite are spatially associated with two-mica granites, including the Fitchburg (Grew, 1973; Nelson and Kuntz, 1973). As these two-mica granites are probably pre-Pennsylvanian in age, the sillimanite and staurolite zone metamorphism is probably also pre-Pennsylvanian in age. The low-grade metamorphism (garnet, biotite, chlorite zones) in the central part of the Worcester area appears to be contemporaneous with the higher grade metamorphism. In general, there is no textural evidence that these low-grade rocks were derived by retrograde metamorphism of higher grade rocks; these rocks are in fault contact or pass gradationally into the higher grade rocks (Grew, 1973, fig.3). Furthermore, retrograded sillimanite and staurolite zone rocks found in the Worcester area are texturally distinct from the low-grade rocks. A considerable part of the low-grade metamorphism thus may actually be pre-Pennsylvanian in age. The Pennsylvanian or younger metamorphism may have affected only the rocks in the narrow belt in which the Pennsylvanian rocks are found, and could have been responsible for some of the retrograde metamorphism in or near this belt. Folding associated with the Pennsylvanian or younger metamorphism probably also was confined to this narrow belt.

There is no isotopic evidence, moreover, for a widespread regional metamorphic event during the Pennsylvanian or Permian in east-central Massachusetts. Zartman and others (1970, p.3368-3369) did not attribute K-Ar ages of 200-260 m.y. on micas in this area to regional metamorphism. Zartman and others (1965), moreover, report a Rb-Sr age of 360 ± 10 m.y. on muscovite from the two-mica granite on Millstone Hill. These authors imply that this granite was not much affected by the Pennsylvanian or younger event that metamorphosed the rocks near the coal mine (Zartman and others, 1965, p. D9).

PENNSYLVANIAN ROCKS AND FAULTS

The geology and field relations of the Pennsylvanian rocks in east-central Massachusetts suggest that the deposition of these rocks was associated with active faulting. The rock types in the Pennsylvanian units are metamorphic equivalents of non-marine sediments such as conglomerate, arkose, and coal, which are characteristic of fault troughs in northeastern North America, as outlined by Klein (1968). Basins typical of the fault trough model, as cited by Klein, include the Narragansett basin (Mutch, 1968) and the Fundy basin (Belt, 1968a). The Pennsylvanian geology of east-central Massachusetts has several other features in common with the Narragansett basin and the Fundy basin, namely thick deposits of non-marine sediments, metamorphism [only "slate grade" in the Fundy basin (Belt, 1968b, p. 109)], and intense deformation. Moreover, in east-central Massachusetts and around the Narragansett basin (Quinn, 1971, p.51), the pre-Pennsylvanian rocks have been little affected by Pennsylvanian or younger metamorphism and deformation, and in Canada, Carboniferous rocks on platforms surrounding the Fundy basin are little deformed (Belt, 1968b, p. 109).

Mapping in east-central Massachusetts, moreover, has revealed the presence of numerous faults, including the Essex fault system, which extends over 100 km across the state (Castle and others, 1976). A genetic relation between the Pennsylvanian rocks and the Essex fault system is suggested by the fact that the Pennsylvanian rocks crop out along or just west of two faults belonging to that system, namely the Essex and Clinton faults (Figure 2). Castle and others (1976) have suggested that this fault system may have been active in Pennsylvanian time. The deposition of the Pennsylvanian rocks thus might have been related to active faulting along the Essex and related fault systems.

Several authors, notably Wilson (1962), Webb (1969), and Skehan (1969), have suggested that the faults in eastern Massachusetts, including the Essex fault system, might connect across the Gulf of Maine and the Bay of Fundy to the fault systems associated with the Fundy basin rift. Kane and others (1972, p. B18) state that "although the present gravity and magnetic data provide no direct evidence...of a gulfward extension of the rift system of Belt (1968) [1968b], the interpretation of these data [from the Gulf of Maine region] is compatible with the location of structures like these within the gulf."

In conclusion, I propose that the Pennsylvanian rocks and associated faults in east-central Massachusetts represent a continuation of the Carboniferous rift system in eastern Canada. In Massachusetts, most of the Carboniferous sediments have been eroded away, exposing a deeper section of the basin. Only a few outliers of the sediments remain, and these have been metamorphosed as a consequence of their deep burial.

WORCESTER COAL MINE

General History

The first settler of Worcester, Ephraim Curtis, arrived in the fall of 1673. "The principal reason of his selecting this locality...was the supposition of mineral wealth in the soil from the report of a valuable lead mine having been discovered in the vicinity by the Indians" (Wall, 1877, p.33). The Nipmuc (Algonquin) Indians had a fishing settlement on nearby Wigwam Hill, and used the meta-anthracite for face paint. In 1812, "black lead" (plumbago) from Elliot's Worcester Coal Mine was shipped to West Millbury where it was ground in a river mill and was sold for painting house roofs and ship bottoms (Town of Millbury, 1915, p. 261-262; Sandrof, 1948, p.28-29).

In this Bicentennial year, it is appropriate to note that the main source of information about the history of the coal mine is the Massachusetts Spy. This newspaper was established in Boston in 1770; in April, 1775, the press was secretly smuggled to Charlestown, and on May 3, 1775, the first issue of the Spy printed in Worcester carried an eye-witness account of the Battle of Lexington. The editor of the Spy during the height of activity at the coal mine (1823-1829) was John Milton Earle, who was well versed in natural history and took a special interest in the mine.

In 1822, coal from the Worcester coal mine was ceremoniously burned in the presence of the Hon. Levi Lincoln, Governor of Massachusetts. From 1824 to 1827, the Trumbull & Ward Brewery in Worcester burned coal from the mine. In November, 1828, the Spy reported that the mine had been extended 60 feet into the hill at a descent of 25°. Coal was sold for $3 per ton.

In 1829, the Worcester Coal Company and the Worcester Railroad Company were incorporated, the latter to construct two rail lines from the mine: one to Lake Quinsigamond and another to a landing on the recently completed Blackstone Canal from Worcester to Providence. The mine tunnel was extended to a length of 300 feet, and a 400-foot side tunnel was dug for water drainage.

About 1830, "the whole enterprise was abandoned chiefly because, as a wag put it, 'there was a damn sight more coal after burning than there was before'" (Nelson, 1934, p. 351). Nevertheless, after the closing of the mine, Lincoln (1837, p.354) lamented that the coal "which might be made to give motion to the wheels of manufacturing and mechanic industry to unlimited extent, has been permitted to rest undisturbed in its bed."

Notes on Scientific History

For nearly 150 years, the Worcester coal mine has drawn the attention of geologists and paleobotanists in this country and overseas. Edward Hitchcock, apparently the first geologist to visit the coal mine, thought that the Worcester meta-anthracite was older than the Rhode Island anthracite and that there was no "geological connection between the Rhode Island and the Worcester coal" (Hitchcock, 1832, p. 44). Lyell (1844, 1845ab), after visiting the mine on his first trip to North America, was of the opinion that the meta-anthracite in Worcester and the Carbonifer-our rocks of the Narragansett basin "belonged originally to the same group of sedimentary strata" (Lyell, 1844, p. 215), though fossil evidence was lacking at the time. Later in the 19th century, Louis Agassiz visited the mine and was surprised that no fossils had yet been found. He is reputed to have exclaimed "'Where are the fossils?'" (Perry and Emerson, 1903, p. 18). Agassiz was convinced "that they were there and would be found, if only careful search were made" (Perry and Emerson, 1903, p. 18). This remark inspired a search, and in 1883 Perry found two specimens of Lepidodendron (Perry, 1885). One specimen was examined by J. D. Dana, who sent a photograph of it to Lesquereux (Perry 1885). Since 1883, more fossils have been collected by Perry (Kemp, 1887), by David White in 1911, by a group led by L. R. Page in 1962, and by Grew in 1968.

Geological Notes

The meta-anthracite in Worcester forms a lens 2 m thick that is exposed only in the coal mine. The lens consists largely of a breccia containing fragments of black slaty rock in a matrix of quartz, muscovite, and chlorite. The remainder of the lens is black slate, which readily breaks into rounded or angular nodular masses, commonly 10 cm across. The surfaces of these masses are shiny, as if polished. In places, the black slate has been crumpled into small folds. The black slate, a very fine-grained tough rock with an earthy luster, contains about 55 percent ash and about 40 percent fixed carbon (Grew and others, 1970; Grew, 1974) and consists of carbonaceous material, quartz, muscovite, marcasite, pyrite, chlorite, and ilmenite. The black slate is commonly cut by veinlets of fibrous chlorite and quartz, with subordinate muscovite and sulfide.

On the basis of published descriptions, J. T. Wilson (1966, p.679) suggested that rocks in the coal mine may be "carbonaceous mylonite" along a fault zone that "marks the line of closure of the Lower Paleozoic Atlantic Ocean." The participants in the field trip may in turn wish to ponder the tectonic significance of the deformation of the meta-anthracite and associated slate and phyllite in the coal mine.

The Pennsylvanian rocks associated with the meta-anthracite and exposed in the outcrops near the coal mine (Figure 3) are carbonaceous (locally also sulfidic) slate and phyllite consisting largely of quartz, muscovite, chlorite, and accessory ilmenite. Marcasite is the dominant sulfide. Garnet is present in the exposures southeast of the mine.

Notes on the Fossils

The nodular masses of black slate commonly break into slabs with flat surfaces. The compressions and impressions of plant fragments illustrated in Grew and others (1970) and in this guide were found on these surfaces. The fossil plant assemblage in my collection from the Worcester coal mine includes calamitean stem fragments (Figure 4), cordaitean foliage (Figure 5), neuropterid pinnules (an example is shown in Figure 6), a *Mariopteris*-like pinnule, and a *Cordaicarpus*-like seed (Grew and others, 1970). The most abundant remains are fragments of cordaitean foliage.

In addition to the fossils described by Grew and others (1970), I collected a distinctive fossil of uncertain origin (Figure 7). Qualitative electron microprobe analysis revealed a few grains of apatite in some of the "teeth" of this unidentified fossil.

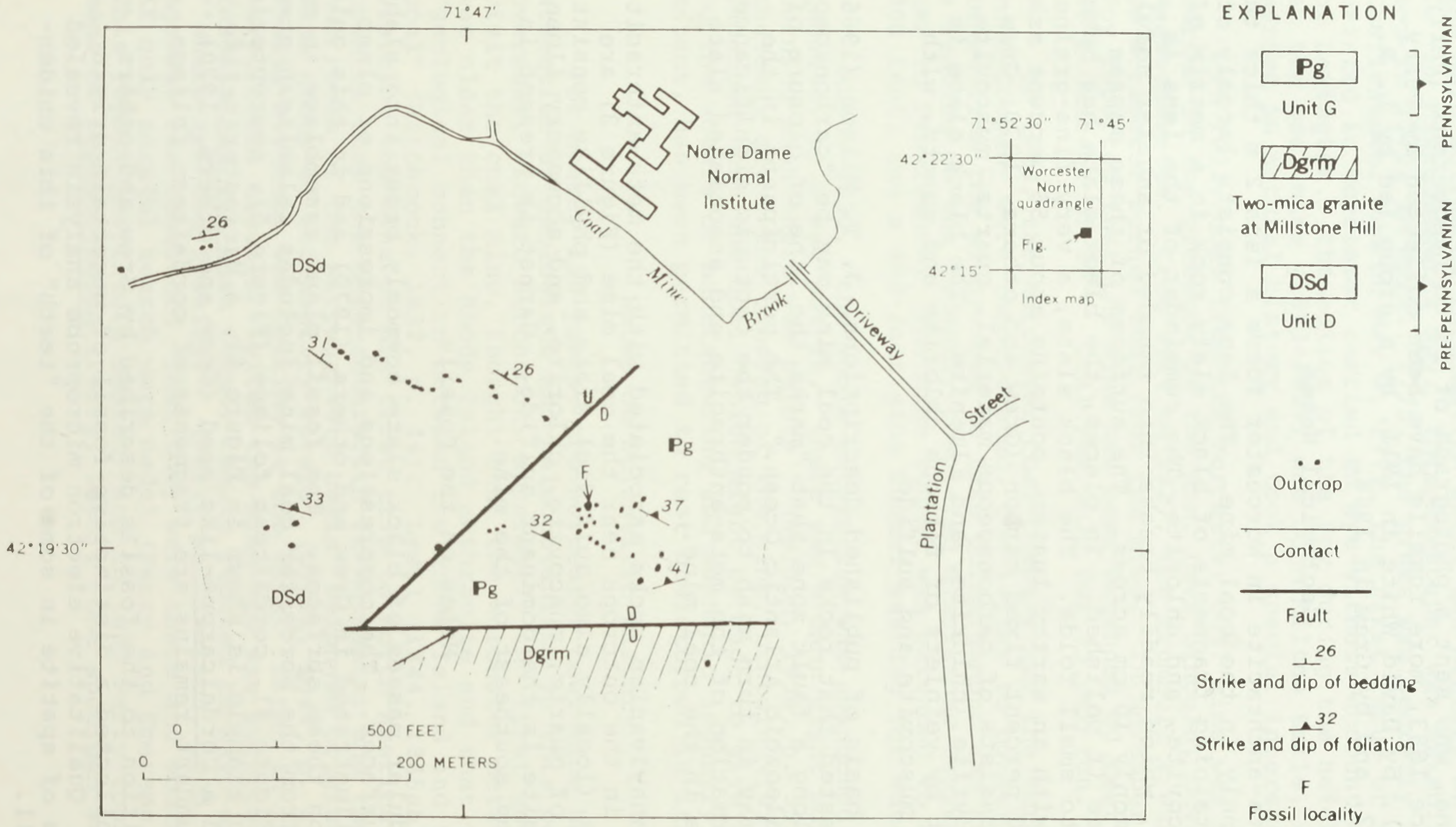

Figure 3. Map showing outcrops in the area around the Pennsylvanian fossil plant locality (F) in the Worcester coal mine (adapted from Grew, 1973, fig. 4). Unit D was mapped by Emerson (1917) as Oakdale quartzite.

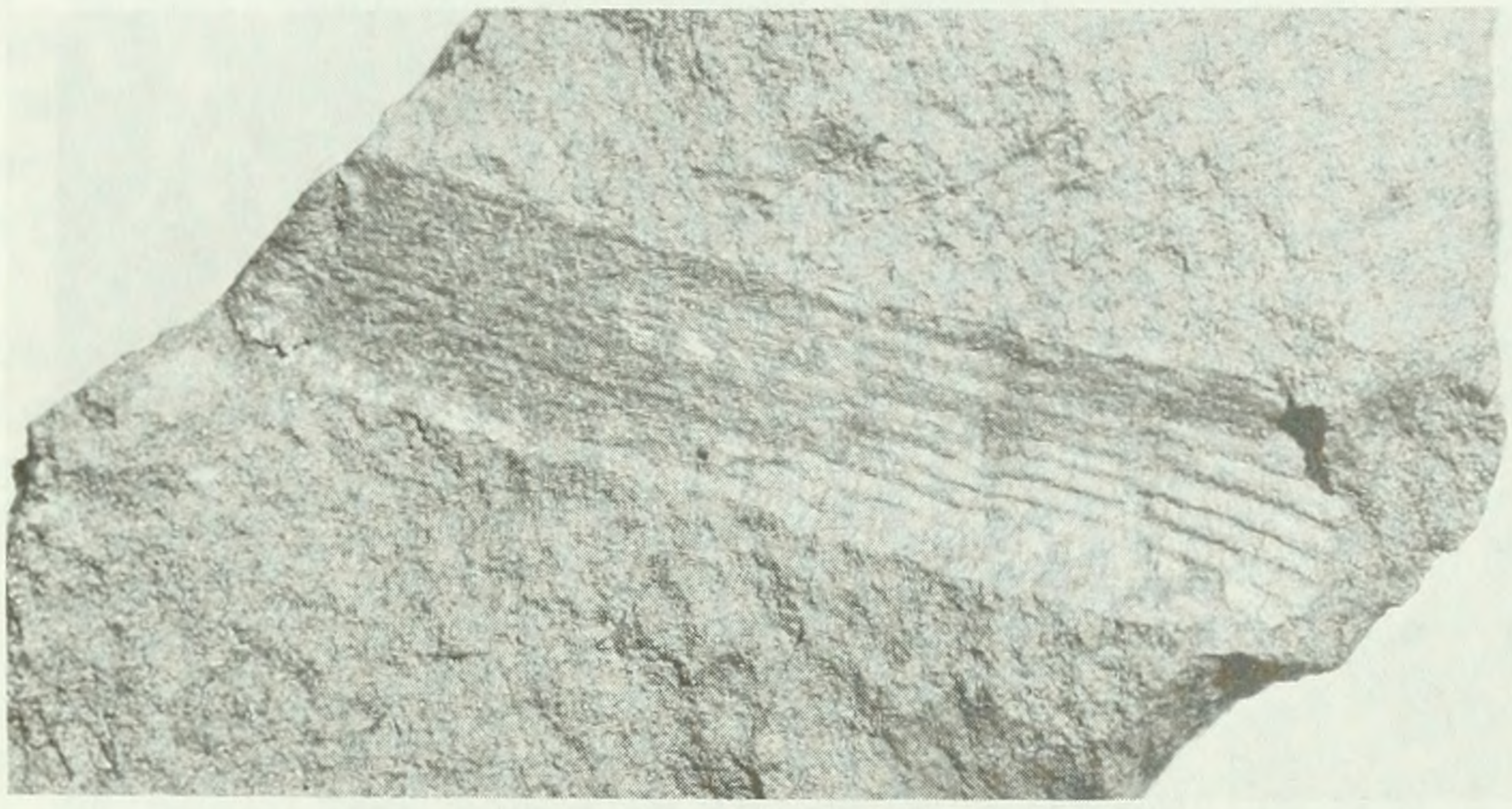

Figure 4. Black slate, Worcester coal mine. Calamites. Stem fragment, 4X. Note graphitic film on fossil (from Grew and others, 1970, Plate 2B).

Figure 5. Black slate, Worcester coal mine. Cordaites. Fragment of leaf, 5X.

Figure 6. Black slate, Worcester coal mine. Neuropterid pinnule, 9X, with basal auriculation and suggestion of a short pedicle (from Grew, 1970, fig.49; cf. Grew and others, 1970, p.121).

Figure 7. Black slate, Worcester coal mine. Unidentified fossil, 9X, possibly a vertebrate jawbone (from Grew, 1970, fig. 50).

I have some doubts concerning the organic origin of the helical pattern in Perry's Lepidodendron specimen from the Worcester coal mine (cf. Billings, 1956, p. 101; Grew, 1970). The ridges bounding the "leaf cushions" are similar to a lineation defined by the intersection of cleavage and bedding, which are not parallel in Perry's specimen. Perry's sample is in a slate similar to that found in the outcrops of Pennsylvanian rocks south and west of the coal mine, but differing from the black slate in which the other plant fossils were found.

The fossils collected by White in 1911 and by Grew in 1968 leave little doubt as to the approximate age of the meta-anthracite in Worcester. According to Grew and others (1970, p.122), these fossils "are clearly of Carboniferous age and most likely of the Pennsylvanian period...most likely early to middle Pennsylvanian (Pottsville)" confirming the earlier age assignment by White (1912). Paul C. Lyons, who has studied the plant fossils of the Norfolk and Narragansett basins (see Lyons and Chase, this guidebook), examined a part of my collection and concluded that the fossils "clearly establish the Pennsylvanian age of the Worcester flora" (Lyons, written communication, 1970).

Because of the poor preservation of the Worcester fossils, it is not possible with certainty to identify species, or, in some cases, even genera. Thus some of the identifications made by Grew and others (1970) are open to alternate interpretation. Lyons (written communication, 1970) observes that the cordaitean foliage (such as that illustrated in Figure 5) appears to be Cordaites principalis. He further notes that the Calamites illustrated in Figure 4 is similar to coarse ribbing that in some Narragansett basin samples can be traced into venation typical of Cordaites principalis. He also suggests that the seed (Grew and others, 1970, plate 1B) may be from a seed fern (possibly Neuropteris ovata) rather than a cordaicarp, and that the neuropterid pinnules that Grew and others (1970, p. 121) considered "reminiscent of Neuropteris pocahontas" could be a fragment of N. scheuchzeri. He further states that the pinnule illustrated in Figure 6 "is definitely a Neuropteris species but the venation is too obscure for full identification" (Lyons, written communication, 1970). In summary, Lyons "observed that the better preserved fossils [from Worcester] indicate an Alleghenian flora comparable to that of the Rhode Island Formation..." (Lyons and others, 1976, p. 183),which he has reported to be closely related in age to the Westphalian C floras of the Canadian Maritime Provinces and Europe (Lyons, 1971).

ACKNOWLEDGMENTS

J. L. Rosenfeld reviewed a draft of this manuscript. P. C. Grew contributed to the section on the general history of the coal mine and provided invaluable help in the final preparation of this report.

ROAD LOG

Stops 1-3 on this field trip are in the Worcester North 7-1/2 minute quadrangle and Stop 4 is in the Ayer 7-1/2 minute quadrangle. Geologic maps are available for the Worcester area (Grew, 1973) and for the Hudson quadrangle (Hansen, 1956), which lies immediately south of the Ayer quadrangle.

Mileage

0.0 Starting point of road log. Exit 11, Millbury and Route 122, of Massachusetts Turnpike (Interstate 90).

0.3 Turn left on Route 122 for Worcester. Follow Route 122 into downtown Worcester.

3.1 Bear right at traffic light, continue on Route 122 (Grafton Street).

3.6 Follow Route 122 around rotary in Billings Square.

4.0 Go under overpass (Interstate 290) and turn right at traffic light in Posner Square, heading for Washington Square.

4.1 Turn right at traffic light onto Franklin Street, passing under overpass (Interstate 290).

4.4 Bear left at blinking light at intersection, staying on Franklin Street.

4.6 STOP 1. Bus will park in front of Stark Electronics.

Granite-pebble conglomerate, arkose, and carbonaceous phyllite containing garnet and biotite are exposed in weathered cuts around Etre's Auto Body Shop, Stark Electronics, and A. V. Ricciardi's rental establishment. Similar rocks are exposed in a cut along Interstate 290 (Figure 1). The arkose and conglomerate generally occur together in lenses up to 2 m thick in the phyllite. These lenses are found only in the eastern part of the cuts; nearer the road, only phyllite is found. Rock types found in the pebbles of the conglomerate are, in decreasing order of abundance, phyllite, quartzite, granite, and vein quartz. The clasts are up to 13 cm in length. Quartz in the granite pebbles and the matrix of the conglomerate commonly is blue-gray and opalescent.

The beds here strike northeast and dip steeply to the west, a trend which is parallel to that of the pre-Pennsylvanian rocks cropping out east of these exposures (Grew, 1973).

Tough, dark-gray conglomerate crops out between Shrewsbury Street and the railroad northeast of here (Figure 1). The pebbles consist mostly of quartz-mica schist containing quartz, plagioclase, muscovite, and biotite, and rarely of vein quartz (no granite pebbles have been found).

The hills across the valley to the northwest (including Millstone Hill) are underlain by two-mica granite, which will be examined at the next stop. The granite pebbles and feldspar detritus in the conglomerate and arkose at Stop 1 may have been derived from this two-mica granite. This interpretation is suggested by the proximity of this particular body of granite to the conglomerate and by the presence of blue-gray opalescent quartz both in the granite and in the conglomerate. In the valley itself, at a depth of 28 feet, carbonaceous phyllite was recovered in a drill hole by J. A. Sinnott (Figure 1). This phyllite is included in the Pennsylvanian sequence.

Proceed northeast along Franklin Street.

5.3 At traffic light, turn left onto Plantation Street.

5.7 Plantation Street bridge over railroad. Pre-Pennsylvanian phyllite, coticule-bearing schist, and quartzite exposed in cuts along railroad east and west of bridge.

5.8 At traffic light, turn left onto Belmont Street (Route 9).

6.3 Outcrops of two-mica granite to right.

6.5 Turn right from Belmont Street onto Skyline Drive. Bus will park in lot of Belmont Home near this intersection.

STOP 2. Two-mica granite in road cuts along Belmont Street west of intersection with Skyline Drive.

This rock has been extensively quarried for building stone. In 1733, "the proprietors of the town [of Worcester]...voted that one hundred acres of the poorest land on Millstone Hill be left common for the use of the town for building stones" (Chase, 1879, p.564). By 1837, the quarry was 3 acres in size (Lincoln, 1837, p.355).

The two-mica granite underlying Millstone Hill (Figure 1) is generally a white to light-gray, medium-grained (0.1-7.0 mm) massive rock consisting of quartz, microcline-perthite, and albite, with accessory muscovite, biotite, chlorite, garnet, epidote, carbonate, apatite, and fluorite.

Features to note in these road cuts are blue-gray opalescent quartz, aplite veins, and cataclastic zones. The cataclastic rocks in these zones, here and elsewhere in the granite body, resemble quartzite and phyllite. One of the "phyllite inclusions" described by Perry and Emerson (1903, p.58-59), which was still accessible in 1967, is actually a cataclastic rock derived from the granite.

Emerson (1917) mapped the two-mica granite as Ayer granite. It differs from typical Ayer, which we will examine at Stop 4, by its lack of feldspar megacrysts and by the presence of widespread accessory fluorite. The two-mica granite at Stop 2 may in fact be younger than the Ayer. Zartman (written communication, 1976) has obtained a Rb-Sr isochron age of 380 ± 15 m.y. on the two-mica granite of Millstone Hill and a U-Th-Pb age of 425 ± 10 m.y. on porphyritic Ayer.

From parking lot, exit onto Skyline Drive and turn left immediately on Belmont Street. Return along Belmont Street back to Plantation Street.

7.2 Turn left at traffic light onto Plantation Street.

7.7 Small outcrops of pre-Pennsylvanian quartz-mica schist along Plantation Street. Millstone Hill to left; to right (east) is Wigwam Hill, which is underlain largely by pre-Pennsylvanian coticule-bearing rocks. Wigwam Hill was the site of a Nipmuc (Algonquian) camp near the fishing waters of Lake Quinsigamond and the plumbago deposit of the coal mine.

8.2 Turn left at entrance to Notre Dame Institute, which can be recognized by stone pillars supporting a large sign over driveway, "Sisters of Notre Dame de Namur."

8.45 Parking lot of Notre Dame Institute. Comfort facilities are available in the basement of the hospital.

STOP 3. Area of the Worcester Coal Mine.

Proceed southeast on foot, crossing Coal Mine Brook on footbridge and following edge of field for 500 feet. Turn right at wooded rise in field and proceed 300 feet west-southwest through woods up hill to coal mine. (Lunch here, weather permitting.)

Meta-anthracite, slate, and phyllite of Pennsylvanian age are exposed only in the small gully near the coal mine (see text). These exposures are bounded to the northwest by calc-silicate rocks and biotite schist [part of Emerson's (1917) Oakdale quartzite], to the south by two-mica granite, and to the east by surficial deposits. The contacts of the Pennsylvanian rocks with the surrounding rocks are not exposed.

Calc-silicate rocks and purplish-gray to gray biotite schist crop out on the hill and along a brook northwest of the coal mine (Figure 3). The calc-silicate rocks are typically green-gray and consist mostly of quartz, plagioclase, K-feldspar, biotite, calcic amphibole, and iron-poor epidote. Diopside has been found in similar rocks elsewhere in the Worcester area.

Return along driveway of Notre Dame Institute to entrance at Plantation Street.

8.7 Turn left and proceed north on Plantation Street.

9.3 At light, turn right onto Lincoln Street.

9.5 Shrewsbury-Worcester Town Line. Proceed east along West Main Street, Shrewsbury, which is the continuation of Lincoln Street, Worcester.

9.7 North end of Lake Quinsigamond. Quinsigamond is an Algonquian name (Rice, 1893, p.87) meaning fishing place for pickerel (a pike). Quaternary deposits and the present lake fill a deep Tertiary river valley (Alden, 1925, fig.3). In drill holes under the bridge for Interstate 290 over the lake, bedrock was reached at depths as much as 181 feet below the present surface of the lake, that is, 77 feet above sea level.

10.0 Proceed under overpass in left lane and take Interstate 290 east towards Marlboro. In entrance ramp are cuts in the pre-Pennsylvanian Nashoba formation. The Nashoba formation in this area consists largely of biotite gneiss with subordinate migmatitic gneiss and augen gneiss.

11.7-13.3 Road cuts of Nashoba Formation.

19.8 Interstate 290 ends. Take Interstate 495 north towards Lowell.

29.7 Exit 16 for Route 111, Harvard and Boxborough. Go right on Route 111 toward Harvard.

30.2 Road cuts of Nashoba formation (Hansen, 1956).

32.5 Bear right on Route 111, proceed along it into Harvard.

32.8 At traffic light, continue straight on Route 111.

33.2 Turn left on Harvard Depot Road (marked by sign for Tensitron). Pin Hill, directly ahead, is the site of numerous small quarries. Whitney (1793, p.156) reported that slate at Pin Hill was quarried for tombstones, door jambs, and hearthstones.

33.4 Crest of Pin Hill is Harvard conglomerate, which we will examine.

33.6 Intersection of Harvard Depot Road with Mill Road. Visible up Mill Road to the right is a brick mill house about 300 years old. Bus will turn left into Sanitary Landfill dump and park.

STOP 4. Ayer granite and Harvard conglomerate.

Proceed on foot to outcrop of Ayer granite at corner of Mill Road and Harvard Depot Road. The porphyritic Ayer granite in this outcrop (see also Thompson and Robinson, this guidebook) consists of microcline, saussuritized plagioclase (An 10), and quartz, with accessory biotite, chlorite, muscovite, clinozoisite, apatite, and zircon, The feldspar and quartz are cut by microveinlets of quartz.

Zartman (written communication, 1976) has obtained Pb-Pb ages on zircon of 422 and 432 m.y. on a sample collected about 4 miles north of here in the same body of Ayer as this outcrop.

Proceed east along Harvard Depot Road to Pin Hill. We will examine the outcrops along the road (WATCH FOR TRAFFIC) and the unconformity in the woods to the north. A detailed description of the Harvard conglomerate and of the unconformity at Pin Hill, including a fine sketch of the unconformity by Peter Robinson, is contained elsewhere in this guidebook (Thompson and Robinson, fig. 1). NO HAMMERS ON THE OUTCROP OF THE UNCONFORMITY, PLEASE!

Return on foot to bus. For the return to Boston, bus will retrace route along Harvard Depot Road back to Route 111.

34.0 Turn left and head north on Route 111.

35.1 Route 2. Head east for Boston. End of road log.

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