STRATIGRAPHY OF THE PENNSYLVANIAN
AND PRE-PENNSYLVANIAN ROCKS OF
THE WORCESTER AREA, MASSACHUSETTS*

EDWARD S. GREW**

ABSTRACT. Pennsylvanian and pre-Pennsylvanian metasedimentary rocks of the Worcester area can be divided into seven map units. These rocks range in metamorphic grade from the chlorite zone to the sillimanite-K-feldspar zone. Five of these units form a north- to northeast-trending, west-dipping sequence about 5000 m thick which apparently tops to the west. The most abundant rock types in these five units are biotite gneiss, mica schist, phyllite, calc-silicate granulite, calcareous and ankeritic granulite, schistose granulite, and quartzite. The five units are pre-Pennsylvanian in age; the two youngest have been tentatively correlated with fossiliferous Silurian and Devonian formations in Maine and New Hampshire. The sixth and seventh units crop out in lenses along a fault. The sixth unit is conglomerate, arkose, and phyllite. The seventh unit is slate and phyllite which contain a lens of impure meta-anthracite. Pennsylvanian plant fossils were recovered from the seventh unit. Field relations, regional considerations, and radiometric ages on granitic rocks suggest that the sixth unit is also Pennsylvanian in age. Intrusion of granitic rocks and a period of uplift and erosion followed the deposition of the five older units and preceded the deposition of the Pennsylvanian units.

INTRODUCTION

Fossil plants of Pennsylvanian age have been recovered from an abandoned coal mine in Worcester, Mass. (Perry, 1885; Kemp, 1887; White, 1912; and Grew, Maman, and Barghoorn, 1970) (figs. 1, 4). As this is the only known fossil locality in east-central Massachusetts, the structural and stratigraphic relations of the fossiliferous rocks to the other rocks of the area are critical to understanding the stratigraphy of this area as a whole. Earlier workers, in particular, Perry and Emerson (1903) and Emerson (1917), believed that the fossiliferous and nonfossiliferous rocks belonged to a conformable stratigraphic sequence of Carboniferous age. Paleontological studies and mapping done in Maine and New Hampshire after the publication of Emerson's (1917) state map of Massachusetts suggested, however, that the rocks to which Emerson had assigned a Carboniferous age are on strike with Devonian and older rocks.

Field relations and radiometric ages in the Worcester and neighboring areas suggest that the fossiliferous rocks and most of the nonfossiliferous rocks are not part of the same conformable stratigraphic sequence (fig. 2). The Pennsylvanian units, which include the fossiliferous rocks and a few lenses of conglomerate, unconformably overlie older rocks and are apparently very limited in areal extent.

STRATIGRAPHY AND LITHOLOGY

General statement.—The metamorphosed sedimentary rocks, which range in grade from the chlorite zone to the sillimanite-K-feldspar zone (fig. 3), are divided into seven map units (fig. 2; table 1). Five of these,

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units A (oldest) through E (youngest), form a conformable sequence that generally strikes north to northeast and dips gently to steeply west. The total thickness of the five units in the Worcester area is about 5000 m. The proposed correlation of units D and E with the Merrimack Group and the Littleton Formation (table 3) suggests that the sequence tops west, that is, is right-side-up. In the Worcester area, primary sedimentary structures indicate topping directions both in agreement and in disagreement with the sequence being right-side-up. Graded beds were observed at three localities in unit E along Wachusett Reservoir and at four localities in unit B near the fault between units B and D south and east of the center of Worcester (fig. 2). None of these localities are near a sedimentary contact between units. The graded beds in unit E indicate that the syncline near point A' in section AA'' (fig. 2) is right-side-up, consistent with the suggested regional topping direction. At three of the four localities in unit B, however, they indicate that the sequence tops east. In outcrop, the graded beds appear to be more highly deformed in unit B than in unit E. This raises the possibility that the inversions in unit B might be related to the fault between units B and D. Rocks of units F and G (unit G contains the Pennsylvanian plant fossils) are not part of the conformable sequence. They crop out in lenses along the faults between units B and D.

Pre-Pennsylvanian rocks of the Worcester area, Massachusetts

Unit A.—Rocks of unit A, which essentially consists of Emerson’s (1917) gneisses and schists of undetermined age, crop out in the southern and eastern part of the map-area (fig. 2), from Auburn to Shrewsbury and Boylston. The bottom of the unit is not exposed in the Worcester area.

Unit A is entirely within the sillimanite and sillimanite-K-feldspar zones (compare figs. 2 and 3). The rocks are mostly gray biotite gneiss composed primarily of oligoclase, quartz, biotite, and subordinate muscovite. Almandine, K-feldspar, and sillimanite are commonly present in small amounts. The feldspar in some of the gneiss forms megacrysts 2 to 5 mm across or aggregates of megacrysts. The biotite gneiss in Shrewsbury and Boylston commonly consists of alternating feldspar-rich layers averaging a few centimeters in thickness and biotite-rich laminae.

### Table 1

<table>
<thead>
<tr>
<th>Age</th>
<th>Columnar section</th>
<th>Approximate thickness (in meters)*</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pennsylvanian</td>
<td></td>
<td></td>
<td>Carbonaceous slate and phyllite with a lens of impure meta-anthracite.</td>
</tr>
<tr>
<td>(sequence of units uncertain)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPg</td>
<td></td>
<td>50+</td>
<td></td>
</tr>
<tr>
<td>IPf</td>
<td></td>
<td>330+</td>
<td>Conglomerate, arkose, and phyllite.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>UNCONFORMITY</strong></td>
</tr>
<tr>
<td>Devonian (?)</td>
<td>Dc, Dem</td>
<td>1000+</td>
<td>Slate, phyllite, mica schist, schistose granulite, and subordinate lenses of calc-silicate granulite, biotite granulite, quartz-feldspar granulite, and quartzite. Dem, two lenses consisting of alternating layers of marble and mica schist.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silurian (?) and Devonian (?)</td>
<td>Dsd, Dsdp</td>
<td>1600+</td>
<td>Calcareous or ankeritic phyllite and granulite; biotite schist, biotite granulite, calc-silicate granulite, and subordinate lenses of carbonaceous or sulfidic phyllite or mica schist. Dsdp, carbonaceous or sulfidic phyllite or mica schist.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silurian (?) or older</td>
<td>Sc</td>
<td>0-130</td>
<td>Quartzite and subordinate lenses of sericite schist or carbonaceous phyllite, interspersed and at the top.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sb, Sbl</td>
<td>1000+</td>
<td>Phyllite, mica schist, and subordinate lenses of quartzite and coticule-bearing phyllite and mica schist. Sbl, biotite schist, biotite granulite, and calc-silicate granulite.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sa</td>
<td>1000+</td>
<td>Biotite gneiss and subordinate lenses of biotite granulite, calc-silicate granulite, marble, or amphibolite.</td>
</tr>
</tbody>
</table>

* Plus sign indicates that part of the unit is missing, either because of faulting or because the top or bottom of the unit is not exposed in the Worcester area.
Fig. 2. Geologic map and sections of the Worcester area, Mass.
Pre-Pennsylvanian rocks of the Worcester area, Massachusetts
Throughout unit A, gneiss with a poorly defined mica schistosity and lacking the feldspar megacrysts forms layers a few centimeters to 2 m thick in gneiss with a well-defined schistosity or in gneiss with the layering described above. Locally, layers as much as 1 cm thick of sillimanite (mostly altered to sericite) and magnetite are abundant in the biotite gneiss. Biotite granulite, calc-silicate granulite, and marble, in lenses a few centimeters to 1 m thick, alternate with the biotite gneiss throughout unit A. In Shrewsbury, amphibolite forms lenses as much as 3 m thick and as much as several hundred meters long. The granulite, marble, and amphibolite constitute only a fraction of 1 percent of the exposed rock of unit A. Pods of pegmatite are abundant in the unit.

Unit B.—Rocks of unit B, which is part of Emerson's (1917) Worcester Phyllite, Boylston Schist, and Oxford Schist, crop out in a narrow belt that extends from Auburn north-northeast to Boylston (fig. 2). An unknown amount of unit B is missing along the fault extending from Auburn to Boylston.

Fig. 3. Sketch map of the Worcester area showing metamorphic zones and faults.
This unit lies within all the metamorphic zones represented here, except the chlorite and sillimanite–K-feldspar zones (fig. 3). The most abundant rocks in unit B are gray phyllite and mica schist, consisting mostly of quartz and muscovite, with lesser amounts of chlorite, oligoclase-andesine, biotite, almandine, chloritoid, staurolite, andalusite, or sillimanite in appropriate metamorphic zones. The phyllite and mica schist are commonly carbonaceous, in places, sulfidic. Cyclical beds, pairs of which range in thickness from a few millimeters to 10 cm, occur in Worcester just east of the fault between units B and D. Some of the beds are graded. Quartzite, coticule-bearing phyllite and mica schist (commonly mapped by Emerson as Oakdale Quartzite), and a mappable
subunit consisting of alternating layers of biotite schist, biotite granulite, and calc-silicate granulite (calc-silicate subunit in fig. 2) occur in lenses throughout unit B. The lenses of quartzite range in thickness from a few centimeters to as much as 25 m, whereas those of the coticule-bearing rocks and of the calc-silicate subunit are as much as 500 m thick. The exposed rock of this unit consists roughly of 70 percent phyllite and mica schist, 20 percent calc-silicate subunit, 5 percent coticule-bearing rocks, a few percent sulfidic phyllite and mica schist, and less than 1 percent quartzite.

Unit C.—Rocks of unit C, which is part of Emerson's (1917) Oakdale Quartzite, crop out in two lenticles, one in Boylston, the other mostly in West Boylston. Unit C is within the biotite and garnet zones. The rocks consist mostly of white to gray quartzite, with lenses of sericite schist and gray carbonaceous phyllite as much as 5 m thick. The quartzite, which generally lacks well-developed bedding, is resistant to weathering and is well-exposed. Almandine and chloritoid occur in the phyllite and schist. At the top of unit C is a gray carbonaceous phyllite in lenses as much as 65 m thick.

Unit D.—Rocks of unit D crop out in two belts, one of which is confined to Boylston, whereas the second extends across the length of the map area from Auburn to West Boylston (fig. 2). This unit is roughly equivalent to Emerson's (1917) Oakdale Quartzite and Paxton Quartz Schist but includes some of his Brimfield Schist and Worcester Phyllite. An unknown amount of this unit is missing along faults.

The unit lies within all the metamorphic zones represented in the Worcester area except the sillimanite-K-feldspar zone. In the chlorite and biotite zones, the rocks are generally green-gray or purple-gray phyllite, schist, or granulite consisting mostly of chlorite, biotite, quartz, plagioclase (generally albite), ankerite, or calcite. The phyllite, schist, and granulite locally alternate in layers 1 to 10 cm thick. In the actinolite, garnet, and sillimanite zones, it is a purple-gray to gray biotite schist or biotite granulite, or green-gray to gray calc-silicate granulite. Quartz, plagioclase (mostly andesine), biotite, calcic amphibole, and iron-poor epidote are the most abundant minerals in the schist and granulite; microcline and diopside are less abundant. The schist and granulite alternate in layers ranging in thickness from 1 mm to 1 m. The biotite schist and granulite are commonly finely layered, the layers ranging in thickness from a fraction of a millimeter to 1 cm. Phyllite, mica schist, and granulite that lack carbonate or calc-silicate minerals (phyllite and mica schist subunit on fig. 2) occur throughout unit D in lenses a few centimeters to 80 m thick. These rocks are commonly carbonaceous or sulfidic and locally have almandine, chloritoid, or sillimanite. They constitute about 5 percent of the exposed rock of unit D.

Unit E.—Rocks of Unit E, which is part of Emerson's (1917) Worcester Phyllite, Boylston Schist, and Brimfield Schist, crop out in two belts; one in Boylston and West Boylston, the second in Holden,
Worcester, and West Boylston. The top of unit E is not exposed in the Worcester area.

This unit lies within all the metamorphic zones represented in the Worcester area, except the sillimanite-K-feldspar zone. The rocks are mostly gray slate, phyllite, mica schist, and schistose granulite. Quartz, muscovite, and biotite are the most abundant minerals in these rocks; chlorite, albite-oligoclase, almandine, staurolite, andalusite, sillimanite, or amphibole occur in appropriate metamorphic zones. The mica schist and schistose granulite commonly alternate in layers a few millimeters to a few centimeters thick. Subordinate lenses of quartz-feldspar granulite, quartzite, biotite granulite, and calc-silicate granulite generally range in thickness from a few centimeters to as much as 2 m. Some beds in the phyllite and some lenses of the quartz-feldspar granulite are graded. Two lenses (Dem in fig. 2), consisting of alternating layers of marble and mica schist, occur about 200 m above the base of unit E. The marble layers range in thickness from 0.3 to 1.3 m, whereas those of the mica schist are 1.7 m or more thick. These two lenses reach a maximum thickness of 80 m. The biotite granulite and the calc-silicate granulite probably constitute a few percent of the exposed rock of unit E, the other rock types, less than 1 percent, and the slate, phyllite, mica schist, and schistose granulite, the remainder. North and west of the sillimanite isograd, pegmatite masses are locally very abundant in unit E. The pegmatite-rich rock was generally mapped by Emerson (1917) as Fitchburg Granite.

Unit E is distinguished from unit B, which consists largely of the same lithologic types, by the presence of marble and absence of coticule. These differences and the absence of quartzite similar to unit C along the contact between units D and E would suggest that units E and B are not equivalent.

Unit F.—Rocks of unit F crop out in two lenses along the fault between units B and D in Worcester. Both lenses are in the garnet zone. The rocks are dark-gray conglomerate (the metamorphic breccia of Perry and Emerson, 1908, p. 41), polymict conglomerate, arkose, and phyllite. The dark-gray conglomerate is massive with pebbles as much as 13 cm long. Most pebbles are quartz–andesine–mica schist and granulite; a few are vein quartz. The polymict conglomerate, arkose, and phyllite alternate in layers 2 mm to 2 m thick. In the larger of the two lenses, the polymict conglomerate appears to be limited to the eastern part of the lens. The pebbles in the polymict conglomerate, in order of decreasing abundance, are phyllite, quartzite and granite, and vein quartz. The pebbles are tabular to subequant and attain a length of 13 cm. They are embedded in a matrix with abundant detrital grains of quartz and feldspar as much as 2 mm across. The arkose is white and massive. The phyllite is gray to black, carbonaceous, and locally has almandine. Phyllite constitutes about half of unit F.
Unit G.—Rocks of unit G, supposedly the type Worcester Phyllite of Emerson (1917), crop out in a single lens along the fault between units B and D in Worcester (fig. 4). Unit G is in the garnet zone. The rocks are gray to black slate and phyllite and contain a lens of impure meta-anthracite. Fossil plants were recovered from the meta-anthracite, the lithology of which has been described in detail elsewhere (Perry and Emerson, 1908, p. 14-19; Grew, Mamay, and Barghoorn, 1970, p. 115-120). The slate and phyllite consist mostly of carbonaceous material, ilmenite, quartz, muscovite, chlorite, or almandine. Some of these rocks are sulfidic. Quartz-rich rock and rock rich in carbonaceous material alternate in layers 1 mm to 3 cm thick. Some of these layers are graded. In places, phyllitic quartz-feldspar granulite forms lenses as much as 0.2 m thick and 1 m long in the phyllite.

Aeromagnetic pattern.—The dominant aeromagnetic pattern of unit A (U.S. Geol. Survey, 1968, 1969a, b) consists of numerous highs and lows with very steep gradients. The highs and lows are elongated parallel to the lithologic contacts. In contrast, the pattern of unit B has few steep gradients and little relief, and those of units D and E lack any significant relief.

Protolith and environment of deposition.—The protoliths of the metasedimentary rocks (table 2) have been inferred mainly from the bulk composition of the rocks and, in a few cases, from relic sedimentary structures. The mineralogy of the rocks gives a rough idea of the bulk composition of the sediment from which they were derived.

Calcareous sediments in the pre-Pennsylvanian units suggest that the rocks are marine. Their great thickness and dominantly clastic character imply that they were deposited in a geosyncline. The coal and plant

Fig. 4. Map showing outcrops in the area around the Pennsylvanian fossil plant locality in Worcester.
fossils in unit G imply that this unit is nonmarine. Unit F may also be nonmarine. The arkose and polymict conglomerate suggest that unit F had a local source area that had considerable relief.

Age and correlation.—Units A through E are not fossiliferous in the Worcester area. An age assignment to these units must thus be based on field relations and on regional correlations (fig. 5; table 3). Radiometric ages are available on a few of the igneous rocks in the Worcester and neighboring areas.

Units A through C cannot be traced along strike into any fossiliferous rocks. An age assignment of these units is thereby somewhat speculative. These three units underlie unit D, which is probably Silurian, and thus must be Silurian or older.

Unit D can be correlated with the Merrimack Group (Billings, 1956, p. 43) of southeastern New Hampshire and southern Maine (Emerson, 1917; Katz, 1917; Billings, 1956; Sriramadas, 1966). The correlation is based on the continuity of unit D with the Merrimack (fig. 5) and on lithologic similarity. The Merrimack Group has been tentatively correlated with a sequence of three formations exposed near Waterville, Maine (Freedman, 1950; Billings, 1956). Two of these formations have Silurian fossils, whereas the youngest is nonfossiliferous and could be either Silurian or Devonian in age (Osberg, 1968). Unit D is thus probably Silurian in age but possibly could also be in part Devonian.

Table 2
Protolith and environment of deposition of the metasedimentary rocks of the Worcester area

<table>
<thead>
<tr>
<th>Unit</th>
<th>Protolith</th>
<th>Environment of deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Carbonaceous shale and siltstone, a lens of coal, and subordinate lenses of argillaceous sandstone.</td>
<td>Nonmarine; coarse clastic rocks; probably had local source of high relief</td>
</tr>
<tr>
<td>F</td>
<td>Conglomerate, arkose, and shale.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>UNCONFORMITY</strong></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Shale, siltstone, sandstone, and subordinate lenses of calcareous or dolomitic siltstone or sandstone. Layers of argillaceous limestone near bottom.</td>
<td>Marine</td>
</tr>
<tr>
<td>D</td>
<td>Calcareous or dolomitic siltstone or sandstone and subordinate lenses of carbonaceous or sulfidic shale.</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Quartz sandstone and subordinate lenses of shale, interspersed and at the top.</td>
<td>Geosyncline</td>
</tr>
<tr>
<td>B</td>
<td>Shale and siltstone, generally carbonaceous and in places sulfidic, and subordinate lenses of calcareous or dolomitic siltstone or sandstone, lenses of quartz sandstone, and lenses of shale or siltstone with layers of manganiferous chert or sandstone.</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Shale and sandstone and subordinate lenses of calcareous or dolomitic siltstone or sandstone, argillaceous limestone, and flows or sills of andesitic composition.</td>
<td></td>
</tr>
</tbody>
</table>
Correlation of unit E with units in southeastern New Hampshire is at best tentative at present, because of the lack of detailed mapping in Massachusetts and parts of southeastern New Hampshire. The belt of unit E that crops out in Boylston and West Boylston was traced by Emerson (1917) into New Hampshire, where Billings (1956) mapped it as a dark-gray phyllite in the Merrimack Group (fig. 5). The belt of unit E that crops out in Holden was traced, not quite continuously, by Emerson (1917) into New Hampshire, where Billings (1956) mapped it as the Littleton Formation (fig. 5). The type Littleton is Devonian in age (Billings, 1956). Thus, unit E could be either Silurian or Devonian in age; it is more likely Devonian.

Units B and C have been intruded by the porphyritic Ayer Granite. Lead-alpha ages on zircons from the Ayer are 420 ± 50, 520 ± 60, and 410 ± 50 m.y. (Zartman and others, 1965); a recently completed U–Th–Pb isotopic analysis gives an age of 435 ± 10 m.y. (Zartman, personal commun., 1971). On Millstone Hill in Worcester, unit D has been intruded

![Diagram](image)

*Sequence of units uncertain.

Fig. 5. Sketch map of the regional geology of east-central Massachusetts and southernmost New Hampshire.
by a nonporphyritic two-mica granite called Ayer by Emerson (1917) but probably unrelated to the type Ayer Granite. A rubidium-strontium total rock isochron age and a rubidium-strontium muscovite age from this body of granite are, respectively, $345 \pm 15$ and $360 \pm 10$ ($\lambda_r = 1.47 \times 10^{-11}$ yr$^{-1}$, Zartman and others, 1965). Unit E has been intruded by a foliated two-mica granite. This two-mica granite and the two-mica granite at Millstone Hill are probably closely related, as the mineralogy of these two rocks is similar. The granite at Millstone Hill, however, is believed to be somewhat younger, as it is generally massive, whereas the two-mica granite is generally foliated. The radiometric ages on the intrusive rocks would thus imply that units B and C were Ordovician or older and that units D and E were Devonian or older.
<table>
<thead>
<tr>
<th>Age</th>
<th>Units (this paper)</th>
<th>Emerson (1917) (rough equivalents)</th>
<th>Clinton quadrangle (Peck, 1971)</th>
<th>Hudson and Maynard quadrangles (Hansen, 1956)</th>
<th>Southeastern New Hampshire (Billings 1956; Sriramadas, 1966)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pennsylvanian (sequence of units uncertain)</td>
<td>G</td>
<td>Worcester Phyllite</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>—</td>
<td>—</td>
<td>Harvard Conglomerate Lentil of the Worcester Formation</td>
<td>—</td>
</tr>
<tr>
<td>Devonian (?)</td>
<td>E</td>
<td>Worcester Phyllite; Boylston Schist; Brimfield Schist</td>
<td>Units 3 and 4 of the first sequence</td>
<td>—</td>
<td>Littleton Formation</td>
</tr>
<tr>
<td>Silurian (?) and Devonian (?)</td>
<td>D</td>
<td>Oakdale Quartzite; Paxton Quartz Schist</td>
<td>Entire second sequence and Unit 2 of the first sequence</td>
<td>Phyllitic facies of the Worcester Formation</td>
<td>Merrimack Group</td>
</tr>
<tr>
<td>Silurian (?) or older</td>
<td>C</td>
<td>Oakdale Quartzite</td>
<td>Unit 1 of the first sequence</td>
<td>Vaughn Hills Member of the Worcester Formation (in part)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Worcester Phyllite; Boylston Schist; Oxford Schist</td>
<td>—</td>
<td>Mica schist facies of the Worcester Formation</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Gneisses and schists of undetermined age.</td>
<td>—</td>
<td>Nashoba Formation</td>
<td>—</td>
</tr>
</tbody>
</table>
Unit G is Pennsylvanian in age on the basis of plant fossils (White, 1912; Grew, Mamay, and Barghoorn, 1970).

Unit F is not fossiliferous. Field relations, radiometric ages, and regional considerations suggest a Pennsylvanian age for unit F. Unit F contains pebbles of granite that may have been derived from the granite at Millstone Hill. This particular body of granite is a likely source as it crops out within 460 m of some of the conglomerate of unit F (fig. 2). The quartz in this particular body of granite, moreover, unlike that in any of the other igneous rocks in the Worcester area, has a blue-gray opalescence. This opalescence is characteristic of the quartz in the detrital grains and in the granite pebbles in unit F. As the radiometric age of this granite is about 350 m.y. or Devonian, unit F is Devonian or younger. Unit F is probably no younger than the Pennsylvanian, as no metamorphosed post-Pennsylvanian, pre-Triassic (oldest nonmetamorphosed rocks) rocks are known in southern New England. Unit F, moreover, crops out within 2300 m of unit G, and unit G lies on strike with it. This relation would suggest that unit F may belong to the same stratigraphic sequence as unit G and thus be Pennsylvanian in age.

The Harvard Conglomerate Lentil of the Worcester (Emerson, 1917; Hansen, 1965), which crops out in Harvard and Bolton, Mass., is an unfossiliferous unit which may be related to unit F. The Harvard unconformably overlies the porphyritic Ayer Granite as may be clearly seen in a single outcrop on Pin Hill, Harvard (Ayer quadrangle, Peter Robinson, oral commun.; outcrop visited by writer). The Harvard, as it crops out in the biotite zone, has been metamorphosed. These field relations, which are analogous to those of unit F, suggest that the Harvard may be Pennsylvanian in age.

**AGE OF METAMORPHISM**

The Pennsylvanian rocks, and some of the pre-Pennsylvanian rocks, were metamorphosed sometime during or after the Pennsylvanian but before the Triassic. The pre-Pennsylvanian rocks were probably also metamorphosed during the Devonian, at the time of intrusion of the two-mica granite. This relation is suggested by the greater abundance of this granite in the sillimanite zone (fig. 3). The areal extent of the Pennsylvanian or younger metamorphism is difficult to determine, for there is no metamorphic discontinuity between the Pennsylvanian and pre-Pennsylvanian rocks, and conclusive evidence for polymetamorphism is lacking. The Pennsylvanian or younger metamorphism may have affected only a narrow zone near the Pennsylvanian rocks. It probably was not of sufficient intensity to produce sillimanite in the Worcester area.

**UNCONFORMITY BELOW THE PENNSYLVANIAN UNITS**

An unconformity below units F and G is indicated by the difference in age of the rocks and by the conglomerate in unit F. Unit G is Pennsylvanian in age, whereas the granitic rocks in the Worcester area appear
to be Devonian or older in age. The granite at Millstone Hill is probably the youngest of the granitic rocks. Unit F, which contains pebbles probably from the granite, would also be younger than all the granitic rocks. The conglomerate in unit F, moreover, implies that a period of uplift and erosion followed the intrusion of the granitic rocks and preceded the deposition of unit F. The period of uplift and erosion probably also preceded the deposition of unit G. As unit E is intruded by granitic rocks, it must have been deposited before the period of uplift and erosion.

The proposed unconformity below the Pennsylvanian rocks is a solution to the controversy over the ages of the metasedimentary rocks of east-central Massachusetts. Perry's and Emerson's interpretation of the field relations implied that a thick, extensive, and mostly marine sedimentary sequence of Pennsylvanian age lay on strike of similar rocks in Maine and New Hampshire, whose age has recently been established from fossils as Devonian and older. Perry's and Emerson's Pennsylvanian rocks, moreover, are different in lithology and inferred environment of deposition from other Carboniferous rocks of New England. Given that the Pennsylvanian rocks shown on figures 2 and 5 unconformably overlie the other rocks in this area, there is no longer any fossil evidence against extending the Devonian and older geosynclinal sequence of southeastern New Hampshire and southwestern Maine into Massachusetts and Connecticut. The inferred non-marine environment of deposition of the Pennsylvanian rocks, moreover, is in accord with that of most of the Carboniferous basins in New England.

Tectonic Significance of the Pennsylvanian Rocks

The metamorphism and deformation of the Pennsylvanian rocks in east-central Massachusetts testify to the importance of late Paleozoic tectonic activity in this area. The metamorphism implies that the Pennsylvanian rocks had been deeply buried, suggesting that a much thicker, and presumably more extensive, sedimentary sequence had been deposited during the Pennsylvanian. The lenses of Pennsylvanian rocks presently exposed may in fact be erosional remnants of a larger basin at least 33 km (21 miles) long, extending from Worcester to Harvard. Parts of east-central Massachusetts must thus have undergone significant subsidence and subsequent uplift and erosion during the Late Paleozoic. Students of New England geology have generally thought that such tectonic activity was restricted to the Carboniferous basins of Rhode Island and eastern Massachusetts. The association of metamorphism with folding in the Pennsylvanian rocks implies, moreover, that the Pennsylvanian or younger metamorphism was not due merely to load, as proposed by Zartman and others (1970, p. 3369), but was dynamic. This dynamic metamorphism may be responsible for some of the Permian K–Ar dates that Zartman and others (1970) believed were due to burial followed by uplift and erosion.
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