THE BELCHERTOWN QUARTZ MONZODIORITE PLUTON, WEST-CENTRAL MASSACHUSETTS: A SYNTECTONIC ACADIAN INTRUSION

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ABSTRACT. The Belchertown Quartz Monzodiorite pluton in west-central Massachusetts has a roughly circular surface area of 120 km². It intrudes lower to middle Paleozoic mantling strata among three gneiss domes of the Bronson Hill anticlinorium. The local Paleozoic stratigraphic sequence, overlying basement gneisses of uncertain ages, includes the Ammonoosucian Volcanics and Partridge Formation (both Middle Ordovician) and the Erving Formation (Lower Devonian). On its south and east sides, where it abuts the Glastonbury and Monson gneiss domes, the Belchertown pluton is quasi-concordant, and its basal contact is close to or within the Partridge Formation. On the north side, the pluton cuts irregularly across a series of early Acadian recumbent folds involving both Paleozoic mantling strata and dome gneisses, and a sill-like apophysis intrudes gneiss of the Pelham dome.

The pluton has a small inner zone containing essentially unmetamorphosed hypersthene-augite quartzo monzodiorite. The primary oxide assemblage of titanohematite-magnetite and the magnesian composition of coexisting silicates suggest that the magma attained a very high oxygen fugacity, probably by devolatilization related to surface eruption. The shallow level of intrusion implied is consistent with a large inclusion of hornfelsed dacite porphyry and with sillimanite pseudomorphs after andalusite in pelitic inclusions. The composition of augite coexisting with hypersthene and the presence of the primary silicate assemblage augite-hypersthene-potassic feldspar-plagioclase quartzo suggest that initially the magma crystallized at 950° to 900°C and had a very low H₂O fugacity. Poikilitic biotite and hornblende appear to have crystallized from small pockets of more H₂O-enriched interstitial liquids at temperatures as low as 650°C.

Outward from the unmetamorphosed quartz monzodiorite, the rocks of the pluton grade to pyroxene-free hornblende-biotite-epidote gneiss that has foliation and lineation parallel to that in adjacent metamorphic country rock. Mineral transformations and bulk-rock analyses of the pluton indicate that mineralogical changes from primary two-pyroxene quartz monzodiorite through transitional augite-hornblende rocks to fully recrystallized gneiss were essentially isochemical except for water and reflect progressive hydration accompanying late Acadian kyanite-grade regional metamorphism. Detailed structural studies show that metamorphic hydration and recrystallization to gneiss was facilitated by influx of H₂O along cataclastic shear zones in already solid quartz monzodiorite.

Gravity and aeromagnetic models suggest a relatively thin (~1 km) disc-shaped mass having a deeper root in the southeast part; the mass may be a funnel-shaped intrusion or the eroded remnant of a once more extensive subhorizontal sheet preserved by gravitationally influenced downfolding among gneiss domes. A U-Th-Pb zircon age determination on the primary quartz monzodiorite of 380 ± 5 m.y. is in excellent agreement with radiometric ages of other plutons in the region that cut across early fold structures but that were themselves deformed and metamorphosed in later stages of the Acadian orogeny. K-Ar determinations on hornblende from the gneiss indicate that metamorphic hydration is at least as old as 361 ± 6 m.y.

INTRODUCTION

The Belchertown Quartz Monzodiorite¹ is a semi-concordant syntectonic Devonian pluton which was emplaced into the gneiss dome terrain

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¹ The term "Belchertown Quartz Monzodiorite" is the formal name adopted for this intrusion by the U.S. Geological Survey on the basis of its dominant composition (Leo, Robinson, and Hall, 1977).
of the Bronson Hill anticlinorium in west-central Massachusetts (fig. 1; Guthrie and Robinson, 1967; Peper, 1967; Thompson and others, 1968; Guthrie, 1972; Hall, ms: Leo, Robinson, and Hall, 1977). The Belchertown pluton, termed "Belchertown batholith" by Guthrie and Robinson (1967), Guthrie (1972), Hall (ms), Ashwal (1974), and Leo, Robinson, and Hall (1977), is the largest unit of the "Belchertown intrusive complex" as used by Guthrie (1972) that also includes early intrusions of hornblende, two subsidiary biotite quartz diorite stocks northeast of the Belchertown pluton (Spear, 1971; Guthrie, 1972), and aplite and pegmatite dikes in surrounding rocks, as well as the Hatfield pluton (Stoek, 1971) west of the Connecticut Valley. Investigations of the Belchertown pluton conducted since 1964 have led to a fairly detailed and coherent understanding of its emplacement, crystallization, and subsequent metamorphic history. The present paper seeks to synthesize the available mineralogical, petrological, geophysical, and geochronological data relating to the pluton as a whole.

COUNTRY ROCKS

The Bronson Hill anticlinorium, into which the Belchertown pluton (fig. 1) is intruded, consists of a series of en echelon gneiss domes and elongate anticlines that extends from northern New Hampshire to Long Island Sound. The stratigraphic sequence of the Bronson Hill anticlinorium, ranging in age from late Precambrian to Early Devonian, has been described in detail by Billings (1937, 1956), Robinson (1967a, b), and Thompson and others (1968). A Late Precambrian age on the core of the Pelham dome was determined by Naylor and others (1973). Details of the lithology and structure at the south end of the Belchertown pluton were described by Leo, Robinson, and Hall (1977). Rocks near the north end were described by Guthrie and Robinson (1967), Guthrie (1972), and Robinson and others (1973). Country rocks to the northeast of the pluton were described by Halpin (ms) and Robinson (1967a, b), and those to the east by Peper (ms and 1967). The interested reader is referred to these sources, and only a brief summary of the stratigraphy in the vicinity of the Belchertown pluton is given here.

The stratigraphic sequence in the vicinity of the Belchertown pluton belongs to four major divisions: (1) gneisses and related rocks in cores of domes, (2) a sequence of metamorphosed Middle Ordovician volcanic and sedimentary rocks, (3) a sequence of metamorphosed Silurian and Lower Devonian sedimentary and volcanic rocks unconformably overlying Middle Ordovician and older rocks, and (4) Lower Jurassic and Upper Triassic clastic sedimentary rocks and basalts west of the Connecticut Valley border fault.

Gneisses and Related Rocks in Cores of Domes

The oldest known rocks in the vicinity are the Dry Hill Gneiss and Poplar Mountain Gneiss and related rocks exposed (Ashenden, 1973) in the core of the Pelham gneiss dome (fig. 1). These are interpreted as metamorphosed felsic volcanic rocks, volcanogenic sedimentary rocks,
Fig. 1. Regional geological setting of the Belchertown pluton.
quartzose sandstones, calcareous sandstones, and shales. Zircons separated from a sample of Dry Hill Gneiss, interpreted as a felsic volcanic rock, yielded a nearly concordant U–Pb age of 565 ± 50^2 m.y. (Naylor and others, 1973) which is similar to ages of rocks known to be late Precambrian near New York City, in eastern Massachusetts, and in southeastern Newfoundland. Rocks lithically like these upper Precambrian rocks are rare elsewhere in the Bronson Hill antclinorium, but they are known in the Stony Creek dome (Sanders, 1968) of southern Connecticut (outside area of fig. 1), and they are abundant in the gneiss domes of southeastern Connecticut (Lundgren, 1966). Overlying the upper Precambrian rocks in the Pelham dome and underlying the Middle Ordovician rocks is a sequence of plagioclase gneisses and amphibolites (Fourmile Gneiss of Ashenden, 1973) of uncertain age. Some pelitic schists within the upper Precambrian section of the Pelham dome contain armored relics of garnet, sillimanite, and orthoclase indicating a pre-Devonian, possibly late Precambrian metamorphism of sillimanite–orthoclase grade (Robinson, Tracy, and Ashwal, 1975).

The rocks exposed in the main body of Monson Gneiss east of the Belchertown pluton are typically massively bedded plagioclase–quartz–biotite gneiss and subordinate interlayered hornblende–plagioclase amphibolite. Brookins and Metfort (1971) obtained an Rb–Sr whole-rock isochron age of 470 ± 15 m.y. from somewhat similar rocks from the Hadam dome of southern Connecticut. Several workers have suggested that the Monson Gneiss grades upward into the overlying Ammonoosuc Volcanics (Middle Ordovician), but Robinson (ns), on the basis of regional relations, suggested an unconformity at this contact and later (Robinson, 1977) located a lens of quartzite and quartz–pebble conglomerate at the base of the Ammonoosuc Volcanics on the west side of the main body of Monson Gneiss.

The rocks exposed in the core of the Glastonbury dome are of two more or less distinct types (Leo, 1977; Leo and Brookins, 1977). The northern part of the Glastonbury Gneiss (Massachusetts and northern Connecticut) is mostly trondhjemitic plagioclase–quartz–biotite–epidote gneiss of plutonic aspect, is compositionally similar to Monson Gneiss, and intrudes the Ammonoosuc Volcanics. The southern part of the Glastonbury Gneiss (central Connecticut) consists of granitic to granodioritic gneiss chemically distinct from Monson Gneiss. U–Pb zircon analyses on the northern and southern parts of the Glastonbury Gneiss support Taconic ages of 460 to 430 m.y. for both (R. E. Zartman, unpub. data). Field relationships, chemistry, and radiogenic ages as presently known suggest that the northern part of the Glastonbury Gneiss is a high-level intrusion associated with volcanic and volcaniclastic rocks (the protolith of the Monson Gneiss?). Possibly, the northern gneiss was produced by anatexis of such rocks soon after their eruption (and/or deposition) and burial.

All radiometric ages given in this paper have been converted to the decay constants recommended by the International Union Geol. Sciences Subcommission on Geochronology (Steiger and Jäger, 1977).
The southern part of the Glastonbury Gneiss appears to have been derived by approximately contemporaneous anatexis of calc-alkaline crust adjacent to the potassium-poor Monson sequence.

**Middle Ordovician Formations**

The Middle Ordovician rocks of the area include the Ammonoosuc Volcanics and the Partridge Formation. The Ammonoosuc Volcanics are a sequence of metamorphosed mafic and felsic volcanic rocks, predominantly volcaniclastic, including subordinate flows and sills and subordinate volcanogenic sedimentary rocks. The lower part of the section is dominated by amphibolites, predominantly containing hornblende, but also containing significant layers that bear cummingtonite, anthophyllite, gedrite, or cordierite, as well as secondary chlorite. The upper part of the section is felsic gneiss dominated by quartz, plagioclase, microcline, biotite, muscovite, and garnet. Overlying the Ammonoosuc Volcanics or in direct contact with Monson Gneiss or with the “Fourmile Gneiss” of Ashenden (1973) is the Partridge Formation, a variable unit of pyrrhotite–graphite–mica schist characteristically weathering “rusty” yellow brown, interbedded with amphibolite and gneiss similar to the Ammonoosuc Volcanics.

**Silurian and Lower Devonian Formations**

The Clough Quartzite (Silurian), a conspicuous marker unit of white orthoquartzite and quartz conglomerate, is nowhere observed in contact with the Belchertown pluton. It is, however, present as thin (3-6 m) layers or scattered quartzite blocks at the base of the Silurian and Devonian section southwest of the Belchertown pluton and is a major unit in the syncline southeast of the pluton. The Littleton formation (Lower Devonian) is also absent from the immediate vicinity of the pluton but is important above the Clough Quartzite in the syncline to the southeast.

In the immediate vicinity of the Belchertown pluton, the Silurian and Devonian are represented mainly by the Erving Formation (Lower Devonian) (Thompson and others, 1968) which directly overlies the Partridge Formation (Middle Ordovician) or, locally, the Clough Quartzite. The Erving Formation is dominated by quartz–plagioclase–biotite granulite grading to pelitic schist. It also contains local thin calc–sillicate beds and discontinuous layers of hornblende–epidote amphibolite reaching a maximum thickness of about 500 m near Quabbin Reservoir (fig. 2). The uppermost Lower Devonian unit is the Waits River Formation consisting of quartz–feldspathic mica schists and interbedded siliceous calcite marble and subordinate micaceous quartzite. The Waits River Formation is exposed only southwest of the Belchertown pluton near the Connecticut Valley border fault.

**Lower Jurassic and Upper Triassic Formations**

The Portland Formation (Lower Jurassic), the uppermost unit of the Connecticut Valley section west and southwest of the Belchertown pluton, is red-brown arkosic sandstone and interlayered pebble and cobble con-
Fig. 2. Geologic map of the Belchertown pluton and related rocks compiled from Guthrie (1972), Hall (ms), Leo, Robinson, and Hall (1977), and J. S. Beard and Peter Robinson (unpub. data, 1978).
glomerate containing a variety of crystalline clasts and local silty inter-beds. Bedding strikes northeast, and dips are low to moderate southeast. Some outcrops near the border fault contain boulders of Belchertown Quartz Monzodiorite as much as 50 cm in diameter. Rocks shown on the map of Guthrie (1972) northwest of the pluron would now be assigned (in ascending order) to the New Haven Arkose (Upper Triassic), the Holyoke Basalt, the East Berlin Formation (sandstone, conglomerate), the Granby Tuff (all Lower Jurassic), and the Portland Formation.

CONTACT RELATIONSHIPS OF THE PLUTON

Contacts of the pluron with adjacent rocks are of several distinct types. On its north margin, the pluron is, for the most part, discordantly intruded into rocks as young as the Erving Formation (Lower Devonian) and as old as the Fourmile Gneiss (Ashenden, 1973) of possible late Precambrian age in the Pelham dome (fig. 2). Here the intrusion cuts across axial surfaces of early Acadian recumbent folds, with northwest to southeast overfolding, that are intimately involved in the early deformational history of the Pelham dome. Extensive intrusive breccia is present along the northern contact. A concordant apophysis of Belchertown gneiss follows the foliation of the Pelham dome for several kilometers (fig. 2) (J. Beard, personal commun., 1977). To the east, the pluron is concordantly intruded into the Partridge Formation (Middle Ordovician) on the east limb of a syncline. To the south, it is nearly concordant at a stratigraphic level near the base of the Erving Formation, and to the west, the Connecticut Valley border fault separates rocks of the pluron from the East Berlin Formation, Granby Tuff, and Portland Formation (all Lower Jurassic) of the Connecticut Valley.

Except for the recently discovered apophysis, the complex northern contact of the pluron was described by Guthrie (1972). Numerous large inclusions varying from several hundred meters to more than 2 km in largest dimension can be correlated only partly with adjacent wall rocks (fig. 2). Extensive amphibolite inclusions cannot be readily correlated, nor can most fragments in intrusive breccia, which is described as amphibolite or hornblendite cemented by diorite and locally cut by pegmatite (Guthrie, 1972, p. 56-57). Inclusions of particular petrologic interest are described in more detail in a subsequent section.

The eastern and southern contacts of the pluron against layered Paleozoic rocks are sharp and essentially concordant and lack significant inclusions or intrusive breccia. These contacts are characterized by parallel attitudes of foliation and lineation in the Paleozoic rocks and the marginal gneiss of the Belchertown pluron, which becomes increasingly foliated and lineated toward the contacts. This is well shown in an abandoned railroad cut that crosses the steeply dipping eastern contact between the pluron and the Partridge Formation (Hall, ms, pl. 1). Exposed intrusive contacts with Paleozoic rocks to the south are mostly with amphibolite of the Erving Formation. Foliation in the plutonic and bedded rocks strikes generally parallel to the contact and dips moderately to
steeply north. These relationships between foliation and lineation in plutonic and country rocks prove that regional deformation and metamorphism during later stages of the Acadian orogeny affected the Belchertown pluton after, if not during, its emplacement.

The fault that marks the western limit of exposure of the pluton is a major structural feature having relative upward displacement of the east side of about 5000 m (Thompson and others, 1968, pl. 15-1a). Along the northwestern side of the pluton, the fault trace is conspicuously sinuous, possibly representing several, more or less straight, intersecting faults. The fault trace itself is topographically evident along most of its length. Locally it is marked by extensive silicified zones and/or sheared rocks of the pluton. The Hatfield pluton (fig. 1; Stoeck, 1971) of the "Belchertown complex," consisting of rocks very similar to the outer and transitional zones of the Belchertown pluton (see below), may be merely the western part of the Belchertown pluton, and connections may have been obscured by postmetamorphic faulting and Mesozoic cover.

INTERNAL STRUCTURE AND PETROGRAPHY

Distribution of Major Rock Types within the Pluton

The major zonation of rock types in the Belchertown pluton (fig. 3) is interpreted to represent a mineralogical and textural transformation of the primary igneous rocks resulting from cataclasis, hydration, and recrystallization along pervasive shear zones in response to deformation during regional metamorphism. Schematically, the pluton can be considered as a network of shear zones varying in size from minute cracks best visible in thin section to thick layers of gneiss including flaser gneiss and mylonite. In the central regions, the shear zones are scarce but are as

![Diagram showing zonation of rock types within the Belchertown pluton](image_url)  

**Fig. 3.** Sketch illustrating mutual relationships of the principal rock types within the Belchertown pluton, observed at both large and small scales. Outermost occurrences of hypersthene-bearing rocks define schematic contact between the inner and transition zones; outermost occurrences of augite-bearing rocks define schematic contact between the transition and outer zones (see fig. 2; also Leo, Robinson, and Hall, 1977).
much as 15 m thick. Near the margins of the intrusion, the shear zones are more numerous, and their effects become more pronounced. The outermost regions of the pluton can be considered as a continuous zone of fully hydrated and recrystallized rocks. Large areas of primary igneous rock, hypersthene–augite quartz monzodiorite, are restricted to the central region, and the boundaries of this inner zone are defined by the outermost occurrences of this primary lithology. Likewise, the boundary between the transition zone and the outer zone is defined by the outermost extent of transitional rocks in which all hypersthene has been destroyed by metamorphic hydration but in which some augite remains.

**Petrography of Plutonic Rock Types and their Metamorphic Equivalents**

*Hypersthene–augite quartz monzodiorite.—* The inner zone of the pluton is composed predominantly of massive medium-grained hypersthene–augite quartz monzodiorite, which is believed to be the least metamorphosed primary rock of the pluton. In some places this rock shows weak subparallel alignment of plagioclase grains, interpreted as igneous flow structure. On fresh surfaces, the rock is pink or reddish because of abundant plagioclase, which contains minute inclusions of Fe–Ti oxides. The quartz monzodiorite has a moderately strong magnetic susceptibility which was found to be a useful attribute for field identification. Mafic minerals, which constitute as much as 35 percent of the rock, include poikilitic brown biotite flakes as much as several centimeters across and stubby crystals of green augite and brown hypersthene. Either pyroxene may form monomineralic aggregates as much as 2 cm long, which are commonly elongated parallel to igneous foliation. The remaining minerals are hornblende, quartz, potassic feldspar and accessory magnetite, titanohematite, apatite, and zircon. Representative modes are shown in table 1.

In thin section, the quartz monzodiorite shows a texture of interlocking subhedral plagioclase and pyroxene crystals and larger poikilitic grains of biotite, potassic feldspar, and olivine-green hornblende. Quartz is interstitial and probably crystallized last. Potassic feldspar is orthoclase microperthite commonly containing areas of coarse plagioclase lamellae near grain centers.

Plagioclase characteristically contains tiny (micron- or sub-micron-sized) inclusions concentrated in the cores of grains; these inclusions are believed to be responsible for the reddish coloration of the rock in hand specimen. Reflected-light microscopy shows that the tiny particles are opaque phases, but they could not be identified positively by optical means. In a study of the bulk magnetic properties of a purified mineral separate of plagioclase containing dustlike inclusions, Ashwal and Hargraves (1977) detected the presence of both magnetite and titanohematite. The presence of these phases is consistent with both the reddish coloration of the plagioclase and the proposed high oxygen fugacity during magmatic crystallization, as discussed below.
### Table 1

Wet-chemical analyses, CIPW norms, and modes of the Belchertown pluton and associated rocks

<table>
<thead>
<tr>
<th>Sample</th>
<th>hip-peg. quartz monzodiorite</th>
<th>leucite, hip-peg. quartz monzodiorite</th>
<th>alkali-feldspar granite</th>
<th>leucogranite</th>
<th>dike-trachytes</th>
<th>ultramafic rocks</th>
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<td>57.13</td>
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</table>

**Notes:**
- CIPW = Calcium-Iron-Johannsen-Plagioclase-Wollastonite.
- Ultramafic rocks include clinopyroxene, orthopyroxene, and olivine.

### Density

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<th>Sample</th>
<th>Density (g/cm³)</th>
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**Notes:**
- CIPW norms are calculated for each sample.
- Density values are provided for comparison.

**References:**
- [Pluton, west-central Mass.: A syntectonic Acadian intrusion](945)
- [Table 1](#) provides a comprehensive analysis of the Belchertown pluton and associated rocks, including wet-chemical and petrographic properties.
**Table 1 (continued)**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Two-pyroxene quartz monzodiorite</th>
<th>Unificado, hypersthene-free quartz monzodiorite and tonalite</th>
<th>Hornblende-diorite quartz gneiss</th>
<th>Metamorphosed diorite porphyry</th>
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<td>Notes</td>
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Nos. 1 through 10 and 12-13, standard wet-chemical rock analyses by Elaine L. Brandt and Edythe E. Engleman; no. 11, rapid-rock analysis (results to three significant figures) by Joseph W. Budinsky; CrO₂ and NiO determined by R. L. Rahill; all of the U.S. Geological Survey. All samples analyzed are from the Ludlow, Mass., 7½-minute quadrangle (Leo, Robinson and Hall, 1977), and more detailed locations are shown therein. NA, not applicable; ND, not determined.

1. Determined colorimetrically; 2. determined by atomic absorption; 3. density determination by Hall (ms) on 69 samples from the three zones of the pluton yielded average values of 2.84 for two-pyroxene quartz monzodiorite, 2.82 for transitional rocks, and 2.79 for fully recrystallized gneiss; 4. oxidation ratio expressed as (2FeO × 100/1) 2Fe₂O₃ + FeO; 5. no. 3; 1500 points; no. 9; 1636 points; no. 10; no modal analysis because of extremely fine-grained granoblastic texture; 6. determined by X′ A (1010) in zone j (001). Not optically determinable in nos. 12 and 13. 8 colorless to grass-green hornblende in rocks of the pluton; colorless clinohumite (cummingitonite) in metaperidotite (nos. 12 and 13); 9. includes titanohematite containing exsolved ferriferous ilmenite, magnetite, and minor sulfides; 10. includes rutile and zircon; 11. includes calcite, prehnite, and sericite.

Sample description and localities for table I.

1. 71-GWL-120, two-pyroxene quartz monzodiorite about 155 m from west end of abandoned railroad cut and about 1.6 km west-northwest of intersection of Main Street and Three Rivers Road, Three Rivers, Mass. For detailed field relations see Ashwal, 1974, figure 5 (sample location A-21).

2. 71-GWL-88-6, two-pyroxene quartz monzodiorite from abandoned railroad cut along north bank of Chicopee River, about 2.4 km west-northwest of intersection near which 71-GWL-120 was collected in Three Rivers, Mass.

3. 71-GWL-95-3, augite-biotite quartz monzodiorite containing remnants of hypersthene and a significant amount of secondary hornblende, 360 m south-southwest of summit of High Hill, on 115-m (310-ft) contour.

4. 71-GWL-95-2, augite-hornblende-biotite quartz monzodiorite, 350 m north-northwest of intersection of Shaw and Ludlow roads, on 174-m (570-ft) contour.

5. 71-GWL-85-1, hornblende-biotite tonalite containing remnants of augite, 80 m south of Red Bridge Road along dirt road, 530 m west of intersection of Red Bridge and Chilson Roads.
Coexisting augite and hypersthene are distinctive and characteristic of the primary quartz monzodiorite and show well developed exsolution features. Augite hosts contain (100) hypersthene lamellae and two sets of finer pigeonite lamellae inclined at small angles to (100) and (001), all of which have been identified and characterized by X-ray single-crystal precession photographs (Jaffe and others, 1975). Hypersthene hosts contain (100) augite lamellae.

Two varieties of hornblende are present in small amounts in the quartz monzodiorite. A primary late-magmatic olive-green hornblende forms poikilitic grains. A later blue-green hornblende is present as thin rims around hypersthene and along thin cracks and is interpreted to represent incipient metamorphic hydration.

The principal opaque mineral in the quartz monzodiorite is a texturally igneous titanohematite containing two sets of ferrian-ilmenite exsolution lamellae. Other opaque minerals include sulfides and magnetite; the latter is present as small irregular inclusions within titanohematite grains and as vernicular intergrowths or rodlike inclusions within mafic silicates.

Recrystallized hornblende-biotite gneiss.—The fully recrystallized counterpart of the primary quartz monzodiorite is hornblende-biotite gneiss (fig. 3) that is modally also quartz monzodiorite (fig. 4). The fully recrystallized gneissic rocks, mostly from the outer zone, studied by Hall (1974), also yield modes that would be classed here as diorite, quartz diorite, tonalite, and granodiorite (Internat. Union Geol. Sci., 1973), but such variations are unknown in the primary rocks. The recrystallized primary rock typically has a well developed tectonic foliation and lineation formed by alignment of biotite, hornblende, and aggregates of quartz and feldspar. Pyroxenes and opaque minerals have been completely consumed during chemical redistribution involving hydration and recrystallization to the new metamorphic mineral assemblage. The rock is medium-grained and gray to greenish gray. Modal data (table 1) indicate that the chemical redistribution has caused the following changes in mineralogy: the gneiss contains important amounts of blue-

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6. A13-2, hornblende-biotite quartz monzodiorite. Railroad cut about 85 m west of where 71-GWL-120 was collected; see Ashwal, 1974, figures 5, 9.
7. 71-GWL-85-3, hornblende-biotite quartz monzodiorite gneiss. About 30 m south of Red Bridge Road at Wilbraham-Palmer town line and 200 m northeast of where 71-GWL-85-1 was collected.
8. A13-1, hornblende-biotite quartz monzodiorite gneiss. Recrystallized shear zone 3 m west of where A13-2 was collected; see Ashwal, 1974, figures 5, 9.
9. 71-GWL-96-2, hornblende-biotite quartz monzodiorite gneiss. 100 m south of summit of High Hill, on 195 m (640-ft.) contour.
10. 71-GWL-86-2, hypersthene-diopside-biotite-hornblende-cummingtonite metadacite. About 50 m north of Red Bridge Road just west of Wilbraham-Palmer town line; about 100 m north of where 71-GWL-85-3 was collected.
11. 71-GWL-32-2, hornblende-biotite olivine pyroxenite; differentiates plug (?) in Belchertown pluton; 550 m southwest of end of Green Ave.
12. 71-GWL-109-4, plagioclase pyroxenite from outer zone of pyroxenite body. About 400 m southwest of end of Green Ave.
13. 71-GWL-103-2, hornblendite, which is the hydrated equivalent of 71-GWL-103-4 (anal. 12), same outcrop, about 1.5 m from where 71-GWL-103-4 was collected.
green hornblende, olivine biotite, epidote, and sphene and contains a
greater proportion of quartz and a smaller proportion of plagioclase
than the primary quartz monzodiorite. Although not consistently
apparent from table 1, a general decrease in modal plagioclase from primary
to recrystallized rocks is apparent from many additional modal analyses
(Hall, ms). Accessory minerals include apatite, zircon, and allanite.

Plagioclase from the recrystallized gneisses lacks the minute opaque
inclusions characteristic of the quartz monzodiorite. Potassic feldspar in
the gneiss shows only sparse perthitic lamellae but has incipient tartan
twinning of microcline, and it has a lower structural state than orthoclase
micropertitite from the quartz monzodiorite (Ashwal, 1974). Blue-green
hornblende looks similar to that forming thin reaction rims around hyper-
sthene in the quartz monzodiorite and commonly forms prismatic grains
integrown with biotite and oriented parallel to the tectonic foliation.
Anhedral grains of epidote and sphene are scattered throughout the rock.

Transitional rocks.—Rocks having all structural and mineralogical
gradations between the primary two-pyroxene quartz monzodiorite and
the fully hydrated and recrystallized hornblende-biotite gneiss have been
identified in the Belchertown pluton. Transitional rocks are defined as
those that possess a massive texture having no tectonite fabric, lack hyper-
sthene, and may or may not contain augite. The reader is reminded that
the boundary between the transition zone and outer zone (fig. 3) is de-
finite as the outer limit of transitional rocks containing augite.

In thin section, transitional rocks show many textural features sug-
uggestive of reaction relations. Aggregates of fine-grained blue-green horn-
blende commonly intergrown with vermicular quartz are clearly pseudo-
morphous after augite and hypersthene. In augite-bearing transitional
rocks, rims of hornblende or quartz-hornblende intergrowths are present
between clinopyroxene and plagioclase. Olive-green biotites commonly contain concentrations of euhedral or subhedral sphene crystals along their edges suggesting breakdown of brown Ti-rich igneous biotite to form Ti-deficient green biotite and sphene. Green biotite also forms rims between orthopyroxene and orthoclase microperthite.

**Structural Relationships Between Plutonic Rock Types**

Structural features of shear zones within the inner zone of the pluton provide information on the nature and timing of metamorphic transformation of the primary rocks. Some shear zones consist of rounded blocks of massive transitional rocks separated by thin zones of highly foliated and lineated gneisses. The folds in foliation that wrap around the blocks are approximately coaxial with the mineral lineation of the gneiss, suggesting that the blocks are elongate mullion-like features having their long axes parallel to mineral lineation, much in the same manner of elongate quartz pebbles in the Clough Quartzite in the surrounding region. Other shear zones contain a thin central core of mylonite and mylonitic gneiss in which the coarse igneous texture of the primary rock has been partly to completely destroyed by cataclasis. Some of the last mylonites to form are clearly products of cataclasis of fully hydrated gneisses, because they contain abundant crushed hornblende and even retain relict coarse hornblende lineation in a slightly different orientation than later fine mylonite lineation. Most zones of mylonitic gneiss, however, have clearly undergone some recrystallization, because they have strong mineral lineations and minor folds nearly coaxial with the mineral lineation of the surrounding gneisses (Ashwal, 1974).

The structural relationships discussed above suggest that the primary quartz monzodiorite was brittle and did not undergo plastic deformation during regional metamorphism. Brittle fractures and cataclastic zones provided channels for the influx of H₂O, probably from outside the pluton, which permitted formation of massive transitional rocks and fully reconstituted gneisses by a continuous process of deformation, hydration, and recrystallization. Where strain rates locally and temporarily exceeded rates of recrystallization, mylonites were formed from fully hydrated rocks (Ashwal, 1974, p. 47-50). Some of these subsequently were recrystallized at lower strain rates to fine-grained mylonitic gneisses.

**Other Rock Types**

*Hornblendite and pyroxenite.*—Mafic and ultramafic inclusions, widely distributed in the Belchertown pluton and as fragments in the intrusive breccia (fig. 2), were described by Guthrie (1972) as being partly amphibolite of metasedimentary or metavolcanic origin and partly an early ultramafic intrusive phase of the Belchertown magma. The latter rocks, which are more abundant, are massive hornblendite, diopside hornblendite, and various meladiorites in which sodic plagioclase is believed to have been introduced from surrounding felsic magma into originally ultramafic fragments. Several of the ultramafic masses are large
enough to be shown on the geologic map (fig 2). At exposed contacts with other plutonic rocks, these ultramafic masses always appear older, but their contacts with inclusions of metamorphic rocks are not well exposed. Similar rocks locally form dikes cutting quartz monzodiorite (Guthrie, 1972; Hall, ms), indicating that the ultramafic rocks may be of two distinct ages.

At the northwestern contact between the inner and transition zones of the pluton is an elliptical mass of ultramafic and mafic rocks measuring about 200 × 300 m (11, 12, 13 on fig. 2). Contact relationships with quartz monzodiorite are not exposed. The rock in the interior of this ultramafic body is dark-green medium- to coarse-grained hornblende-biotite-olivine pyroxenite (table 1, no. 11). The texture is dominated by euhedral to subhedral augite, and smaller grains of bronzite and subrounded magnesian olivine (Fo₈₅) are present. Large plates of orange-brown biotite and pargasitic hornblende poikilitically enclose the other minerals. Pyroxene exsolution features in this rock have been described by Jaffe and others (1975; their samples 447-1 and 447-2), who reported extremely magnesian compositions for coexisting orthopyroxene (Woₓ-Enₛ₁ Fs₈₁₁) and augite (Woₓ₆₈En₄₅Fs₈₆).

The pyroxenite grades outward to an irregular zone of olivine-free plagioclase pyroxenite (table 1, no. 12), which in turn grades to hornblende (table 1, no. 13). The latter two rocks are essentially isochemical except for the higher H₂O content of the hornblende, which may have resulted from a process analogous to the metamorphic hydration of the outer zone of the entire pluton.

We are uncertain as to the origin of this olivine-bearing ultramafic body and of the possibly related ultramafic rocks near the northern contact. The presence of olivine and the extremely magnesian pyroxene composition appear to be incompatible with an origin as an early cumulate phase of the main Belchertown magma, but the existence of a cogenetic ultramafic magma cannot be ruled out. The possibility that the pyroxenite could represent mantle-derived inclusions (for example, see Carswell, 1968; Beeson and Jackson, 1970) was considered but was rejected for lack of a plausible mechanism for transporting such volumes of rock into the upper crust.

The elliptical shape of the ultramafic body and the zoned nature and distribution of rock types are somewhat reminiscent of the zoned, "Alaskan-type" ultramafic complexes described by Murray (1972), which are thought to have formed by fractional crystallization and slow differentiation. Such an origin requires that the ultramafic rocks be younger than the pluton, which is not incompatible with the observations of Guthrie (1972) and Hall (ms) referred to earlier.

Metamorphosed dacite inclusion.—Gray, hornfelsed dacite porphyry crops out near the southern edge of the pluton (no. 10 on fig. 2 and table 1). Although contacts with quartz monzodiorite are not exposed, available outcrops suggest that the body is roughly equant and measures between 10 and 30 m in diameter. The rock is finer grained than the en-
closing quartz monzodiorite and is thoroughly recrystallized, showing a relict porphyritic texture and well preserved features of the original dacite. Recrystallized phenocrysts include relict, strongly zoned plagioclase; augitic clinopyroxene; hypersthene, locally replaced by pale green amphibole; and granoblastic, commonly skeletal intergrowth of green hornblende, red-brown biotite, clinopyroxene, quartz, feldspar, and opaque granules. These intergrowths may be pseudomorphous after primary augite. The groundmass consists of finely granoblastic quartz, feldspars, clinopyroxene, and opaque minerals. Clinopyroxene granules have developed within relict plagioclase partly by diffusion of Ca++ from surrounding haloes, which contribute to the patchy zoning effect. Estimated compositions determined by maximum-extinction angles in albite twins are An_{15} in haloes and as much as An_{62} in plagioclase cores, although a more common compositional range is An_{17-47}. Mineralogically and chemically the dacite porphyry generally resembles the primary Belchertown Quartz Monzodiorite (table 1; figs. 4 and 5).

The formation of metamorphic clinopyroxene, the stability of hypersthene, the granoblastic texture, and the unusually low water content all indicate that the dacite recrystallized under high temperature contact metamorphism. This is in accord with the temperatures at which the

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**Fig. 5.** Modified ACF diagrams, based on molecular proportions, showing analytically determined mineral and bulk-rock compositions for the Belchertown pluton. Short-dashed lines surround compositions of primary hypersthene-augite quartz monzodiorite, transitional rocks and fully recrystallized hornblende-biotite gneiss after subtraction of modally determined amounts of appropriate biotite compositions (table 2).
pluton is believed to have crystallized. Given its compositional affinity to plutonic Belchertown rocks, the metamorphosed dacite thus could represent a foundered block of an early volcanic or hypabyssal phase of Belchertown magma. The pronounced granoblastic character of the dacite, which stands in striking contrast to the strongly foliated character of nearby gneiss, probably may be attributed to primary dense cryptocrystalline texture and lack of joint planes which enabled the block largely to escape shearing and hydration during Acadian metamorphism.

Pelitic inclusion.—A septum of pelitic schist of the Parridge Formation extends 5 km into the pluton from the northeast corner (Guthrie, 1972; fig. 2, this paper). The northern 1 km of this septum, near the outer border of the pluton, is quartz-muscovite-biotite-garnet-staurolite-kyanite schist. The kyanite has fibrolitic sillimanite overgrowths. The middle 2 km of the septum is quartz-muscovite-biotite-garnet-sillimanite schist with minor staurolite. The sillimanite is fibrolitic. The southern 2 km, closest to the inner zone of the pluton, is very coarse quartz-biotite-garnet-sillimanite schist in which part of the sillimanite forms pseudomorphs after andalusite as long as 10 cm, and the remainder is fibrolitic. The fact that neither muscovite nor orthoclase is present in this schist suggests that alkalies may have been lost to adjacent melt. The distribution of phases in the pelitic schist septum suggests (1) early contact metamorphism of the inner end of the schist septum at temperatures less than the aluminum silicate triple point, followed by increased pressure as the rocks were brought to maximum temperature; (2) a hot spot caused by the pluton that locally disturbed the regional metamorphic gradient long after crystallization of the plutonic rocks, causing fibrolite to form in rocks that normally would have contained only kyanite.

IGNEOUS AND METAMORPHIC PETROLOGY

Bulk Chemistry of the Principal Rock Types

Wet chemical analyses, norms, and modes of rocks of the pluton are given in table 1 (nos. 1-9). The plutonic rocks include primary two-pyroxene quartz monzodiorite, fully hydrated and recrystallized gneiss, and transitional types. Despite the different mineral assemblages in plutonic rocks from core to margin, bulk-compositional differences are not great. The principal chemical variation is a three-fold increase in water from primary magmatic rocks to gneiss which reflects the metamorphic hydration. The Mg/Fe ratio, which is unusually high for such felsic rocks, is attributed to conditions of high oxygen fugacity during magmatic crystallization as discussed below.

All the norms and all but one of the modes of the analyzed rocks are in the compositional field of quartz monzodiorite (fig. 4). Additional modes (Guthrie, 1972; Hall, ms), especially of hydrated gneisses, correspond to granodiorite, tonalite, quartz diorite, and diorite as defined in figure 4. Modes of the analyzed rocks are somewhat scattered. The corresponding normative points are less scattered and show a general enrich-
ment in K-feldspar relative to the modes that is certainly due in part to modal biotite. The normative points, moreover, show a slight and progressive enrichment in quartz and orthoclase from the anhydrous two-pyroxene rocks to the recrystallized gneisses.

Mineral Chemistry

Five wet-chemical and eight electron-microprobe analyses of representative minerals from a quartz monzodiorite (table 1, no. 1) and a fully recrystallized gneiss (table 1, no. 8) are given in table 2.

Plagioclase from the primary quartz monzodiorite varies in composition between An_{23} and An_{26} (avg = An_{24}). Some grains are nearly homogeneous, whereas others show normal zoning between the indicated compositions. The composition of the orthoclase host in microperthite from the quartz monzodiorite is approximately Or_{80}Ab_{11}. However, an estimate of bulk composition, prior to unmixing, of Or_{23}Ab_{24}An_{3} was obtained by incorporating both host and lamellar phases within the microprobe analysis spot. Although feldspar compositions of the primary quartz monzodiorite and of the fully recrystallized gneiss overlap considerably, plagioclase from the gneiss is generally less potassic and more sodic, varying between An_{17} and An_{27} (avg = An_{22}), and the potassic feldspar from the gneiss is generally less sodic, averaging Or_{88}Ab_{12}An_{0}.

These compositions are suggestive of a wider plagioclase–potassic feldspar miscibility gap in the recrystallized gneiss, as would be expected at a metamorphic temperature lower than that of magmatic crystallization.

Microprobe analyses of coexisting pyroxenes in the quartz monzodiorite are essentially in agreement with the wet-chemical analyses in table 2 which yield compositions of Wo_{44}En_{41}Fs_{15} and Wo_{4}En_{58}Fs_{51} for augite and hypersthene, respectively, if total Fe is assumed to be Fe^{2+}, or Wo_{44}En_{33}Fs_{16} and Wo_{4}En_{58}Fs_{29} if analyzed Fe^{3+} is taken into account. Low modal abundance of primary olivine hornblende in the quartz monzodiorite (table 1) precluded separation of sufficient pure material for wet-chemical analysis, but an average microprobe analysis is given in table 2. The high proportion of ferric iron in this hornblende (Fe^{3+}/(Fe^{2+} + Fe^{3+}) = 0.52), calculated on the basis of ideal hornblende stoichiometry and theoretical charge-balance considerations (Robinson and others, 1971; Ashwal, 1974), is consistent with the proposed high oxygen fugacity during magmatic crystallization, as discussed in the next section. Compared with this igneous hornblende, the blue-green metamorphic hornblende has a higher Fe^{2+}/(Fe^{2+} + Mg) ratio (0.25), more Ca, and less Al, Fe^{3+}, Ti, and alkalies (table 2). Olive-green metamorphic biotite has much lower Ti and a slightly higher Fe^{2+}/(Fe^{2+} + Mg) ratio (0.31) than the brown igneous biotite (0.29) in the quartz monzodiorite.

Microprobe analyses of ilmenohematite grains from the quartz monzodiorite yield compositions of Ilm_{47}Hem_{53} and Ilm_{02}Hem_{98} for the host titanohematite and lamellar ferrian ilmenite, respectively. Attempts were made to reintegrate the primary "hypersolvus" bulk Fe–Ti oxide compo-
Table 2
Wet-chemical and electron microprobe analyses of minerals from primary quartz monzodiorite and fully recrystallized gneiss of the Belchertown pluton

<table>
<thead>
<tr>
<th>Component</th>
<th>Primary quartz monzodiorite (ppm, n = 3)</th>
<th>Fully recrystallized gneiss (ppm, n = 3)</th>
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<tbody>
<tr>
<td>FeO</td>
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<td>65.64 65.64 65.64</td>
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<tr>
<td>CaO</td>
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<td>65.54 65.54 65.54</td>
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<td>11.60 11.60 11.60</td>
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<tr>
<td>MgO</td>
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<td>5.20 5.20 5.20</td>
</tr>
<tr>
<td>CaO</td>
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<td>8.30 8.30 8.30</td>
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#### Ionic ratios

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#### Inter-element covariances

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<th>Fully recrystallized gneiss (ppm, n = 3)</th>
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<tr>
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</tbody>
</table>

#### Notes

- Analysis represents intermediate value of 6 individual analyses which ranged between An30 and An60. b wet chemical analysis, Shiro Imai, analyst, Japan Analytical Research Institute; c average of 6 microprobe analyses; d recalculated assuming ideal stoichiometry; e bulk composition of exolved ilmenohematite obtained by reintegrating host and lamellar microprobe analyses in the proportions given by point-counted modes of grain photographs; f analysis represents intermediate value of 6 individual analyses which ranged between An30 and An60. g total Fe as FeO; h determined by qualitative spectrographic analysis; i calculated from ideal hornblende stoichiometry and charge balance considerations.
pluton, west-central Mass.: A syntectonic Acadian intrusion  955

dition. Rapid oscillation of a coarsely exsolved grain beneath the micro-
probe analysis spot yielded a composition of Ilm35Hem65, and a reinte-
gregation of host and lamellar compositions in the proportions given by
point-counted modes of grain photographs gave a bulk composition of
Ilm35Hem65 (table 2). This latter value is considered to be more represen-
tative of the primary Fe–Ti bulk composition, since the oscillation micro-
probe analysis may be too rich in hematite component due to possible
failure to incorporate sufficient ilmenite lamellae. In any case, it is dif-
ficult to assess the accuracy of these reintegration techniques. Minor co-
exisiting magnetite is homogeneous, and microprobe analyses yield a com-
position of Mag97.5Usp2.5 (table 2).

Magmatic Crystallization

Any petrogenetic model of the primary quartz monzodiorite of the
Belchertown pluton must take into account the following textural and
mineralogic features.

Magmatic crystallization under conditions of high oxygen fugacity
is indicated by: (1) the presence of magmatic titanohematite having a
primary composition between Ilm35Hem65 and Ilm35Hem65 coexis-
ting with magnetite having a composition of Mag97.5Usp2.5, (2) the unusually
magnesian composition of the pyroxenes in such a felsic rock, and (3) the
high estimated Fe3+ content of the igneous hornblende. Although the
extremely hematite-rich composition of the primary titanohematite is
outside the range of usable compositions for the Fe–Ti oxide geother-
nometer-oxygen barometer of Buddington and Lindsley (1964 and cor-
rected version, Lindsley, 1976, personal commun.), reasonable extrapolation
does suggest equilibration at oxygen fugacities between those of the
nickel–nickel oxide and hematite–magnetite buffers. The oxygen fugacity
of the Belchertown magma thus appears to have been as extreme as that
of the granite of the Finnemarca Complex (Czamanske and Wones,
1973), although the Mn enrichment shown in Finnemarca ilmenites is
not observed here. D. R. Wones (personal commun., 1974) has sug-
gested that the extremely high oxygen fugacity of the intrusion could only have
originated by massive devolatilization associated with surface eruptions
of an originally H2O-rich magma. Certainly the country rocks, which
contain abundant graphitic schists, could have contributed little to gen-
erate this composition directly, although they could have provided H2O.
It seems at first incongruous to think of this pluton, intimately involved
in a gneiss-dome terrain and with kyanite-zone schists, as a high-level
one capable of such surface interactions. However, the metadacite in-
clusion described above, with its hornfelsed porphyritic texture, does hint
that liquids roughly equivalent to the Belchertown magma may have
erupted and chilled at the surface and later been engulffed in the upper
reaches of the Belchertown pluton. The presence of sillimanite pseudo-
morphs after andalusite in pelitic schist inclusions may also be indicative
of early lower pressure contact-metamorphic effects prior to movement
of the body into its present kyanite-grade regional setting.
The assemblage augite–hypersthene–quartz–plagioclase–potassic feldspar in the primary quartz monzodiorite resembles that in charnockitic rocks and alkali charnockites; hence it is analogous to granulite facies equilibration at high temperature and low $a_{\text{H}_2\text{O}}$ (activity of water). Such low $a_{\text{H}_2\text{O}}$ and the onset of rapid pyroxene crystallization may both have been brought about by the massive devolatilization and oxidation discussed above. Comparing the measured augite composition with the augite–orthopyroxene solvus of Ross and Huebner (1975) suggests a pyroxene crystallization temperature between 950° and 900°C. Abundant preserved orthopyroxene–potassic feldspar contacts show that a high proportion of the rock was crystallized before poikilitic brown biotite and olive-green hornblende began to form from residual, presumably H$_2$O-enriched, interstitial liquid.

Values of H$_2$O fugacity during late stages of magmatic crystallization may be evaluated using the equation of Wones (1972) modified by Czamanske and Wones (1973), assuming that quartz, potassic feldspar, biotite, magnetite, and titanohematite were all in equilibrium at these stages:

$$\log f_{\text{H}_2\text{O}} = \frac{7409}{T} + 4.25 + 8.1/2 \log f_{\text{O}_2} + 3 \log X_{\text{An}_{88}^{\text{Bt}}} +$$

$$2 \log X_{\text{O}_{1}^{\text{Bt}}} - \log a_{\text{K}_{2}\text{Si}_{3}\text{O}_{8}} - \log a_{\text{Fe}_{2}\text{O}_{4}}$$

(1)

where $T$ (temperature) is in °K; $\log f_{\text{O}_2}$ (extrapolated from $\log f_{\text{O}_2}$ of co-existing oxides and from Buddington and Lindsley, 1964) was taken as $-15.2(600°C), -13.7(650°C), -13.0(675°C), -12.4(700°C)$; $X_{\text{An}_{88}^{\text{Bt}}} = \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg} + \text{Fe}^{3+} + \text{Ti} + \text{Al}[\text{VI}]) = 0.231; X_{\text{O}_{1}^{\text{Bt}}} = [2 - (\text{Cl} + \text{F})]/2 = 0.916; a_{\text{K}_{2}\text{Si}_{3}\text{O}_{8}} = 0.75; \text{and } a_{\text{Fe}_{2}\text{O}_{4}} = 0.96$. If probable difficulties due to high Fe$^{3+}$ and Ti in biotite are ignored, the equation yields the following $f_{\text{H}_2\text{O}}$ values in bars: 1970(600°C), 3840(650°C), 5280(675°C), and 6630(700°C). When plotted, these values define a curve that intersects the H$_2$O-saturated granite minimum melting curve (Tuttle and Bowen, 1958), corrected for plagioclase An$_{28}$ (von Platen, 1965), at about 660°C and $f_{\text{H}_2\text{O}} = 4300$ bars.

Metamorphic Hydration and Recrystallization

Very late during, or subsequent to, magmatic crystallization, the major part of the Belchertown pluton was subjected to deformation along shear zones, influx of H$_2$O, hydration, and recrystallization in response to regional deformation while the surroundings were undergoing kyanite-grade regional metamorphism. This caused the conversion of the primary mineral assemblage to the amphibolite facies assemblage present in the recrystallized gneisses. Aluminum silicate relationships in pelitic inclusions suggest that at this time the interior of the pluton was probably under sillimanite-grade conditions and may have been at the center of a metamorphic hot spot. The postcrystallization history of the pluton is considered to be one of continuously decreasing temperature and in-

---

This sign is "+" in the original version by Wones (1972) and was incorrectly copied as "−" in the version by Czamanske and Wones (1973).
increasing $P_{H_2O}$, although no quantitative estimate of late metamorphic temperature and pressure conditions is offered at this time.

The transformation that converted the primary igneous mineralogy to the younger metamorphic assemblage can be considered as a chemical redistribution by a series of reactions involving mainly the progressive addition of $H_2O$ in rocks of otherwise fairly constant bulk composition. The most apparent mineralogical change between the primary and recrystallized rocks involves the breakdown of pyroxenes and the formation of blue-green hornblende and epidote. These changes can be considered as having taken place by means of two qualitatively expressed reactions:

\[
\text{hypersthen}e + \text{augite} + \text{plagioclase} + H_2O \rightarrow \text{blue-green hornblende} + \text{quartz} \quad (2)
\]

\[
\text{augite} + \text{plagioclase} + H_2O \rightarrow \text{blue-green hornblende} + \text{epidote} + \text{quartz} \quad (3)
\]

The topologies of this proposed sequence of metamorphic hydration reactions are shown on two ACF diagrams modified for the purposes of plotting mineral and bulk-rock analyses in figure 5.\(^{4}\) Reaction (2) causes the breakdown of hypersthene, resulting in the assemblage augite + blue-green hornblende + plagioclase, which is quite common in transitional rocks (table 1). The quartz–hornblende intergrowths that are closely associated with pyroxenes as reaction rims and pseudomorphs may be considered a direct result of this reaction. In reaction (3), all augite is used up and yields the final metamorphic assemblage: blue-green hornblende + epidote + plagioclase.

The metamorphic blue-green hornblende has about the same $Fe^{2+}/Mg$ ratio as the combined pyroxenes of the monzodiorite and a major $Fe^{3+}$ content derived from opaque minerals. Additional $Fe^{3+}$ is incorporated in epidote. The green biotite in the hornblende–biotite gneiss, although slightly less abundant, is slightly higher in $Fe^{3+}$ and much lower in Ti than the primary brown biotite in the quartz monzodiorite. The remaining Ti is incorporated in sphene. The plagioclase of the two rocks is nearly identical in composition, indicating that Ca is used in making hornblende from plagioclase and pyroxenes is roughly made up by Ca from breakdown of augite. The overall reaction by which the primary igneous monzodiorite is converted to recrystallized gneisses can be summarized as follows:

\[
\text{augite} + \text{hypersthen}e + \text{plagioclase (An}_{28}) + \text{high-Ti biotite} + \text{potassic feldspar} + \text{olive-green hornblende} + \text{titanohematite} + \text{magnetite} + H_2O \rightarrow \\
\text{blue-green hornblende} + \text{quartz} + \text{plagioclase (An}_{90}) + \text{epidote} + \text{low-Ti biotite} + \text{sphene} \quad (4)
\]

\(^{4}\) The bulk-rock analyses shown in figure 5 do not plot within the area of intersection of the igneous and metamorphic three-phase regions, because both rocks contain biotite, which is not considered as a participant in these simplified reactions. Subtraction of modal amounts of biotite of appropriate composition shifts the bulk-rock compositions to the area of overlap between the two regions.
This reaction leads to the total elimination of both pyroxenes, titanohematite, and magnetite, and the production of blue-green metamorphic hornblende, epidote, and sphene.

The compositions of green biotite and orthoclase from the gneiss may be used to calculate minimum values of $f_{H_2O}$ using eq (1) above, assuming the presence of magnetite and the same temperatures and oxygen fugacities. At the same $f_{H_2O}$ and $f_{O_2}$, the gneiss would require at least 15°C lower temperature. At the same temperature and $f_{O_2}$, it would require at least 600 to 1000 bars higher $f_{H_2O}$. Although the oxides, the specific indicators of oxygen fugacity, are destroyed by the metamorphism, the bulk-rock analyses do not suggest any significant change in $Fe_2O_3$ content and do suggest that the oxygen fugacity of the hydrating fluids was probably buffered by the surrounding plutonic rocks.

GEOPHYSICS
Gravity

A simple Bouguer gravity map (fig. 6) indicates that the Belchertown pluton correlates with a broad low-amplitude (+4 mgal) gravity high. A relatively steep gravity gradient immediately east of the pluton marks the western margin of a north-trending gravity high which corresponds to the metamorphosed sedimentary and volcanic rocks east of the pluton and east of the Monson Gneiss (fig. 1). The Pelham and Glastonbury domes, to the north and south of the pluton, respectively, and the Tri-
assic and Jurassic basin of the Connecticut valley west of the pluton (fig. 1) all correlate with gravity lows (−1 to −3 mgals).

A residual gravity map (fig. 7) isolates the anomaly due to the pluton from the effects of the eastern gravity high. On the residual map, the Belchertown pluton correlates with a roughly circular gravity high having an amplitude of 9 mgal, and the pluton is roughly outlined by the +4-mgal contour. Within the +7-mgal contour, a northwest-trending gravity high may be caused by the density (ρ) contrast between the two-pyroxene quartz monzodiorites of the inner zone (ρ = 2.84 g/cm³) and the hydrated gneissic rocks of the outer zones (ρ = 2.79 g/cm³) (Hall, ms).

The highest residual value of +9 mgal in the northwest part of the pluton may be caused by locally abundant high-density ultramafic material (3.24-3.02 g/cm³).

Some idea of the three-dimensional shape of the pluton may be obtained by using the calculated residual gravity anomaly (Dobrin, 1960; Kane and Bromery, 1968). Using an average density of 2.84 g/cm³ for the plutonic rocks, and of 2.67 g/cm³ for the dome gneisses and rocks of the Triassic and Jurassic basin, the closest fit to the calculated gravity anomaly is produced by a thin (1.5 km) disk-shaped intrusive mass (Hall, ms).

This model, however, cannot be applied to the eastern and southeastern parts of the pluton, because no appreciable density contrast exists between rocks of the pluton and the surrounding metamorphosed Paleozoic stratified rocks. A model for the three-dimensional shape of the pluton as a whole was obtained using aeromagnetic data discussed below.

Fig. 7. Residual simple Bouger gravity map of the Belchertown pluton and adjacent units. Interval of isopleths (solid lines), 1 mgal. Geologic contacts (dashed lines) and faults are shown as in Figure 2. Modified from Hall (ms).
Aeromagnetics

Aeromagnetic maps (U.S. Geol. Survey, 1968a,b; 1969a,b) of the area east of the Belchertown pluton show a distinctive pattern of steep gradients and north-trending linear anomalies as high as 4200 gammas and as low as 3000 gammas that correlate well with Monson Gneiss. The area west of the pluton has much broader gradients between 3100 and 3300 gammas. The Ammonoosuc Volcanics correlate well with aeromagnetic highs of 3300 to 3400 gammas. The Belchertown pluton shows up (fig. 8) as a broadly circular aeromagnetic low. Within this low a high of 3380 gammas and a low of 2772 gammas constitute the magnetic signature of the two-pyroxene quartz monzodiorite in the core of the pluton. Near the northern edge of the pluton, several large inclusions of amphibolite and granofels (fig. 2) approximately correlate with highs of 3300 to 3400 gammas.

As pointed out by Hall (ms), if the magnetic high near the center of the pluton is associated with the magnetic low to the southeast, then this would imply that the plutonic rocks possess a strong natural remanent magnetization (NRM) having a southerly (reversed) direction of polarization. This implication has been confirmed by paleomagnetic measurements made by Ashwal and Hargraves (1977) who found that the two-pyroxene quartz monzodiorites of the inner zone possess a strong, stable, and consistently oriented NRM vector, whereas the hydrated gneisses of the outer zone have neither appreciable remanence nor sus-

![Aeromagnetic map of Belchertown pluton and adjacent units. Interval of isopleths (solid lines) is 100 gammas above arbitrary datum plane. Geologic contacts (dashed lines) and faults are shown as in figure 2. Modified from U.S. Geological Survey (1968a, b; 1969a, b).]
ceptibility. Computer modeling by Ashwal and Hargraves (1977) of the three-dimensional shape of the pluton on the basis of the observed aeromagnetic anomaly and the measured NRM vector indicated that the primary igneous rock (inner zone) is a thin (0.5 km) slab having a deeper (5 km) root under the 2772 gamma low southeast of the present surface exposure of primary rocks. This shape may be interpreted either as a deep downfold of primary plutonic rocks in the synclinal corner between the Glastonbury dome and the main body of Monson Gneiss or as a cylindrical feeder pipe for the entire intrusion. Ashwal and Hargraves (1977) also noted that the orientation of the mean Belchertown NRM vector is discordant with respect to that of the mean North American Devonian vector, as obtained from paleomagnetic studies of the Perry Formation of Maine and New Brunswick (Irving and Opdyke, 1965), in such a direction as to suggest that the entire inner zone of the pluton, if not the entire pluton, has undergone about 30° to 60° of tectonic rotation to the northwest about a northeast-southwest axis. A similar rotation of the pluton between 30° and 40° to the north about a roughly east-west axis would be indicated using the North American Devonian vector recently obtained by Kent and Opdyke (1978) from paleomagnetic studies of Catskill red beds in New York State. Because the Curie temperature of the phases mainly responsible for the remanent magnetization appears to be between 625° and 550°C (Ashwal and Hargraves, 1977, p. 1319), it is suggested here that the rotation may have taken place during late stages of Acadian dome formation during, or more probably just subsequent to, formation of the recrystallized hornblende-biotite gneisses.

Three-dimensional Form of the Pluton

Mapped contact relationships and gravity and magnetic data suggest that the intrusion has the form of a semiconcordant sheet intruding the Partridge Formation (Middle Ordovician) and Erving Formation (Lower Devonian); the intrusion only locally cuts the underlying Ammonoosuc Volcanics or the gneisses that now form the cores of gneiss domes. Indications that this intrusive sheet once may have had a much greater areal extent and that the present exposure is merely an uneroded remnant folded down among three gneiss domes include: (1) the exposures west of the Connecticut Valley in the so-called Hatfield pluton (Emerson, 1917; Stoerck, 1971); (2) several small exposures of enigmatic Belchertown-like rocks exposed along the Connecticut Valley border fault tens of kilometers north of the Belchertown pluton; (3) abundant boulders of Belchertown and Belchertown-like rocks in Mesozoic conglomerates; and (4) abundant grains of hypersthene with titanohemerite lamellae in Jurassic sandstone from Meriden, Conn. (Reed, ms), opposite the southern part of the Glastonbury dome.

As stated earlier, magnetic data suggest either a very deep and tight downfold of the plutonic rocks or a pipelike feeder for the entire pluton. Alternatively, a feeder might have been located in the vicinity of the intrusive breccias in or near the north end or in regions presently covered
by Mesozoic rocks. The positive gravity anomaly formed by the pluton and the density contrast between the plutonic rocks (2.79-2.84 g/cm³) and the cores of adjacent gneiss domes (2.65-2.72 g/cm³) show that the plutonic rocks would have behaved as a gravitational sinker during rise of the adjacent domes. Such a mechanism could help explain the present outcrop distribution of Belchertown rocks. Late twisting of the entire body of inner zone rocks within the sinking mass, in the constricted corner between the Glastonbury dome and the main body of Monson Gneiss, could account for the rotation suggested by Ashwal and Hargreaves (1977).

RADIOMETRIC AGE DETERMINATIONS

The Belchertown pluton has been recognized as a syntectonic Devonian intrusion by its field relationships, and new radiometric age determinations reported here agree with this observation. The Prescott Intrusive Complex, which occupies a similar structural setting some 20 km to the north (fig. 1), has yielded a Rb–Sr whole-rock isochron age of 377 ± 20 m.y. (Naylor, 1970). Farther north in eastern Vermont and in western Maine, several other late orogenic intrusions are now known to have been emplaced during this same late Early to early Middle Devonian time interval (Naylor; 1971; Moench and Zartman, 1976).

A fresh sample of two-pyroxene quartz monzodiorite typical of the inner core of the Belchertown pluton was collected for zircon age determination from the western end of the Three Rivers railroad cut (fig. 2, no. 1). Both a bulk-rock analysis (table 1, no. 1) and mineral analyses (table 2) were also carried out on this sample. The rock was chosen to be representative of the magmatic stage of emplacement least affected by metamorphic hydration. The results are summarized in table 3, and the details of the analytical procedure are given in the appendix.

The calculated U–Pb ages of the two zircon size fractions are concordant within analytical error. This concordance implies closed-system behavior for the mineral since the time of original crystallization. An age of 380 ± 5 m.y. (2σ confidence level) encompasses all the U–Pb data. This

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Uranium–thorium–lead isotopic ages of zircon from the Belchertown pluton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concentration [ppm]</td>
</tr>
<tr>
<td></td>
<td>U</td>
</tr>
<tr>
<td>Mesh size</td>
<td>(ppm)</td>
</tr>
<tr>
<td>-100+150</td>
<td>230.5</td>
</tr>
<tr>
<td>-200+270</td>
<td>294.4</td>
</tr>
</tbody>
</table>

*Analyses by Margarita D. Gallego and Robert E. Zartman, U.S. Geological Survey. Decay constants: ²³⁵U – λ = 1.55125 × 10⁻⁹ yr⁻¹; ²³⁸U – λ = 9.8485 × 10⁻¹⁵ yr⁻¹; ²³⁶Th − λ = 4.9475 × 10⁻²¹ yr⁻¹. The isotope ratios of the common lead used to correct for the nonradiogenic lead present in the zircon are ²⁰⁶Pb/²⁰⁶Pb = 18.2, ²⁰⁷Pb/²⁰⁶Pb = 15.6, and ²⁰⁸Pb/²⁰⁶Pb = 38.0.

* The determination of Th is considered to be accurate to only ± 4 percent; see appendix.
age is in excellent agreement with the earlier findings of Naylor (1970, 1971) and Moench and Zartman (1976) for other plutons in New England and is midway between the extreme ages for Acadian plutonic rocks in southern New Hampshire reported by Lyons and Livingston (1977). Lyons and Livingston's (1977) date of 402 ± 19 m.y. for the Kinsman Quartz Monzonite that intrudes the Littleton Formation (Lower Devonian) suggests that perhaps 20 to 25 m.y. intervened between deposition of the Erving and Waits River Formations (Lower Devonian) and the emplacement of the Belchertown pluton. Particularly here, astride the Bronson Hill anticlinorium, the evidence is compelling for very intense deformation in Early Devonian time, during which at least two generations of giant nappes were produced (Thompson and others, 1968). Intrusion of the Belchertown and Prescott plutons took place following the culmination of this most intense deformation but before the main stage of gneiss dome formation, an extended period during which pervasive deformation and recrystallization continued.

The time of hydration and metamorphic recrystallization of the pluton is a point of considerable interest, as it could yield some clues to the duration of the Acadian orogeny beyond its most intense phase. Superficially, it would seem that such information could be provided by a K–Ar age on one of the hydrous minerals, such as hornblende or biotite. However, Zartman and others (1970) have shown that the pluton is within a broad area of southeastern New England affected by a Permian thermal disturbance. This somewhat enigmatic younger event has completely reset K–Ar biotite ages and, on the basis of very limited sampling, has partially reset K–Ar hornblende ages of nearby rocks. Nevertheless, hornblende samples from two localities within the pluton were analyzed in order to see if they contained useful information about the time at which the quartz monzodiorite was hydrated to hornblende–biotite gneiss. The discrepant results in table 4 suggest to us that these hornblendes have indeed been subjected to later disturbance. On the other hand, the age difference could, in part, be explained by a small contribution of biotite to sample

### Table 4

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>K,0 (wt. percent)</th>
<th>40Ar radiogenic (moles/g)</th>
<th>Percentage of 36Ar of radiogenic origin</th>
<th>Age (m.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71-GWL-119-1</td>
<td>0.926</td>
<td>5.33 × 10⁻¹⁰</td>
<td>93</td>
<td>361 ± 6</td>
</tr>
<tr>
<td>A 13-1</td>
<td>0.704</td>
<td>3.61 × 10⁻¹⁰</td>
<td>70</td>
<td>325 ± 6</td>
</tr>
</tbody>
</table>

Analyses by Richard F. Marvin, Harold II. Melvurt, John D. Obradovich, and Kiyoto Fita, U.S. Geological Survey. Decay constants $\lambda_B = 4.962 \times 10^{-10}$ yr⁻¹, $\lambda_e = 0.581 \times 10^{-10}$ yr⁻¹, $^{40}K/^{40}Ar = 0.01167$ atom percent. Potassium and argon determinations by isotope-dilution techniques.

* Hornblende–biotite quartz monzodiorite gneiss from outer zone of Belchertown pluton, south bank of Chicopee River directly north of intersection of Baptist Hill and Red Bridge Roads; b table 1, no. 8.
A13-I (table 1, no. 8), inasmuch as the mica would probably give a Permian age. If subsequent heating has caused only diffusive loss of radiogenic argon, the data can be used to establish a minimum age of $361 \pm 6$ m.y. (Middle to Late Devonian) for the formation of the hornblende.

OTHER PLUTONS OF SIMILAR COMPOSITION

The composition of the Belchertown pluton is quite unusual, and similar rocks, both within and outside New England, appear to be rare. The only intrusions in New England known to the writers that approximate the Belchertown composition are the Exeter Diorite pluton and related smaller diorite plugs in southeastern New Hampshire (Sundeen, 1971) and the granodiorite at Umbagog Lake in western Maine (Milton, 1961). The Exeter Diorite is compositionally similar to the Belchertown pluton (Sundeen, 1971, tables 8 and 11) but lacks pyroxenes except for traces of relict augite. The “Umbagog granodiorite” contains augite and locally hypersthene (Milton, 1961, table 13). Both the Exeter Diorite and the “Umbagog granodiorite” are of variable composition and fall at least partly in the quartz monzodiorite field as used in this paper.

The Belchertown pluton is strikingly similar to Adamant pluton in British Columbia west of the Rocky Mountain trench (Fox, 1969). Adamant pluton, in addition to having a chemical and mineralogical composition similar to that of the Belchertown pluton, also has the same kind of zoning from an anhydrous two-pyroxene quartz monzonite core to a more hydrated, hornblende-bearing gneiss. Accessory magnetite and ilmenite-hematite-rutile, moreover, indicate a state of oxidation comparable to that of the Belchertown. Oxidation ratios $(2Fe_2O_3 \times 100)/(2Fe_2O_3 + FeO)$ decrease progressively outward in Adamant pluton, but no such regularity appears to exist in the Belchertown pluton (table 1).

Adamant pluton is interpreted as a mesozonal diapir intruded in a largely solid condition, the recrystallized outer zone being attributed to shearing effects during tectonic emplacement of the mass (Fox, 1969, p. 77-79). This origin differs substantially from that postulated for the Belchertown pluton which is regarded as having been emplaced into high crustal levels and having been involved subsequently in an environment of active dynamothermal metamorphism.

SUMMARY AND CONCLUSIONS

The foregoing observations on the Belchertown pluton permit the following conclusions regarding its history.

1. The mineralogy and bulk composition of the primary quartz monzodiorite indicate that prior to crystallization the original melt had attained an extremely high oxygen fugacity anywhere between the oxygen fugacities of the Ni-NiO and Mag-Hem buffers. Although no quantitative model is given, this high oxygen fugacity seems most likely to have arisen by massive devolatilization of a magma chamber associated with surface eruptions. Such an original shallow level of intrusion, as compared to the present setting among gneiss domes in a kyanite-grade metamorphic terrain, is consistent with (A) the presence of a hornfelsed dacite
porphyry inclusion of bulk composition related to that of the pluton, (B) the presence of pseudomorphs of sillimanite after andalusite in a large pelitic schist inclusion near the center of the pluton, and (C) the fact that of all the rocks now exposed east of the Connecticut Valley border fault, only rocks of the Belchertown pluton can be recognized with certainty in the Jurassic fanglomerate to the west.

2. The compositions of coexisting primary augite and hypersthene in the quartz monzodiorite indicate initial crystallization at 950° to 900°C, and the primary assemblage augite–hypersthene–quartz–potassic feldspar–plagioclase–titanohematite–magnetite indicates conditions of low fugacity of H₂O. Poikilitic brown biotite and olive-green hornblende appear to have crystallized from pockets of H₂O-enriched residual liquid at temperatures as low as 650°C and T₃H₂O as high as 4000 bars. U–Pb data from two size fractions of zircon from typical primary quartz monzodiorite yield a concordant age of 380 ± 5 m.y. for the age of igneous crystallization, consistent with ages of other syntectonic to late tectonic intrusions in the region.

3. Contact relationships, geophysical data, and miscellaneous other information tentatively suggest that the intrusion initially had the form of a semiconcordant sill, perhaps of great areal extent, in Paleozoic strata overlying the Ammonoosuc Volcanics and the gneisses now exposed in the domes. In this interpretation, the present area of exposure is an erosional remnant of downfolded Belchertown rocks among the domes.

4. Subsequent to solidification, the pluton long remained hotter than surrounding rocks and was subjected to the intense late stages of the Devonian Acadian orogeny involving gravitational upward movement of the low-density cores of the Pelham and Glastonbury gneiss domes and the main body of Monson Gneiss. The Belchertown rocks, being of similar density to the Paleozoic mantling strata of the domes, behaved as a gravitational sinker among the rising domes. It was probably during this sinking that sillimanite formed pseudomorphs after andalusite, that fracturing and cataclasis took place, and that primary quartz monzodiorite was hydrated and recrystallized to hornblende–biotite gneiss. K–Ar ages on hornblende from the gneiss set a minimum age of 361 ± 6 m.y. for the recrystallization.

ACKNOWLEDGMENTS

The field and laboratory work of Ashwal, Robinson, and Hall was supported in part by National Science Foundation Grants GA-390, GA-33857, and GA-33857A1 (to Robinson) and GA-31989 (to Jaffe and Robinson), by U.S. Geological Survey Grants G-340 and G-400 (to Robinson), and by a Grant from the Penrose Bequest of the Geological Society of America (to Hall). Our attention was called to the problems of the Belchertown pluton by the mapping of James O. Guthrie and John D. Peper. Ashwal was assisted in the field by Donald W. Curran. Hall was assisted by Farrukh Ahmad, Richard C. Felkel, Jr., and Wayne Dowdall. John F. Kick made available some of his unpublished gravity data and provided valuable discussion of geophysical interpretation, as did Randolph
W. Bromery and Laurie Brown. The electron microprobe analyses were done by Robert J. Tracy. Howard W. Jaffe provided abundant advice on mineralogic aspects of the project and assisted Ashwal with mineral separations. Stephen E. Haggerty gave advice on the identification and interpretation of opaque minerals. David R. Wones gave early advice on field and theoretical aspects of the project and reviewed a version of the manuscript. O. Don Hermes and Richard S. Naylor reviewed the final version. Several of the figures were lettered by Marie Litterer. To each of these persons and institutions we express our grateful acknowledgment.

Appendix

U-Th-Pb zircon analytical procedure

A zircon concentrate was separated from the sample of quartz monzodiorite (no. 1, fig. 2 and table 1), and the least magnetic portion was split into various size fractions. All impurities remaining in these fractions, -100+150 and -200+270 mesh, were carefully hand picked, leaving a population of euhedral to subhedral zircon grains, which are considered to be primary crystallizing phases of the rock. Prior to dissolution, the zircon was submersed in hot 6N HCl and 6N HNO₃ rinses for 20 min each to remove any soluble surface contamination or inclusions accessible to the acid.

The chemistry was carried out using a modified Krogh (1973) method of HF-HNO₃ bomb digestion after which lead was purified by chloride-form anion-resin exchange columns and anodic electrodessition. Lead concentration was determined by isotope dilution on an aliquot of the sample removed after bomb digestion but otherwise subjected to a parallel treatment with the isotope-composition fraction. A combined U and Th tracer was added to the whole sample prior to digestion, and uranium and thorium were separated together by the nitrate-form anion-resin method of Tatsumoto (1966) from the elutriant off the resin column of the lead-isotope composition fraction.

Mass-spectrometric analysis (1) for lead was by surface ionization from a single rhenium filament containing a H₂PO₄-silica gel emitter and (2) for uranium and thorium was by volatilization off two rhenium side filaments onto a rhenium ionizing filament. Ion currents were measured by means of a vibrating-reed electrometer, and a digital voltmeter was connected to an on-line computer for data reduction.

Recent innovations in chemical technique and mass spectrometry have greatly reduced the amount of material required for an analysis. At the present time, a complete determination can be made using about 30 mg of sample. A small correction for an average analytical blank of 2 ng Pb per analysis has been applied to the raw data as given in table 3. U and Pb concentrations are considered accurate to ±1 percent (2σ confidence level), and the following uncertainties are assigned to the measured lead-isotope ratios:

\[ ^{206}\text{Pb}/^{204}\text{Pb} \pm 1 \text{ percent} \]
\[ ^{207}\text{Pb}/^{204}\text{Pb} \pm 0.1 \text{ percent} \]
\[ ^{208}\text{Pb}/^{204}\text{Pb} \pm 0.1 \text{ percent} \]

Some difficulty in determining the concentration of Th was experienced in our laboratory during the course of this work. Consequently, a lesser accuracy of ±4 percent is quoted for this element, and we note only the general agreement of the \(^{207}\text{Pb}/^{207}\text{Th}\) age with those of the more precise U-Pb method in interpreting the results.

References


