Glastonbury Gneiss and Mantling Rocks (a Modified Oliverian Dome) in South-central Massachusetts and North-central Connecticut: Geochemistry, Petrogenesis, and Isotopic Age

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1295

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By GERHARD W. LEO, ROBERT E. ZARTMAN, and DOUGLAS G. BROOKINS[1]

ABSTRACT

The Glastonbury dome is a long, narrow structure trending approximately 70 km north-northeast through Connecticut and Massachusetts along the west side of the Bronson Hill anticlinorium. Structurally and stratigraphically the dome is analogous to the Oliverian domes of New Hampshire. It is cored by Glastonbury Gneiss and is mantled by Ammonoosuc Volcanics and Partridge Formation (or their equivalents) of Ordovician age. The Glastonbury Gneiss intrudes the Ammonoosuc and, thereby, establishes the relative age of the two units. Monson Gneiss, which unconformably underlies the Ammonoosuc Volcanics in the Monson anticline to the east, is not in contact with Glastonbury Gneiss except near Stafford Springs, Conn., where the contact may be gradational. In some places, Monson Gneiss shows evidence of plastic flow and potential anatexis. The northern part of the Glastonbury Gneiss typically is leucocratic, granoblastic, relatively potassium-poor gneiss that appears homogeneous in outcrop, but proves to be chemically and modally inhomogeneous over short distances, as shown by variation diagrams and REE plots. The gneiss straddles the compositional fields of trondhjemite, tonalite, and granodiorite, and partly overlaps that of Monson Gneiss. The southern part of the Glastonbury Gneiss is consistently more potassic than the northern, having compositions ranging from granite to granodiorite. All of the Glastonbury Gneiss show pervasive, strong foliation, deformation, and local shearing related to the Acadian orogeny.

Field relations, textures, and chemistry of the northern part of the Glastonbury suggest an origin by anatexis of the premetamorphic Monson sequence at temperatures of about 690°C to 750°C and pressures of <3kbars. The southern part of the Glastonbury appears to have been generated contemporaneously but not comagmatically from calc-alkaline crust. U-Pb zircon ages for both the northern and southern bodies are slightly discordant with $^{207}Pb/^{206}Pb$ ages of 445 to 467 m.y. At first these results seem to contradict the known stratigraphic position of the Glastonbury relative to the Monson, which yields distinctly younger zircon $^{207}Pb/^{206}Pb$ ages of 428 to 440 m.y. However, this apparent discrepancy in the radiometric ages—younger Monson, older Glastonbury—could be resolved by postulating either (1) a small component of old inherited zircon in the Glastonbury or (2) preferential metamorphic overprinting of the zircon in the Monson. In any case, the isotopic age discrepancy is not so large as to render the proposed Monson anatectic model implausible. Rb-Sr whole-rock data show a large amount of scatter on an isochron diagram and hence do not permit a reliable estimate of age. This condition may reflect inhomogeneities in the initial $^{87}Sr/^{86}Sr$ ratio or may have been also induced by later Acadian or Alleghanian metamorphism.

An early Silurian to Middle Ordovician age of the Glastonbury Gneiss gives evidence of higher heat flow and more extensive plutonism in the Taconic than has generally been recognized. With certain qualifications, the Glastonbury and associated volcanic rocks are compatible with recent plate-tectonic models involving the Bronson Hill anticlinorium.

INTRODUCTION

The Glastonbury dome is a narrow, elongate structure that extends from just south of the Belchertown Quartz Monzodiorite pluton (Ashwal and others, 1979) in central Massachusetts to the vicinity of Middle Haddam, Connecticut. The term "Glastonbury dome" as used henceforth refers to the tectonic feature with constituent lithologies, whereas "Glastonbury Gneiss" refers only to the core gneiss itself. A parallel distinction applies to the terms "Oliverian dome(s)" and "Oliverian core gneiss(es)". The Glastonbury dome constitutes part of the Bronson Hill anticlinorium (Billings, 1956; Thompson and others, 1968), a complexly folded and deformed sequence of lower Paleozoic metasedimentary, metavolcanic, and plutonic rocks trending south-southwest from northern New Hampshire to Long Island sound (fig. 1). The stratified rocks are intruded by a variety of granitic plutons that constitute several plutonic or plutonic-volcanic suites ("magma series" of Billings, 1937, 1956) and range in age from Middle Ordovician to Cretaceous. The age of the Oliverian Plutonic Suite in New Hampshire has been reliably established as Middle Ordovician (Naylor, 1969; Foland and Loiselle, 1980; Zartman and Leo, 1981). Oliverian plutons form the cores of a number of gneiss domes mantled by the Ammonoosuc Volcanics of the Middle Ordovician age (Naylor, 1968, 1969; Leo, 1980a,b). The Ammonoosuc Volcanics are a mostly bimodal sequence of metamorphosed tholeiite and quartz keratophyre tuff, locally associated with sills and stocks of trondhjemite (Leo, 1980c; Leo and Gromet, 1981).

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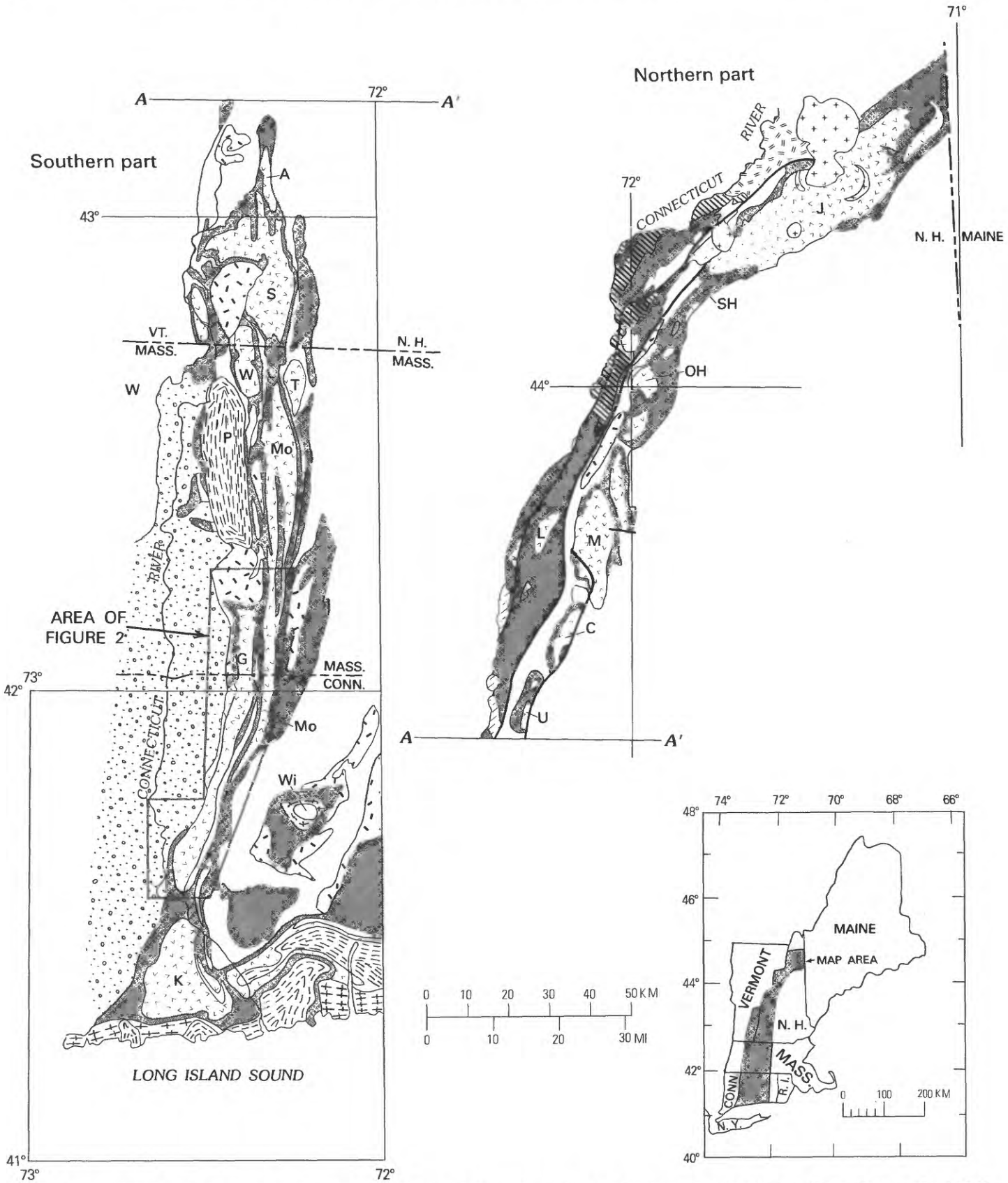

FIGURE 1.—Simplified geologic map showing the central part of the Bronson Hill anticlinorium, emphasizing the Oliverian domes and Ammonoosuc Volcanics. Geology east and west of the Ammonoosuc Volcanics mostly omitted. Adapted from Robinson and Hall (1980, fig. 1) and Billings (1955). Letter symbols for Oliverian and other domes (see explanation) as follows (generally north to south): J, Jefferson; SH, Sugar Hill pluton; OH, Owls Head; M, Mascoma; L, Lebanon; C, Croydon; U, Unity; A, Alstead; S, Swanzey; W, Warwick; P, Pelham; T, Tully; Mo, Monson Gneiss; G, Glastonbury; Wi, Willimantic; K, Killingworth.

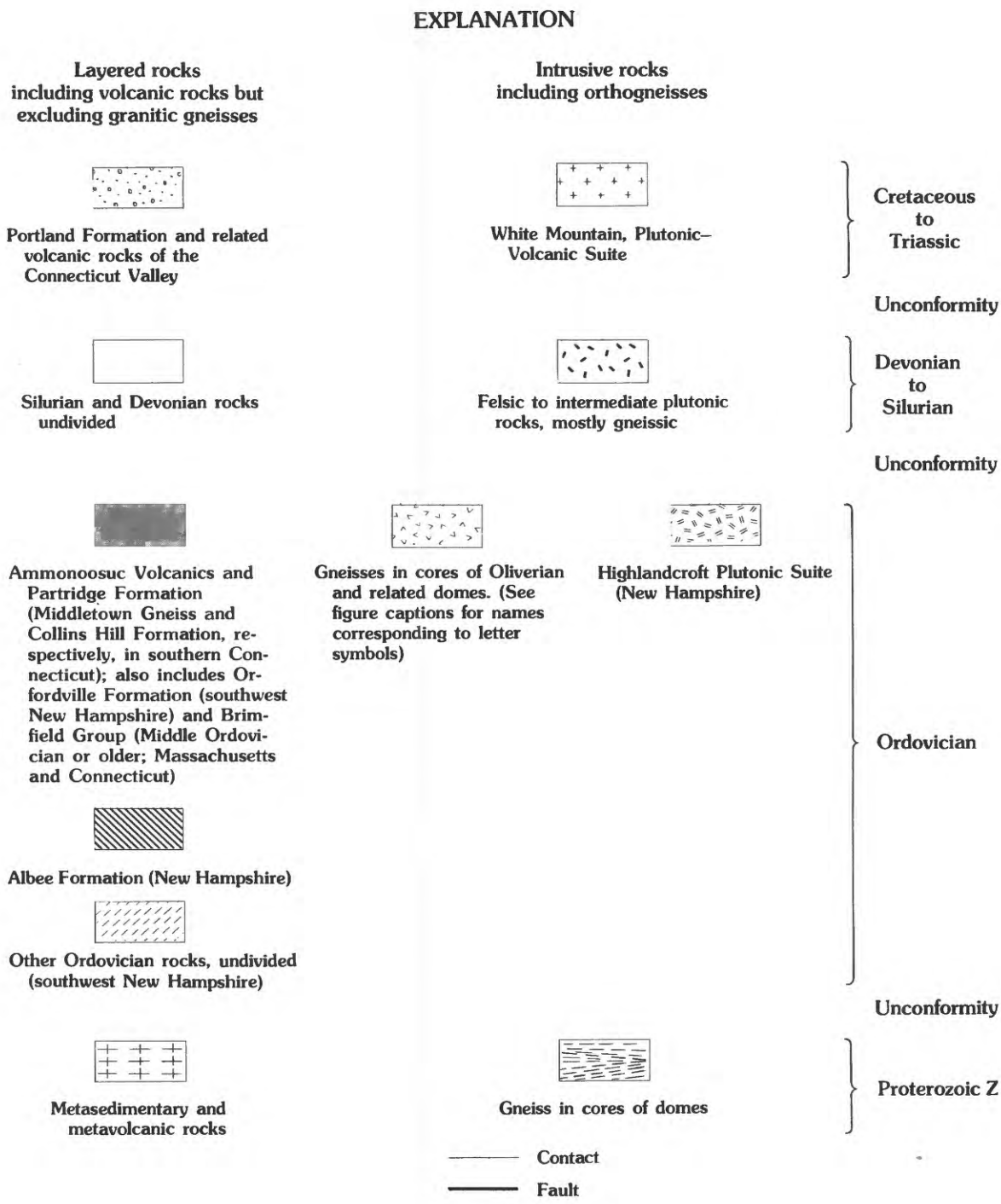

FIGURE 1.—Continued

The Glastonbury Gneiss resembles Oliverian core gneisses in that (1) it also is mantled by Ammonoosuc Volcanics (and, at its southern end, by the Collins Hill Formation of Rodgers and others, 1959, hereby adopted for U.S. Geological Survey usage), which overlies the Ammonoosuc Volcanics or its correlative, the Middletown Gneiss in Connecticut, and intrudes these strata along much of the western side of the dome; and (2) the dome is pervasively metamorphosed at middle amphibolite facies grade and exhibits Acadian deformation.

The Glastonbury Gneiss (fig. 2) can be divided into two parts, northern and southern, on the basis of minerology and chemistry. The northern part of the gneiss (henceforth referred to informally as "northern Glastonbury Gneiss" or "northern gneiss") is typically low in potassium (compositionally trondhjemite to tonalite), although the composition is variable on a local scale. The southern part of the gneiss (henceforth referred to informally as "southern Glastonbury Gneiss" or "southern gneiss") is much more potassic and is mostly granite. Field relationships and chemical data suggest that the northern gneiss was produced by anatexis of Middle Ordovician volcanic rocks (the protolith of the Monson Gneiss).

In several of the northern domes, notably the Mascoma dome (Naylor, 1969; fig 1), K-poor, felsic, stratified rocks of volcaniclastic aspect mantle the intrusive core gneiss. Naylor applied the term "stratified core gneiss" to these rocks in the Mascoma dome and regarded them as an integral part of the Oliverian lithology, although he left open the possibility that they might represent a downward continuation of the Ammonoosuc Volcanics. Further study (Leo, unpub. data) has shown that somewhat similar rocks underlie the Ammosuc in several, but by no means all, of the other Oliverian domes. It seems appropriate, therefore, to put such rocks in a special category, for example, an informally designated "pre-Ammonoosuc volcanic section," and to discontinue the use of the term "Oliverian" as part of their name.

In New Hampshire and Vermont, intrusive trondhjemite is associated with the Ammonoosuc Volcanics in several of the Oliverian domes, commonly as sills and other minor intrusions. In three small domes, trondhjemite constitutes the entire core gneiss (Leo and Gromet, 1981). These trondhjemites differ somewhat from the northern Glastonbury Gneiss in that they contain relatively lower K_2O and CaO and higher Na_2O. Thus they define a different compositional field on normative diagrams (table 1; figs. 8 and 9). Trace element abundances, including rare earths, are also somewhat different and suggest a mantle origin for at least some of the New Hampshire and Vermont trondhjemites (Leo, unpub. data). By contrast, field relationships as well as textural and chemical features of the northern Glastonbury Gneiss suggest that it originated in the upper crust by anatexis of a premetamorphic Monson lithology. Nevertheless, as will be discussed below, the possibility that the northern Glastonbury Gneiss represents a magmatic Ammonoosuc phase, analogous to the trondhjemites to the north, cannot be completely discounted.

If the mode of origin here proposed for the northern Glastonbury Gneiss is correct, it implies a higher heat flow related to the Taconic orogeny than has heretofore been proposed or documented.

ACKNOWLEDGMENTS

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REGIONAL GEOLOGY

The layered rock units described below are arranged in order from oldest to youngest based on field relationships and not on the somewhat anomalous radiometric dates for the Monson and Glastonbury Gneisses (to be described below). The Glastonbury Gneiss is listed last (youngest) because it cuts Ammonoosuc Volcanics; however, the Glastonbury has not been shown to cut the Partridge and (or) the equivalent Collins Hill Formations that conformably overlie Ammonoosuc Volcanics. It is therefore conceivable that the Glastonbury is actually older than the Partridge/Collins Hill. This relationship is not basic to the subject of this paper.

MONSON GNEISS

The Monson Gneiss (Monson granodiorite of Emerson, 1917, p. 241–243) underlies the Ammonoosuc Volcanics from southern New Hampshire to Long Island Sound. The Monson is exposed in broad domes in northern Massachusetts ("main body" and "Tully dome" of Robinson and Hall, 1980); and in southern Connecticut (Killingworth dome) (fig. 1). Between these two areas it constitutes a stratigraphic layer, locally much faulted and displaced (fig. 2). Quartz-plagioclase gneisses in the Willimantic dome (fig. 1) and the Selden Neck dome to the south, traditionally correlated with Monson Gneiss to the west across the Chester syncline (not shown in fig. 1), are reported to show chemical and

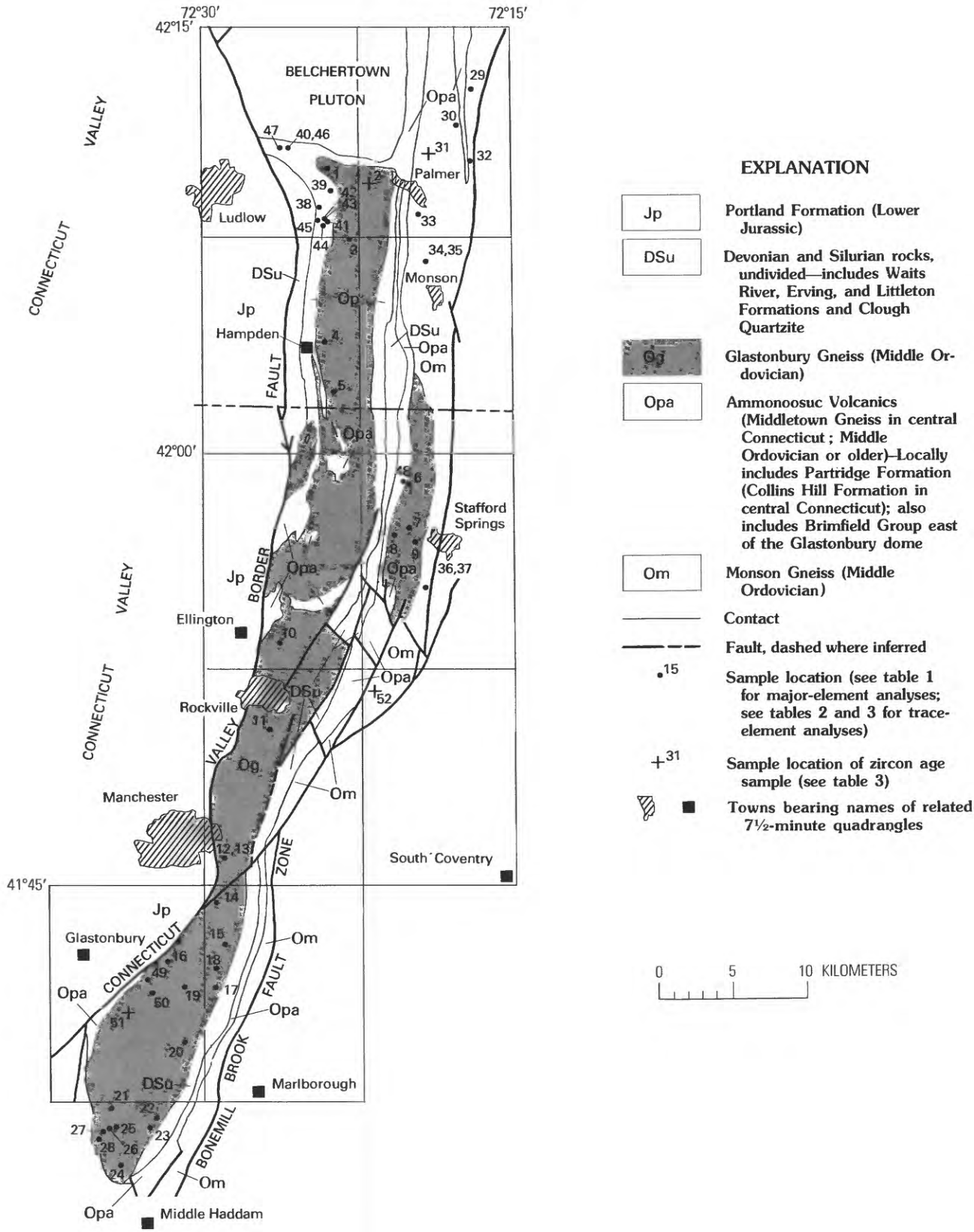


Figure 2.—Geologic sketch map of the Glastonbury Gneiss dome and adjacent lithologic units. Compiled from published sources (Collins, 1954; Aitken, 1955; Herz, 1955; Snyder, 1970) and from various unpublished data, mainly those of M. H. Pease, Jr., and J. D. Peper of the U.S. Geological Survey. Sample locations are keyed to tables 1-4. Locations within the Ludlow quadrangle, Massachusetts, are shown more accurately in Leo and others, 1977.

mineralogical features which make such a correlation doubtful (Wintsch, 1980).

Contacts between the Monson Gneiss and overlying Ammonoosuc Volcanics are poorly exposed and are as yet somewhat problematical. Peper (1966) described the contact as gradational, although subsequent inspection of one of the better exposures (unnamed hill 0.8 km west of Palmer Center, Palmer 7½-minute quadrangle, Massachusetts) suggested that the contact is sharp and unconformable. Robinson (1979, p. 137) has cited a quartz-pebble conglomerate on the contact. On the basis of isotopic ages determined for the Monson Gneiss (see below), it appears that any unconformity between the Monson and the Ammonoosuc must represent a relatively short interval of erosion.

The Monson Gneiss is commonly a light-gray quartz-plagioclase rock with less than 15 percent mafic minerals (including biotite, hornblende, and epidote). K-feldspar is typically absent, but locally constitutes 10 percent or more. Ordinarily the gneiss shows some degree of lithologic banding that may or may not be related to primary layering (fig. 3*B–D*). Sharply bounded, tabular amphibolite layers are very probably sills (fig. 3*C, D*). Where observed, such sills are pre-Acadian and thus could be Ammonoosuc feeders. Banding in Monson may be swirled, shadowy, and suggestive of incipient anatexis (fig. 4*A, B*). Locally, banded gneiss grades to nearly homogeneous, weakly foliated rock resembling some exposures of Glastonbury Gneiss (fig. 3*E*). Locally, as at the Flynt quarry north of Monson (loc. 34, 35, fig. 2), the gneiss lacks layering and shows a number of features suggestive of plastic flow (fig. 4*C–E*). In these places, the rock is massive, faintly foliated, and compositionally inhomogeneous and is traversed by felsic veins and streaks, mafic schlieren, and localized sharp to shadowy contacts between more felsic and more mafic rock (fig. 4*E*). Discordant, typically ellipsoidal inclusions of amphibolite are abundant (fig. 4*C, D*). Their contacts against enclosing felsic gneiss are sharp, and the gneissic foliation flows around the inclusions. Felsic layers within amphibolite have a blotchy texture suggestive of segregation in response to partial melting, but such layers are more or less sharply truncated against the enclosing gneiss. These features suggest that the felsic gneiss reached the condition of anatexis and plastic flow, disrupting mafic layers and carrying fragments from the site of anatexis.

Textures of the Monson Gneiss generally reflect thorough recrystallization. Textures are generally granoblastic, with more or less distinct foliation, which is parallel to original layering where the latter is recognizable. The variation in grain size within a thin section ranges from an estimated 1:5 to 1:25 or more. Large grains of quartz and plagioclase in a much finer granoblastic matrix are characteristic. Quartz tends to form interstitial, elongate patches, locally virtual ribbons, with scalloped margins against adjacent minerals. These quartz patches are evidently the result of metamorphic recrystallization under stress and (or) cataclasis. Plagioclase forms large, undisturbed grains with scalloped margins which evidently are porphyroblasts (possible recrystallized clasts).

The mineralogy, textural features, megascopic appearance, layered character, and associated amphibolite tend to confirm the impression of earlier workers that the Monson is dominantly, if not entirely, of volcaniclastic origin. This view is reinforced by the bulk chemical compositions and norms of the analyzed samples (table 1).

AMMONOOSUC VOLCANICS

The Ammonoosuc Volcanics is a lithologically diverse unit of volcanic, volcaniclastic, and epiclastic origin of Middle Ordovician age that mantles Oliverian core gneisses from northern New Hampshire to Connecticut. Northwest of the Oliverian domes (northwestern New Hampshire and eastern Vermont), the Ammonoosuc overlies the quartzose to pelitic, largely nonvolcanic Albee Formation along a gradational contact. Southeast of a line corresponding roughly to the axis of the Bronson Hill anticlinorium, the Albee Formation is lacking and Ammonoosuc Volcanics is intruded by Oliverian core gneisses.

The Ammonoosuc Volcanics includes mafic hornblende-plagioclase amphibolite and felsic granofels consisting mostly of quartz and sodic plagioclase, thus quartz keratophyre, in addition to intrusive trondhjemite (see below). Rocks of other compositions are widespread, notably such that contain Ca-poor amphiboles, and in some cases these have an intermediate chemical character (dacite or andesite). Nevertheless, the dominant Ammonoosuc assemblage is bimodal as well as K-poor. At least some metabasaltic rocks correspond to oceanic tholeiite (Aleinikoff, 1977; Leo, unpub. data). Associated felsic rocks, especially where thinly banded (fig. 3*A*), are almost certainly tuffaceous. More massive layers of felsic Ammonoosuc could be flows, though primary textures, if any, have been obliterated. Geochemical characteristics of the Ammonoosuc Volcanics are compatible with the development of these rocks in an environment suggestive both of an island-arc and a continental-margin regime (Leo and Gromet, 1981; Leo, unpub. data). Textures and mineralogy, especially of the felsic Ammonoosuc near the Glastonbury dome, have been described in more detail elsewhere (Leo and others, 1977; Leo, 1977). Eleven analyses of felsic layers of Ammonoosuc Volcanics are given in table 1.

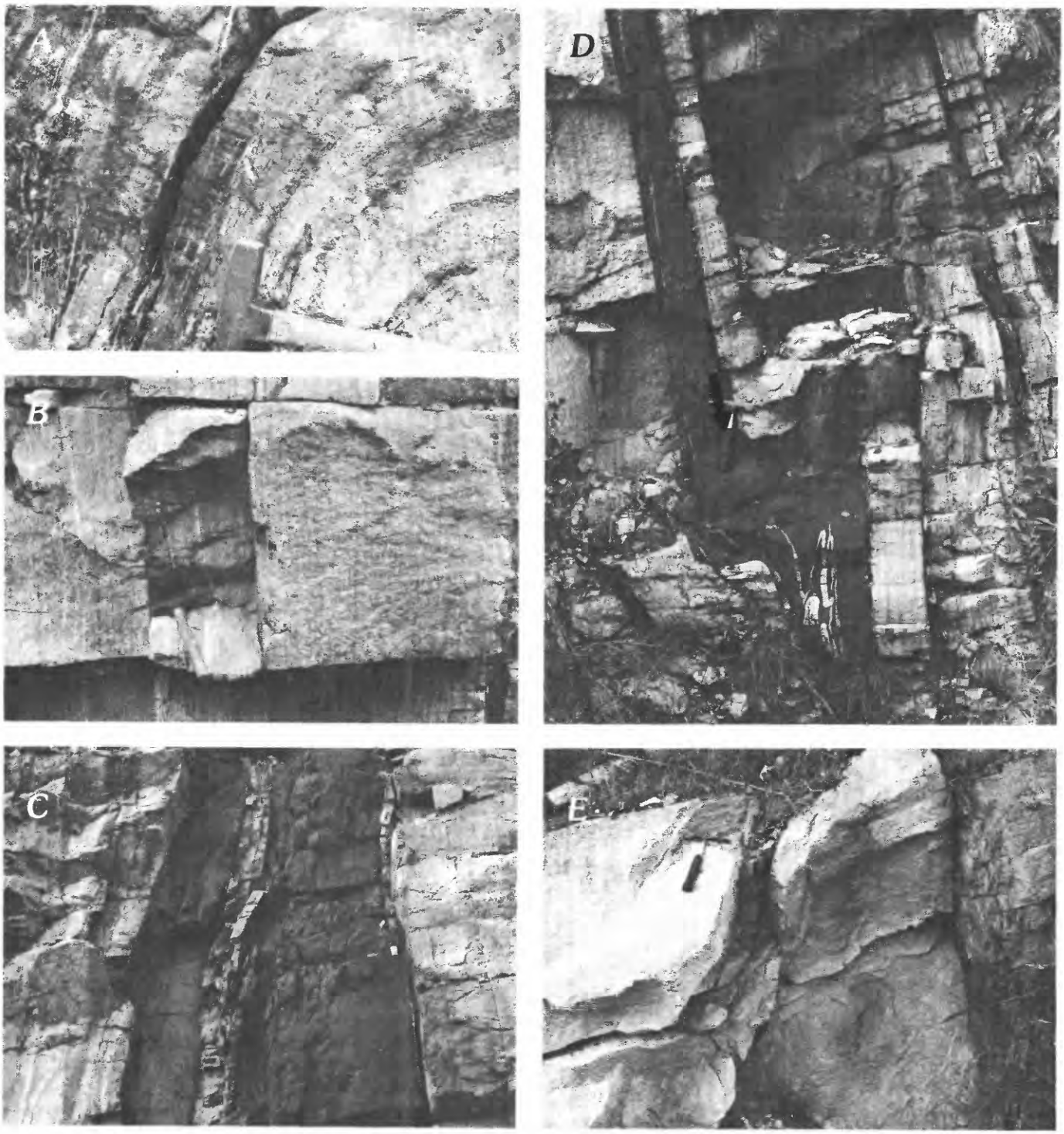


FIGURE 3.—Ammonoosuc Volcanics and Monson Gneiss. *A,* Typical association of mafic and felsic layers in folded Ammonoosuc Volcanics. Southeast side of Minechoag Mountain, Ludlow 7½-minute quadrangle, Massachusetts (fig. 2, loc. 47). *B,* Monson Gneiss showing vertical compositional banding (not necessarily primary) in north side of cut on Massachusetts Turnpike (I–90), 2.5 km north-northeast of center of Palmer, directly east of Breckenridge Street overpass, Palmer 7½-minute quadrangle, Massachusetts (fig. 2, loc. 31). *C,* One-meter wide amphibolite sill in Monson Gneiss. Note sharp contacts and septum of Monson in left half of sill. Same location as *B. D,* Folded amphibolite sill in banded Monson Gneiss. The fold is a north-plunging S-fold related to the Acadian deformation that involved both the amphibolite and the gneiss. One hinge of fold is under hammer (arrow along fold axis). Same location as *B. E,* Imperceptible transition from banded Monson Gneiss (right side of photo) to weakly foliated but unlayered rock (under hammer) similar to some northern Glastonbury Gneiss. Same location as *B.*

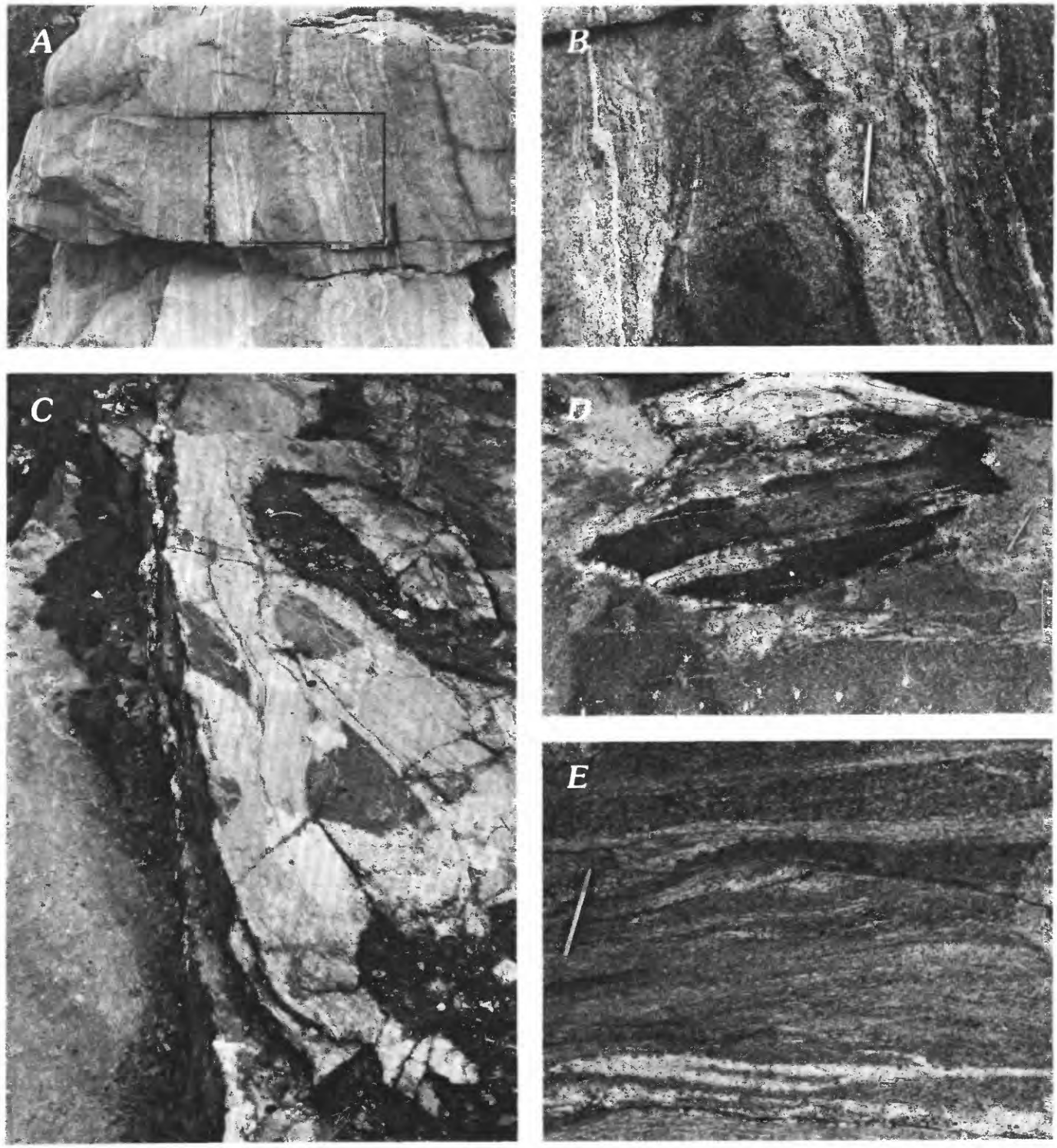


FIGURE 4.—Monson Gneiss showing partial anatexis and plastic flow. *A,* Gneiss showing swirled banding and local felsic segregations (incipient anatexis). Massachusetts Route 2, southwest ramp of Orange exit, 3.3 km south-southeast of center of Orange, Orange 7½-minute quadrangle, Massachusetts. Adjacent gneiss is mostly finely banded, comparable to figure 3*B*. *B,* Detail of *A*. *C,* Ellipsoidal amphibolite inclusions evidently alined by flow of felsic Monson Gneiss. Flynt quarry, east side of upper Palmer Road, about 2 km north-northwest of Monson, Mass. (fig. 2, loc. 34, 35). *D,* Detail of *C*. Note blotchy texture of felsic layer in amphibolite that is indicative of partial melting in this layer, apparently preceding detachment of amphibolite block. Note also sharp boundary of inclusion against gneiss, except for apparent felsic reaction rim along top and left margins. *E,* Swirled and diffuse banding, mafic schlieren (upper right), and felsic (anatectic?) veins (bottom) in gneiss that has apparently flowed plastically. Flynt quarry.

In several areas in western New Hampshire, locally abundant trondhjemite sills intrude the layered Ammonoosuc and core gneiss in three of the smaller domes is trondhjemite (Leo and Gromet, 1981; Leo, unpub. data). The chemistry and mineralogy of the trondhjemite are in most respects similar to that of the layered felsic Ammonoosuc, but there are some consistent differences in rare earth element (REE) patterns (Leo and Gromet, 1981). The trondhjemites of New Hampshire will be discussed further in the context of the northern Glastonbury Gneiss.

The Ammonoosuc Volcanics has been correlated with the lithologically similar Middletown Gneiss in central Connecticut (Eaton and Rosenfeld, 1960, 1972). Herz (1955) mapped the Middletown along the west edge of the Glastonbury dome in the Glastonbury quadrangle (fig. 2); the southward extension of this formation into the Middle Haddam quadrangle, however, was regarded by Eaton and Rosenfeld (1972) not as Middletown but as a distinct unit of possible Permian age (amphibolite of Reservoir Brook of Eaton and Rosenfeld, 1972).

PARTRIDGE AND COLLINS HILL FORMATIONS

The Partridge and Collins Hill Formations of Middle Ordovician age are discussed here only in the context of the regional stratigraphy but are not otherwise involved in the study. The two formations are stratigraphically equivalent and conformably overlie with the Ammonoosuc Volcanics. The name Partridge Formation is applied principally to rocks north of the Connecticut boundary, whereas Collins Hill is the named used for stratigraphically equivalent rocks in the Middle Haddam quadrangle, Connecticut. Both units consist of micaceous schists containing graphite and sulfide (commonly pyrrhotite) with associated calc-silicate and siliceous granofels, coticule, and mafic and felsic volcanic layers (Thompson and others, 1968, p. 206; Eaton and Rosenfeld, 1960, 1972). The sulfide results in a characteristic yellow-brown weathering crust.

GLASTONBURY GNEISS

STRUCTURAL CHARACTER

The Glastonbury dome has only some of the structural attributes of a dome. For this reason it was previously (Leo, 1977) referred to as a body instead of a dome, but the more traditional term of dome is again used here. Flanking units (Ammonoosuc Volcanics in the north, Collins Hill Formation and Silurian and Devonian rocks in the south) wrap around the ends of the Glastonbury Gneiss (fig. 2), but foliation trend lines do not appear to close (Gordon Eaton, oral commun., 1975). Foliation in the gneiss trends predominantly north to northeast with low to moderate northwest dips (fig. 5*D*), and mineral lineations and minor fold axes mostly plunge north to northwest. These minor structures, which generally parallel those of the mantling rocks, indicate a moderate east to southeast overturn of the body and are assumed to be related to the Acadian orogeny.

CONTACT RELATIONSHIPS

Exposed contacts between the Glastonbury Gneiss and adjacent rocks are rare, but outcrop patterns are clear in a number of places. Glastonbury Gneiss intrudes Ammonoosuc Volcanics on the southeast side of Baptist Hill in the Palmer quadrangle (fig. 5*A*). The crosscutting relations are seen in several outcrops over a distance of about 50 m. The contact is sharp, without any evidence of reaction or other alteration. Glastonbury Gneiss from near the contact is among the least potassic encountered. This is the most clearly exposed intrusive contact known to us. Smaller dikes or sills of the Glastonbury in the Ammonoosuc are locally observed (fig. 5*B*). Elongate lenses of Glastonbury within Ammonoosuc in the southern part of the Ludlow 7½-minute quadrangle (Leo and others, 1977) are probably intrusive, but contacts are not exposed.

Evidence for intrusion of the Ammonoosuc Volcanics by the Glastonbury Gneiss on a much larger scale is found along the western margin of the dome south of the Ludlow quadrangle. In the southern part of the Hampden quadrangle, the gneiss has breached the Ammonoosuc in several partly crosscutting sills, creating inliers and roof pendants ranging from a few meters to several kilometers in diameter; one such semiconcordant inlier rifted from the Ammonoosuc section trends more than 4 km south from the town of Hampden (Peper, 1977; fig. 2). Sharp contacts between the Ammonoosuc amphibolite and the Glastonbury Gneiss are locally exposed. Similar relationships are found in the Ellington 7½-minute quadrangle to the south; large blocks of amphibolite in that area, such as that at Soapstone Mountain, are interpreted as roof pendants of the Ammonoosuc in the Glastonbury (M. H. Pease, oral commun., 1974). South of the Ellington quadrangle the Glastonbury dome is mostly fault bounded on both sides. At the southern end of the dome in the Middle Haddam quadrangle, strongly foliated, hornblende-bearing Glastonbury Gneiss crops out a few meters from the lithologically distinct Collins Hill Formation, but an intrusive contact cannot be proved at this locality. Large tabular mafic inclusions along the eastern border of the Glastonbury Gneiss (fig. 7*E*) suggest an intrusive relationship with the Middletown/Ammonoosuc, but inasmuch as the latter is structurally separated

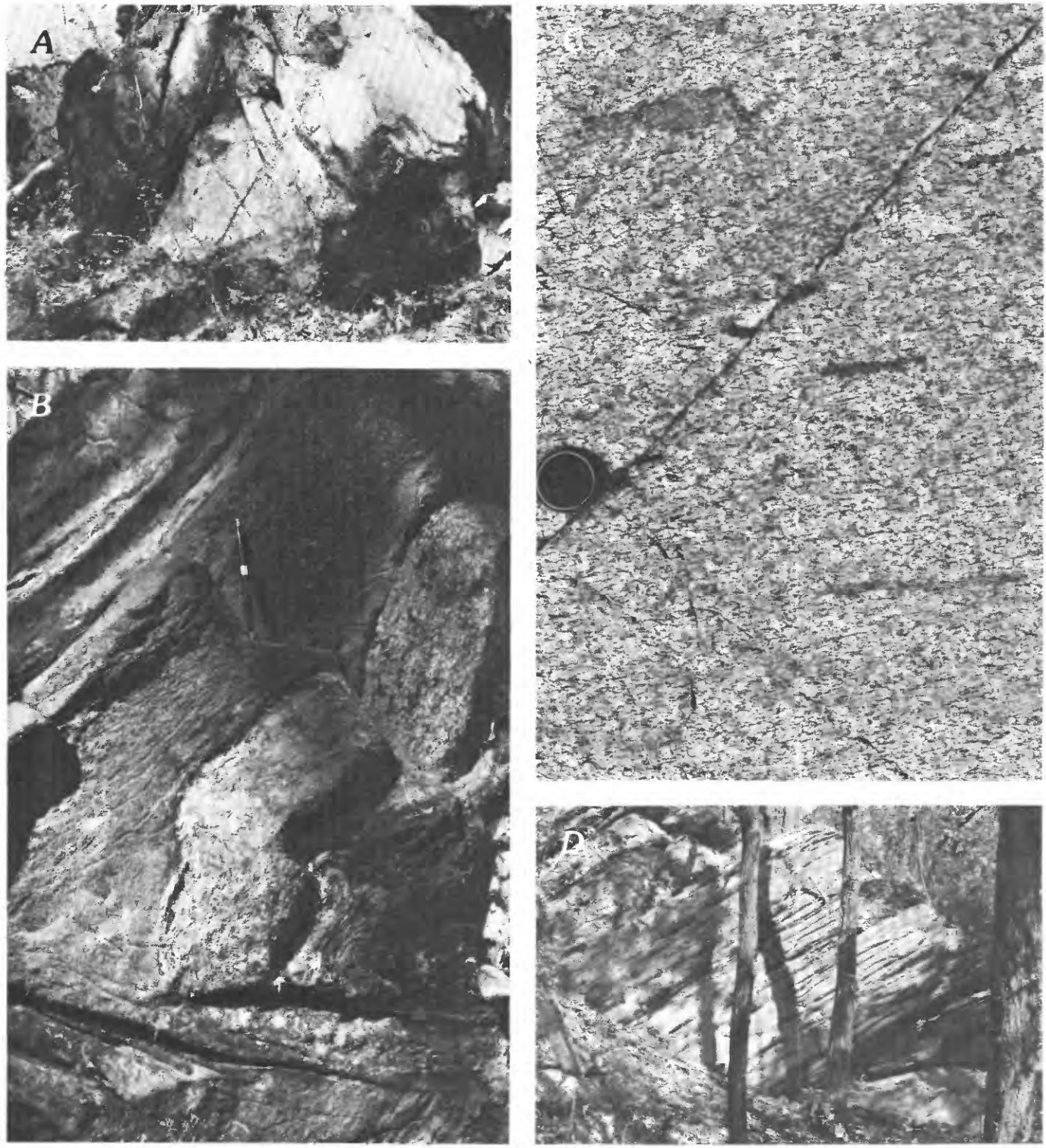


FIGURE 5.—Structures and textures in the northern Glastonbury Gneiss. *A*, Intrusive contact between Glastonbury Gneiss (light gray) and Ammonoosuc amphibolite. Southeast side of Baptist Hill, Palmer 7½-minute quadrangle, Massachusetts (fig. 2). *B*, Folded sill of Glastonbury Gneiss (right center) in Ammonoosuc amphibolite. Hillside north of Root Road at origin of Schanade Brook, 2.4 km east-southeast of North Somers, southeastern part of Hampden quadrangle, Massachusetts. *C*, Massive, well-foliated and lineated Glastonbury Gneiss in cut on north side of Massachusetts Turnpike (I–90) just east of Kelly Hill Street overpass, about 3 km west of center of Palmer, Mass. (fig. 2, loc. 2). Note flattened mafic inclusions parallel or subparallel to foliation. Lens cap (left) gives scale. *D*, Strongly foliated Glastonbury Gneiss outcrops on north side of Shenipsit Lake road, 3 km east of Ellington, Conn. (fig. 2, loc. 10). View looking northeast.

from the Glastonbury in this area (Snyder, 1970), an intrusive contact also cannot be documented here.

The contact between the Glastonbury Gneiss and the Clough Quartzite of Early Silurian age, which flanks the dome along its southeast side, is not exposed. Snyder (1970) mapped the Glastonbury-Clough contact as a fault that was assumed to have obliterated an intrusive contact. In the light of the newly established Early Silurian to Middle Ordovician age of the Glastonbury the contact probably is an unconformity.

LITHOLOGIC CHARACTER

The northern Glastonbury Gneiss is weakly to conspicuously foliated and typically has a well-defined lineation (fig. 5*C*). Despite a superficially homogeneous appearance, the composition of the gneiss varies significantly from outcrop to outcrop, mainly in the relative proportions of quartz and feldspars (fig. 6). Mafic inclusions are common and locally abundant; they are generally small, disk-shaped, and subparallel to foliation (fig. 5*C*). Rare tabular amphibolite bodies (late-Ammonoosuc or post-Ammonoosuc feeders?) as much as 50 cm thick are partly concordant with foliation and partly crosscutting.

The northern gneiss consists dominantly of quartz and plagioclase with subordinate K-feldspar, biotite, and epidote (both as isolated grains and as idiomorphic granules scattered through plagioclase), and may or may not contain minor muscovite, hornblende, garnet, and various other accessories (table 1). A strong lineation is produced by alinement of biotite-epidote clusters and elongate aggregates of quartz grains. Textures range from equigranular to highly inequigranular; in some cases large porphyroblasts of quartz and plagioclase cut across a granoblastic matrix. Overall, the textures are metamorphic, giving no definite clues to a preexisting igneous fabric.

Modal K-feldspar in the northern gneiss ranges from 0 to 10.4 percent, with a median value of 4.5 percent (table 1, fig. 6). The K-feldspar has the grillwork twinning of microcline and generally occurs in small interstitial grains, or as larger, locally crosscutting patches. Where samples are closely spaced, notably in the northern end of the main body and in the eastern outlier in the Monson and Stafford Springs quadrangles, rocks deficient in K-feldspar are near the margins of the mass, and more potassic rocks are near the center.

South of the Ellington quadrangle the Glastonbury Gneiss shows pervasive changes in texture and composition (Aitken, 1955; Herz, 1955; Snyder, 1970; Eaton and Rosenfeld, 1974). The most consistent compositional change is an increase in the proportions of K-feldspar and a roughly proportional decrease in quartz and plagioclase (fig. 6). The K-feldspar content for nine hornblende-free rocks is 12.4 to 33.0 modal percent, with a median value of 22.1 percent (table 1). Along the southwest side of the gneiss in the Middle Haddam quadrangle, a progressive change in composition toward the margin from granite to granodiorite and tonalite is marked by the appearance of hornblende and increasing amounts of biotite and epidote (table 1). The southern gneiss is granodioritic to granitic and shows essentially no compositional overlap (fig. 6) with the tonalitic to granodioritic northern gneiss.

The range of textural variations in the southern gneiss likewise appears considerably greater than in the northern gneiss. In the northern part of the Rockville quadrangle (fig. 2, loc. 11) the rock is weakly lineated and foliated, medium-grained flaser gneiss with prominent blotchy biotite aggregates (fig. 7*A*); 9 km to the south the rock is comparatively massive and contains prominent microcline porphyroblasts (fig. 2, loc. 12, 13; fig. 7*B*). In the Glastonbury quadrangle, roadcuts along Connecticut Route 2 within the Glastonbury body show the following variations over less than 2.5 km from the western margin southeast towards the interior: closely foliated, biotite-rich gneiss; weakly foliated, porphyroblastic, fine-grained granitic gneiss; somewhat coarser grained, better foliated gneiss containing ovoid microcline prophyroblasts as much as 2 cm long (fig. 7*C*) that grades gradually to abruptly to much finer grained, nonporphyritic gneiss; and gneiss with ellipsoidal microcline augen (this is probably sheared porphyritic gneiss). Variations such as these led Aitken (1955), and to a lesser extent Herz (1955), working the Rockville and Glastonbury quadrangles, respectively, to regard the southern Glastonbury Gneiss as having originated by granitization of preexisting metasedimentary rocks. Eastwards into the Glastonbury body the rocks are generally more homogeneous and less strongly foliated; thin, continuous mafic bands in otherwise massive gneiss (fig. 7*D*) are locally developed but are not typical. Three texturally distinct gneisses from the Glastonbury quadrangle have fairly similar compositions (nos. 16, 19, and 20 in fig. 2 and table 1).

Textural variations at the south end of the Glastonbury dome in the Middle Haddam quadrangle are less extreme and appear to be controlled largely by the proportion of mafic minerals. Hornblende-free granitic gneiss in the center and southeastern part of the dome is relatively massive with faint but distinct regional foliation. Hornblende- and biotite-bearing gneiss is increasingly foliated towards the southwest margin.

Mafic inclusions of two general types are locally abundant: (a) an angular, irregular-shaped, sharply bounded type (fig. 7*B*) and (b) a more or less ellipsoidal type, which is stretched parallel to foliation and is sharply bounded to shadowy and diffuse (fig. 7*C*). The latter type probably was produced by shearing of originally

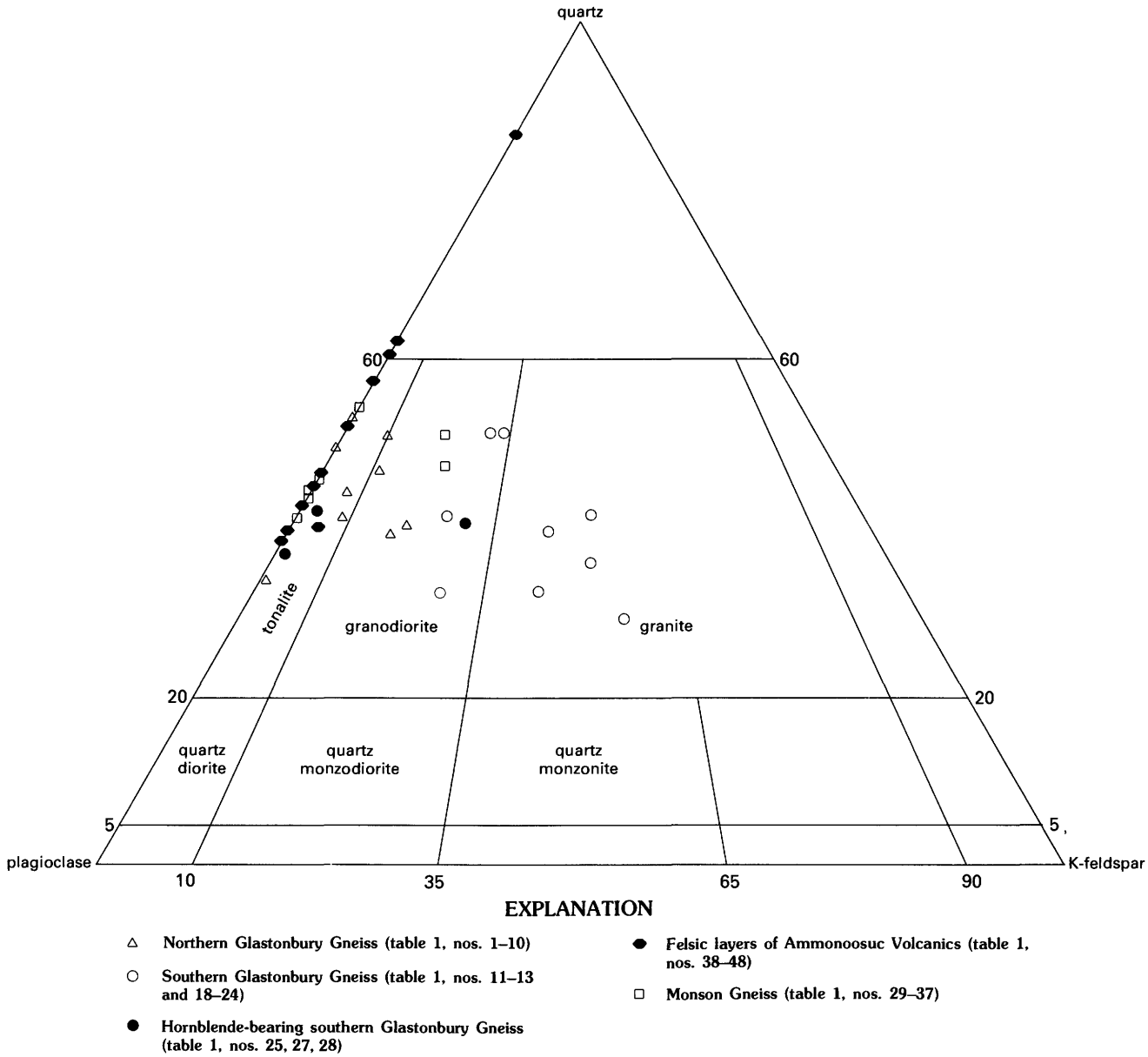


FIGURE 6.—Ternary diagram showing modal variations in the Glastonbury Gneiss, Monson Gneiss, and felsic Ammonoosuc Volcanics. Rock classification according to International Union of Geological Sciences (Geotimes, 1973).

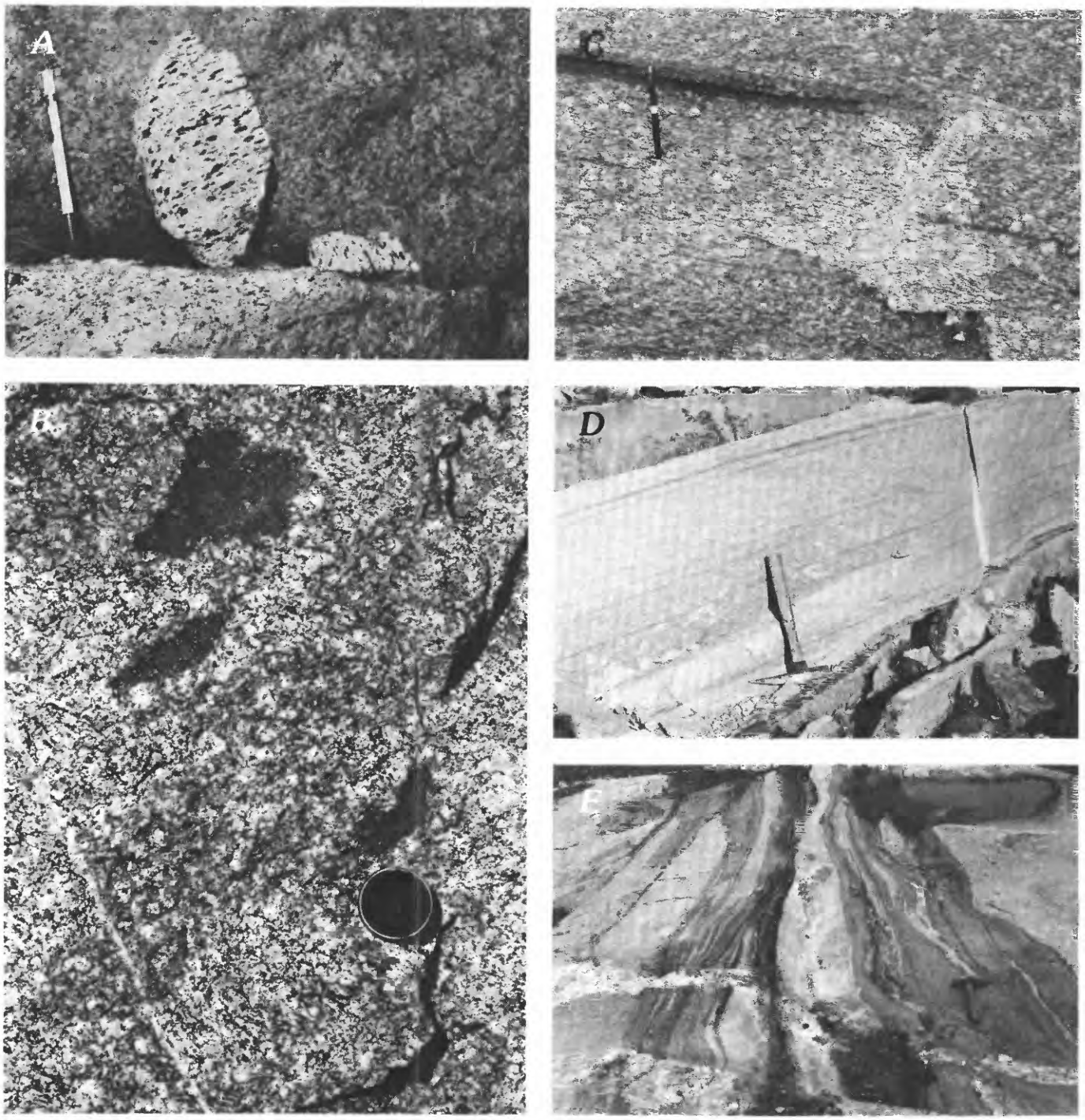


FIGURE 7.—Structures and textures in the southern Glastonbury Gneiss. *A,* Flaser gneiss containing blotchy biotite aggregates. Roadcut on north side of Connecticut Route 15-Route (I–86), 1.5 km south of Rockville, Conn. (fig. 2, loc. 11). *B,* Massive Glastonbury Gneiss, approximate center of roadcut on north side of Connecticut Route 15 (I–84) directly east of Wyllys Street overpass and approximately 0.8 km east of Highland Street exit (fig. 2, loc. 12, 13). Shows indistinct foliation, conspicuous microcline porphyroblasts, and angular amphibolite inclusions. *C,* Porphyroblastic, plastically sheared gneiss containing highly stretched, ellipsoidal mafic inclusions. West side of Connecticut Route 2, 0.7 km north of Quarry Street overpass, Glastonbury quadrangle, Connecticut (fig. 2, loc. 50). *D,* Faint, continuous mafic septa in otherwise homogeneous, equigranular gneiss. Tower Hill quarry, south of New London Turnpike, 0.9 km northwest of intersection with Quarry Street, Glastonbury quadrangle, Connecticut (fig. 2, loc. 51). *E,* Partly assimilated, plastically deformed mafic layers, assumed to be Middletown Formation, parallel to strong regional foliation in otherwise homogeneous granitic Glastonbury Gneiss. Pegmatite (foreground) cuts inclusions and Glastonbury gneiss. Hebron Avenue gravel pit south of Connecticut Route 94, west side of Marlborough quadrangle, Connecticut (fig. 2, loc. 18).

angular inclusions (of Ammonoosuc amphibolite?). Pegmatites are abundant (fig. 7*E*), especially along an axial line of the dome in the Glastonbury quadrangle (Herz, 1955).

Microtextures in the southern Glastonbury Gneiss are generally comparable with those in the northern part, except that microcline is more abundant both as small interstitial grains and as large, ragged, crosscutting plates. The patchy microcline porphyroblasts replace plagioclase along margins and contain partly resorbed plagioclase remnants. Much of the quartz, too, occurs in isolated patches of strongly sutured and strained grains elongated parallel to the foliation and locally replaces plagioclase. These features suggest late redistribution, and possibly some late introduction, of silica and alkalies in the southern part of the Glastonbury. As in the northern part, epidote and biotite are ubiquitous and seemingly stable, suggesting that conditions of metamorphism were similar throughout the Glastonbury Gneiss.

ANALYTICAL RESULTS

MAJOR ELEMENTS

Major-element compositions of Glastonbury Gneiss, Monson Gneiss, and felsic layers of Ammonoosuc Volcanics are listed in table 1 and graphically portrayed in figure 10; normative diagrams are shown in figures 8 and 9. For the purpose of this study only felsic (no mafic) Ammonoosuc was analyzed in order to provide a comparison with Monson and northern Glastonbury compositions.

AMMONOOSUC VOLCANICS AND MONSON GNEISS

On a normative An-Ab-Or diagram (fig. 8) Ammonoosuc and Monson plot fairly close to the An-Ab join and all fall into the compositional field of trondhjemite and tonalite. Ammonoosuc compositions, moreover, are mostly encompassed by the field of oceanic plagiogranite as defined by Coleman and Donato (1979). Inasmuch as trondhjemites and plagiogranites are magmatic rocks and Ammonoosuc is dominantly tuffaceous, the significance of these comparisons should not be overdrawn; they are useful, however, in pointing up the typically low abundance of potassium in these Ordovician volcanic rocks.

On the normative Q-Ab-Or diagram (fig. 9), which does not reflect variations in the An content of plagioclase, the fields of Monson and felsic Ammonoosuc appear smaller but are still partly overlapping and more clearly depict the somewhat more potassic nature of Monson Gneiss relative to felsic Ammonoosuc. The bulk compositions of these two units are notably inhomogeneous. Variation diagrams of various oxides plotted against SiO_2 (fig. 10*A*) show significant scatter, especially in regard to Al_2O_3, Fe_2O_3, FeO, and CaO. The alkalies show more constant abundances; K_2O is conspicuously low throughout, especially in Ammonoosuc (0.34 percent average for 11 samples). The relatively large degree of variation that is also seen in Ti and P, elements that are normally stable during alteration or low-grade metamorphism (see Gottfried and others, 1978, for discussion), suggests that the scatter in the abundances of other elements probably reflects a varied source for the Monson and the Ammonoosuc, rather than differential leaching or mobilization in the course of alteration. This observation is in accord with the apparent volcaniclastic nature especially of the felsic Ammonoosuc. Unsystematic variations in some stable trace elements (next section) support the idea of inhomogeneous source material. Nevertheless, some alteration following eruption or deposition may have occurred in old, deformed, and polymetamorphosed rocks such as these, although its effect cannot be quantitatively assessed with the available data.

GLASTONBURY GNEISS

Analyses of Glastonbury Gneiss fall into two distinct compositional fields with very little overlap (figs. 8 and 9). The northern gneiss straddles the compositional boundary between tonalite, granodiorite, and trondhjemite (fig. 8), whereas the southern gneiss is granite gradational to granodiorite. The rather extensive compositional field of granitic Oliverian core gneisses (Leo, unpub. data) encompasses all but one of the southern Glastonbury Gneiss samples (fig. 8).

On both figures 8 and 9 the shaded field of Ammonoosuc-related trondhjemite from the northern Oliverian domes (Leo, unpub. data) is compositionally distinct from northern Glastonbury Gneiss, indicating relatively lower K_2O and higher Na_2O. This distinction is taken as partial evidence for the postulated different origin for the two units, as discussed below.

Variation diagrams of both northern and southern Glastonbury have generally smoother trends against SiO_2 than do the Monson and the Ammonoosuc (fig. 10*B*). Of the two areas of Glastonbury Gneiss, greater irregularities are apparent in the northern gneiss, particularly for CaO, Na_2O and K_2O. K_2O contents are relatively low (1.73 percent average for 10 samples), whereas Na_2O contents are consistently higher than in the southern gneiss. These variations, which are clearly reflected in the modal analyses (table 1), are compatible with an origin of the northern gneiss by partial anatexis of K-poor volcanic rocks. Anatexis would be initiated by eutectic melting to relatively potassic liquid in

TABLE 1.—*Chemical compositions (major elements), norms and modes of Glastonbury Gneiss, Monson Gneiss, and felsic layers of Ammonoosuc Volcanics (in percent)*

[Rapid rock analyses (three significant figures) by Paul Elmore, Joseph Budinsky, Herbert Kirschenbaum, and Lowell Artis under direction of Leonard Shapiro. Standard rock analyses (four significant figures) by Elaine L. Brandt and Christel Parker under direction of Lee C. Peck. n.d., not determined; —, absent or not calculated because inapplicable. Analysis numbers match location numbers in fig. 2. See Appendix.]

	Northern Glastonbury Gneiss									
Analysis No.	1	2	3	4	5	6	7	8	9	10
Major elements										
SiO_2	74.0	76.	75.3	76.5	74.9	75.2	72.	72.4	71.7	69.3
TiO_2	0.11	0.10	.16	0.28	0.10	0.19	0.23	0.25	0.22	0.27
Al_2O_3	13.7	13.	13.2	12.5	14.3	13.9	14.	14.8	14.8	15.9
Fe_2O_3	0.80	3.3	1.1	1.2	0.90	0.70	1.4	1.2	1.2	1.3
FeO	1.3	n.d.	1.4	1.2	0.92	1.3	n.d.	2.6	1.5	1.0
MnO	.0	0.07	0.0	0.04	0.06	0.03	0.08	0.17	0.09	0.03
MgO	.51	0.58	0.54	0.25	0.28	0.57	0.65	0.84	0.64	0.80
CaO	1.7	2.65	2.6	3.6	2.9	1.3	3.03	1.4	3.5	5.0
Na_2O	4.1	3.30	4.1	3.1	3.8	4.2	3.30	3.2	3.1	4.3
K_2O	2.3	2.10	1.5	0.57	1.5	1.7	2.38	1.8	2.4	1.1
H_2O^+	.84	n.d.	0.43	0.64	0.69	0.61	n.d.	0.97	0.68	0.73
H_2O^-	.02	n.d.	0.01	0.02	0.01	0.01	n.d.	0.03	0.01	0.05
P_2O_5	0.07	<0.10	0.06	0.08	0.08	0.07	<0.10	0.04	0.13	0.22
CO_2	0.02	n.d.	0.02	0.02	0.04	0.06	n.d.	0.04	0.06	0.02
F	0.03	n.d.	0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	0.062	<0.10	0.039	n.d.	n.d.	n.d.	<0.10	n.d.	n.d.	n.d.
Subtotal	99.	101.	100.	100.	100.	100.	99.	100.	100.	101.
Less O	—	—	—	—	—	—	—	—	—	—
Total	99.	101.	100.	100.	100.	100.	99.	100.	100.	101.
Norms										
Q	37.04	41.34	38.96	48.09	40.14	40.29	36.41	41.24	35.76	29.19
Or	13.65	12.39	8.82	3.37	8.82	10.06	14.04	10.70	14.14	6.50
Ab	34.40	27.87	34.24	26.23	32.00	35.58	27.89	27.13	26.20	36.38
An	7.71	13.12	12.29	17.23	13.58	5.71	16.35	6.54	16.27	20.83
C	1.75	.38	.36	.47	1.42	3.06	.20	5.21	1.14	—
Di	—	—	—	—	—	—	—	—	—	1.91
Wo	—	—	—	—	—	—	—	—	—	1.01
En	—	—	—	—	—	—	—	—	—	0.76
Fs	—	—	—	—	—	—	—	—	—	0.12
Hy	2.83	1.44	2.73	1.45	1.58	2.97	1.62	5.79	3.16	1.46
En	1.28	1.44	1.34	.62	.69	1.42	1.62	2.10	1.59	1.23
Fs	1.55	—[2]	1.39	.82	.89	1.55	—[2]	3.69	1.57	.23
Mt	1.17	—[2]	1.59	1.74	1.30	1.02	—[2]	1.74	1.74	1.88
Il	.21	.15	.30	.53	.19	.36	.17	.48	.42	.51
Ap	.17	—	.14	.19	.19	.17	—	.10	.31	.52
CC	.05	—	.05	.05	.09	.14	—	.09	.14	.05
Ab/An	4.5	2.1	2.8	1.5	2.4	6.2	1.7	4.1	1.6	1.7
Plag. comp. calc.	An_{18}	An_{32}	An_{28}	An_{40}	An_{30}	An_{14}	An_{37}	An_{19}	An_{38}	An_{44}
Plag. comp. observed	An_{10}	n.d.	An_{10-17}	An_{25-37}	An_{23-31}	An_{6-13}	n.d.	An_{23}	An_{20-28}	An_{25-32}
Modes[5]										
Quartz	43.5	n.d.	44.7	47.6	40.1	34.4	34.2	39.9	34.2	26.8
Plagioclase	44.1	n.d.	41.5	42.6	46.6	45.7	41.5	39.1	44.3	56.1
K-Feldspar	5.5	n.d.	4.5	—	3.7	4.7	10.4	—	9.6	.6
Biotite	2.6	n.d.	4.9	3.1	6.5	8.0	8.5	11.7	8.1	12.6
Muscovite	3.8	n.d.	.2	.3	.3	6.0	1.7	8.7	—	1.5
Epidote	.3	n.3.	.2	6.1	2.5	1.2	3.8	—	3.7	5.4
Hornblende	—	n.d.	—	0.2	—	—	—	—	—	—
Other amph.	—	n.d.	—	—	—	—	—	—	—	—
Garnet	.2	n.d.	—	—	—	—	—	.3	—	—
Opaque	—	n.d.	.1	—	—	—	—	.2	—	—
Remainder[3]	—	n.d.	—	—	—	—	tr.[4]	—	—	—

See footnotes at end of table.

TABLE 1.—*Chemical compositions (major elements), norms and modes of Glastonbury Gneiss, Monson Gneiss, and felsic layers of Ammonoosuc Volcanics (in percent)*—Continued

	Southern Glastonbury Gneiss								
Analysis No.	11	12	13	14	15	16	17	18	19
				Major elements					
SiO_2	75.1	68.1	66.3	73.56	66.54	74.08	76.30	75.	71.9
TiO_2	.12	.37	.40	.17	.39	.15	.09	.05	.24
Al_2O_3	13.1	14.7	15.0	14.00	15.00	13.68	12.90	14.	13.8
Fe_2O_3	.50	1.9	2.3	.48	1.80	.61	.26	1.4	.60
FeO	.76	1.2	1.4	1.08	2.25	.88	.86	n.d.	.96
MnO	.03	.07	.07	.06	.10	.03	.05	.04	.03
MgO	.40	1.0	1.2	.46	1.94	.45	.21	.35	1.1
CaO	4.0	4.4	5.0	1.98	4.16	1.76	.92	1.61	1.9
Na_2O	3.1	2.8	2.7	3.24	2.44	2.90	3.15	3.25	2.8
K_2O	3.5	3.6	3.4	4.28	4.10	4.59	4.72	4.30	4.8
H_2O^+	.54	.57	.69	.30	.87	.33	.28	n.d.	.61
H_2O^-	.04	.02	.20	.04	.07	.14	.07	n.d.	.10
P_2O_5	.09	.16	.25	.05	.10	.04	.02	<.10	.12
CO_2	.04	.06	.05	.01	.02	.01	0.3	n.d.	.02
F	n.d.	n.d.	n.d.	.04	.05	.06	.04	n.d.	n.d.
Cl	n.d.	n.d.	n.d.	.00	.00	.00	.00	<.10	n.d.
Subtotal	101.	99.	99.	99.75	99.83	99.71	99.88	—	99.
Less O	—	—	—	.02	.02	.03	.02	—	—
Total	101.	99.	99.	99.73	99.81	99.68	99.86	100.	99.
				Norms					
Q	35.64	28.72	27.02	33.13	24.73	35.21	37.46	36.57	31.83
Or	20.41	21.50	20.30	25.32	24.27	27.21	27.93	25.82	28.66
Ab	25.89	23.94	23.10	27.45	20.68	24.62	26.52	27.95	23.94
An	11.34	17.90	18.97	9.18	17.90	8.02	3.97	6.65	8.60
C	—	—	—	.68	—	1.02	1.19	—	.89
Di	3.68	2.77	3.23	—	1.38	—	—	1.13	—
Wo	1.87	1.47	1.73	—	.71	—	—	.60	—
En	.98	1.22	1.44	—	.45	—	—	.52	—
Fs	.83	.08	.07	—	.21	—	—	—	—
Hy	—	1.38	1.66	2.46	6.37	2.06	1.83	.36	3.70
En	—	1.30	1.58	1.15	4.39	1.12	.52	.36	2.77
Fs	—	.08	.07	1.31	1.98	.94	1.31	—[2]	.94
Mt	.72	2.78	3.37	.89	2.61	.86	.38	—[2]	.88
Il	.23	.71	.77	.32	.74	.29	.17	.09	.46
Ap	.21	.38	.60	.12	.24	.10	.05	—	.29
CC	.09	.14	.12	.02	.05	.02	.07	—	.05
Ab/An	2.3	1.3	1.2	3.0	1.2	3.1	6.7	4.2	2.8
Plag. comp. calc.	An_{30}	An_{43}	An_{45}	An_{25}	An_{46}	An_{46}	An_{13_5}	An_{19}	An_{26}
Plag. comp. observed	n.d.	An_{25}	An_{25-27}	n.d.	n.d.	n.d.	n.d.	n.d.	n.d
				Modes[5]					
Quartz	46.3	32.8	24.1	n.d.	n.d.	n.d.	n.d.	30.0	30.5
Plagioclase	29.5	28.2	25.7	n.d.	n.d.	n.d.	n.d.	35.7	28.4
K-Feldspar	15.3	22.1	33.0	n.d.	n.d.	n.d.	n.d.	27.3	26.8
Biotite	7.0	9.5	10.7	n.d.	n.d.	n.d.	n.d.	7.1	11.8
Muscovite	.8	—	—	n.d.	n.d.	n.d.	n.d.	—	1.7
Epidote	.7	7.4	5.9	n.d.	n.d.	n.d.	n.d.	—	.6
Hornblende	.1	—	—	n.d.	n.d.	n.d.	n.d.	—	—
Other amph.	—	—	—	n.d.	n.d.	n.d.	n.d.	—	—
Garnet	.1	—	—	n.d.	n.d.	n.d.	n.d.	—	—
Opaque	—	—	—	n.d.	n.d.	n.d.	n.d.		—
Remainder[3]	.2	tr.	.7	n.d.	n.d.	n.d.	n.d.	tr.	.2

See footnotes at end of table.

TABLE 1.—*Chemical compositions (major elements), norms and modes of Glastonbury Gneiss, Monson Gneiss, and felsic layers of Ammonoosuc Volcanics (in percent)*—Continued

	Southern Glastonbury Gneiss—Continued								
Analysis No.	20	21	22	23	24	25	26	27	28
				Major elements					
SiO_2	76.2	66.7	74.7	76.3	75.7	63.8	56.8	56.0	57.4
TiO_2	.11	.29	.14	.10	.07	.42	.47	.55	.55
Al_2O_3	12.9	16.2	14.1	12.8	13.7	16.2	17.7	17.4	17.3
Fe_2O_3	.29	2.0	.16	.9	.14	2.3	2.8	3.2	3.3
FeO	.92	1.5	1.4	1.1	.76	2.2	3.8	4.1	3.4
MnO	.02	.04	.16	.06	.06	.12	.17	.19	.18
MgO	.23	1.1	.43	.31	.22	1.7	2.8	3.3	2.8
CaO	1.1	4.6	2.0	1.5	1.7	5.8	8.3	8.9	8.2
Na_2O	3.0	2.6	3.5	3.1	3.0	2.6	2.6	2.1	2.5
K_2O	4.4	3.7	2.6	3.8	4.1	3.4	2.6	1.9	2.0
H_2O^+	.49	.97	.64	.82	.58	.90	1.1	1.2	1.2
H_2O^-	.00	.04	.00	.02	.02	.00	.03	.04	.04
P_2O_5	.02	.17	.06	.03	.06	.22	.31	.27	.38
CO_2	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d
Subtotal	100.	100.	100.	100.	100.	100.	99.	99.	99.
Less O	—	—	—	—	—	—	—	—	—
Total	100.	100.	100.	100.	100.	100.	99.	99.	99.
				Norms					
Q	38.80	26.12	38.54	39.26	38.21	21.68	10.99	13.58	15.06
Or	26.08	21.88	15.38	22.45	24.45	24.25	20.16	15.44	11.91
Ab	25.47	22.02	29.65	26.22	25.41	22.08	22.12	17.92	21.31
An	5.34	21.62	9.54	7.24	8.05	22.57	29.10	32.72	30.30
C	1.25	—	2.04	.93	1.18	—	—	—	—
Di	—	.08	—	—	—	3.91	8.35	8.14	6.56
Wo	—	.04	—	—	—	2.03	4.28	4.19	3.42
En	—	.03	—	—	—	1.35	2.54	2.59	2.94
Fs	—	.01	—	—	—	.53	1.53	1.36	.94
Hy	1.88	3.40	3.58	2.66	1.83	4.04	7.17	8.71	6.81
En	.57	2.71	1.07	.77	.55	2.90	4.74	5.70	4.79
Fs	1.31	.69	2.51	1.89	1.28	1.14	2.70	3.01	2.02
Mt	.42	2.90	.23	.13	.20	3.35	4.08	4.68	4.82
Il	.21	.55	.27	.19	.13	.80	.90	1.05	1.05
Ap	.05	.40	.14	.07	.14	.52	.74	.65	.91
CC	—	—	—	—	—	—	—	—	—
Ab/An	4.8	1.0	3.3	3.7	3.2	.98	.76	.55	.70
Plag. comp. calc.	An_{17}	An_{50}	An_{24}	An_{22}	An_{24}	An_{50}	An_{57}	An_{65}	An_{59}
Plag. comp. observed	An_{13-32}	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
				Modes[5]					
Quartz	n.d.	41.1	38.0	29.7	39.6	28.8	n.d.	24.0	18.5
Plagioclase	n.d.	27.0	40.0	44.8	27.1	30.2	n.d.	32.2	31.2
K-Feldspar	n.d.	12.4	14.2	17.6	28.9	12.8	n.d.	1.1	0.5
Biotite	n.d.	12.5	7.5	7.7	4.4	14.6	n.d.	21.4	22.6
Muscovite	n.d.	—	—	—	—	—	n.d.	—	—
Epidote	n.d.	6.7	—	.1	—	10.0	n.d.	13.3	16.5
Hornblende	n.d.	tr.	—	—	tr.	5.5	n.d.	7.8	10.1
Other amph.	n.d.	—	—	—	—	—	n.d.	—	—
Garnet	n.d.	—	.3	—	—	—	n.d.	—	—
Opaque	n.d.	—	—	—	—	—	n.d.	—	—
Remainder[3]	n.d.	.4	.1	.2	—	.2	n.d.	.2	.5

See footnotes at end of table.

TABLE 1.—*Chemical compositions (major elements), norms and modes of Glastonbury Gneiss, Monson Gneiss, and felsic layers of Ammonoosuc Volcanics (in percent)*—Continued

	Monson Gneiss								
Analysis No.	29	30	31	32	33	34	35	36	37
Major elements									
SiO_2	77.2	75.4	77.	75.3	76.2	73.9	65.9	75.1	67.4
TiO_2	.15	.25	<.02	.25	.11	.03	.36	.21	.26
Al_2O_3	12.9	14.5	12.	12.7	12.9	16.1	17.2	13.7	18.4
Fe_2O_3	.61	.40	1.5	1.1	.50	.27	1.7	1.2	1.1
FeO	.72	1.4	n.d.	2.3	1.4	.36	2.3	1.3	1.4
MnO	.00	.01	.06	.03	.05	.06	.09	.02	.03
MgO	.16	.64	.10	1.1	.32	.03	1.4	.28	1.0
CaO	1.0	2.8	.65	1.2	2.0	4.0	5.6	2.4	5.8
Na_2O	4.0	3.4	3.93	4.1	4.1	4.2	3.4	3.8	3.4
K_2O	1.9	.73	1.68	.93	2.2	.22	.57	.70	.54
H_2O^+	.51	.63	n.d.	.91	.53	.42	.71	.73	.75
H_2O^-	.03	.02	n.d.	.09	.01	.01	.00	.11	.06
P_2O_5	.04	.10	<.10	.05	.02	.04	.21	.05	.14
CO_2	.02	.02	n.d.	.02	.02	.02	.06	.02	.02
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Subtotal	99.	100.	—	100.	100.	100.	100.	100.	100.
Less O	—	—	—	—	—	—	—	—	—
Total	99.	100.	97.	100.	100.	100.	100.	100.	100.
Norms									
Q	44.47	45.21	48.23	42.47	38.17	40.01	29.65	44.59	31.39
Or	11.31	4.30	10.27	5.49	12.95	1.30	3.39	4.15	3.18
Ab	34.09	28.68	34.09	34.66	34.56	35.65	28.91	32.27	28.68
An	4.70	13.11	3.24	5.53	9.68	19.56	26.19	11.55	27.68
C	2.57	3.29	2.36	2.92	.21	1.81	1.44	2.48	2.04
Di	—	—	—	—	—	—	—	—	—
Wo	—	—	—	—	—	—	—	—	—
En	—	—	—	—	—	—	—	—	—
Fs	—	—	—	—	—	—	—	—	—
Hy	.98	3.43	.25	5.69	2.85	.58	5.90	1.79	3.77
En	.40	1.59	.25	2.74	.79	.08	3.50	1.70	2.48
Fs	.57	1.34	—[2]	2.95	2.06	.50	2.40	.09	.28
Mt	.89	.58	—[2]	1.59	.72	.39	2.48	1.75	1.59
Il	.29	.47	—	.47	.21	.06	.69	.40	.49
Ap	.10	.24	—	.12	.05	.10	.50	.12	.33
CC	.05	.05	—	.05	.05	.05	.18	.05	.05
Ab/An	7.3	2.2	10.5	6.3	3.6	1.9	1.1	2.8	1.0
Plag. comp. calc.	An_{12}	An_{31}	An_9	An_{14}	An_{22}	An_{35}	An_{47}	An_{26}	An_{49}
Plag. comp. observed	n.d.	An_{27}	n.d.	n.d.	An_{22-25}	An_{37-40}	An_{47-58}	An_{23-27}	An_{35}
Modes[5]									
Quartz	43.4	48.6	n.d.	36.0	46.7	40.0	38.7	41.2	37.9
Plagioclase	37.6	41.0	n.d.	44.4	35.3	57.4	47.5	49.4	48.5
K-Feldspar	11.4	—	n.d.	—	9.6	—	—	—	—
Biotite	5.3	10.0	n.d.	19.0	5.6	.9	7.0	7.2	8.5
Muscovite	2.1	—	n.d.	—	.8	1.0	—	.6	—
Epidote	—	—	n.d.	—	1.6	.2	.1	.3	1.1
Hornblende	—	—	n.d.	—	—	—	6.3	—	3.9
Other amph.	—	—	n.d.	—	—	—	—	—	—
Garnet	—	—	n.d.	.2	.5	.5	.1	—	—
Opaque	—	—	n.d.	.4	—	—	.3	.9	.1
Remainder[3]	—	.4	n.d.	—	—	—	—	.4	—

See footnotes at end of table.

TABLE 1.—*Chemical compositions (major elements), norms and modes of Glastonbury Gneiss, Monson Gneiss, and felsic layers of Ammonoosuc Volcanics (in percent)*—Continued

	Ammonoosuc Volcanics										
Analysis No.	38	39	40	41	42	43	44	45	46	47	48
Major elements											
SiO_2	77.63	73.3	74.6	68.0	66.7	63.2	67.54	75.18	67.79	70.39	79.87
TiO_2	.11	.24	.24	.31	.29	.35	.50	.22	.68	.40	.22
Al_2O_3	12.97	13.6	12.7	14.9	15.9	16.4	14.20	13.41	13.91	13.08	10.16
Fe_2O_3	.54	1.5	1.5	1.9	2.0	2.9	2.85	.88	3.34	3.24	.77
FeO	.54	1.9	1.6	3.6	3.9	3.5	4.59	1.19	3.20	2.52	1.62
MnO	.02	.00	.00	.00	.00	.12	.20	.03	.12	.08	.07
MgO	.14	.86	1.3	1.8	1.8	1.8	2.13	.66	1.99	1.15	1.12
CaO	.86	3.3	3.4	5.9	5.3	7.9	2.76	3.76	2.79	2.70	1.84
Na_2O	5.82	4.1	4.3	2.8	3.5	2.9	3.21	4.01	5.35	4.92	3.81
K_2O	1.00	.76	.03	.35	.13	.28	.79	.12	.17	.07	.06
H_2O^+	.17	.59	.62	.75	.54	.80	.88	.23	.31	.36	.25
H_2O^-	.09	.00	.00	.02	.02	.04	.11	.08	.08	.12	.05
P_2O_5	.01	.10	.06	.08	.08	.09	.09	.05	.23	.12	.03
CO_2	.01	.02	.02	.02	.02	.02	.01	.01	.02	.02	.01
F	.01	.01	.01	.01	.01	n.d.	.04	.02	.03	.01	.06
Cl	.01	.013	.06	.013	.015	n.d.	.01	.01	.00	.01	.01
Subtotal	99.93	100.	100.	100.	100.	100.	99.91	99.86	99.99	99.19	99.95
Less O	—	—	—	—	—	—	.02	.01	.01	.00	.03
Total	99.93	100.	100.	100.	100.	100.	99.89	99.85	99.98	99.19	99.92
	2.65						2.79	2.70	2.76	2.74	2.71
Norms											
Q	37.88	37.63	40.58	33.50	29.96	25.84	34.66	42.16	27.53	33.80	51.23
Or	5.91	4.48	.18	2.06	.77	1.65	4.67	.71	1.01	.41	.36
Ab	49.21	34.52	35.01	23.51	29.52	24.47	27.11	33.91	44.30	41.57	32.18
An	4.07	15.54	15.81	26.97	25.67	30.81	12.82	18.18	12.16	12.49	8.45
C	.84	.34	—	—	.24	—	3.39	.05	.67	1.14	.75
Di	—	—	.34	1.24	—	6.21	—	—	—	—	—
Wo	—	—	.17	.62	—	3.15	—	—	—	—	—
En	—	—	.12	.31	—	1.68	—	—	—	—	—
Fs	—	—	.05	.31	—	1.38	—	—	—	—	—
Hy	.75	3.98	4.35	8.36	9.53	5.08	0.94	2.80	7.18	4.30	4.90
En	.35	2.13	3.10	4.16	4.49	2.79	5.31	1.65	4.96	2.86	2.79
Fs	.40	1.85	1.25	4.20	5.04	2.29	5.63	1.15	2.22	1.44	2.11
Mt	.78	2.17	2.16	2.74	2.91	4.19	4.14	1.28	4.85	4.70	1.12
Il	.21	.45	.45	.59	.55	.66	.95	.42	1.29	.76	.42
Ap	.02	.24	.14	.19	.19	.21	.21	.12	.56	.28	.07
CC	.02	.05	.05	.05	.05	.05	.02	.02	.05	.05	.02
Ab/An	12.1	2.2	2.2	.87	1.2	.79	2.1	1.9	3.6	3.3	3.8
Plag. comp. calc.	An_8	An_{31}	An_{31}	An_{53}	An_{46}	An_{56}	An_{32}	An_{35}	An_{22}	An_{23}	An_{21}
Plg. comp. observed	An_{4-6}	An_{31-34}	An_{25-32}	An_{40-53}	An_{32-37}	An_{32-60}	An_{20-35}	An_{29-38}	An_{25}	An_{23}	An_{25}
Modes[5]											
Quartz	39.0	50.5	56.6	40.3	35.5	29.0	48.3	48.7	33.2	35.9	73.2
Plagioclase	55.2	36.8	33.8	37.2	43.3	38.6	31.2	44.2	52.7	58.4	11.0
K-Feldspar	2.7	—	—	—	—	—	—	—	—	—	—
Biotite	1.1	9.6	—	3.6	.4	3.5	12.7	2.1	1.1	.2	5.2
Muscovite	.2	—	—	—	—	—	—	—	—	—	—
Epidote	—	1.7	—	—	—	—	—	.4	.3	—	—
Hornblende	—	—	8.8	17.2	19.0	21.2	—	3.9	1.7	tr	3.0
Other amph.	—	—	—	—	—	—	—	—	[6]7.6	[6]6.9	[6]7.0
Garnet	—	—	—	1.2	1.6	7.5	4.7	—	—	—	—
Opaque	—	1.1	.8	.6	.2	—	2.8	.7	3.1	2.0	.6
Remainder[3]	.7	.3	—	—	—	—	.3	.1	.2	.2	—

[1]Partial analysis; SiO_2, Al_2O_3, total iron as Fe_2O_3, MnO and P_2O_5 by XRF, J. S. Wahlberg, USGS, analyst; MgO, CaO, Na_2O and K_2O by AAS, Violet Merritt, USGS, analyst.
[2]Due to the absence of FeO determinations in analyses 2, 7, 18, and 31, Fs and Mt=0, and the norms contain, respectively, 3.29, 3.20, 1.42, and 1.37 percent hematite (hm).
[3]Remainder includes sphene, apatite, zircon, carbonate, and allanite.
[4]Trace.
[5]No modal analyses for Nos. 2, 15, 16, 17 20, 26, and 31 because thin sections unavailable.
[6]Col. 40: cummingtonite; col. 47: anthophyllite-cummingtonite; col. 48: tremolite.

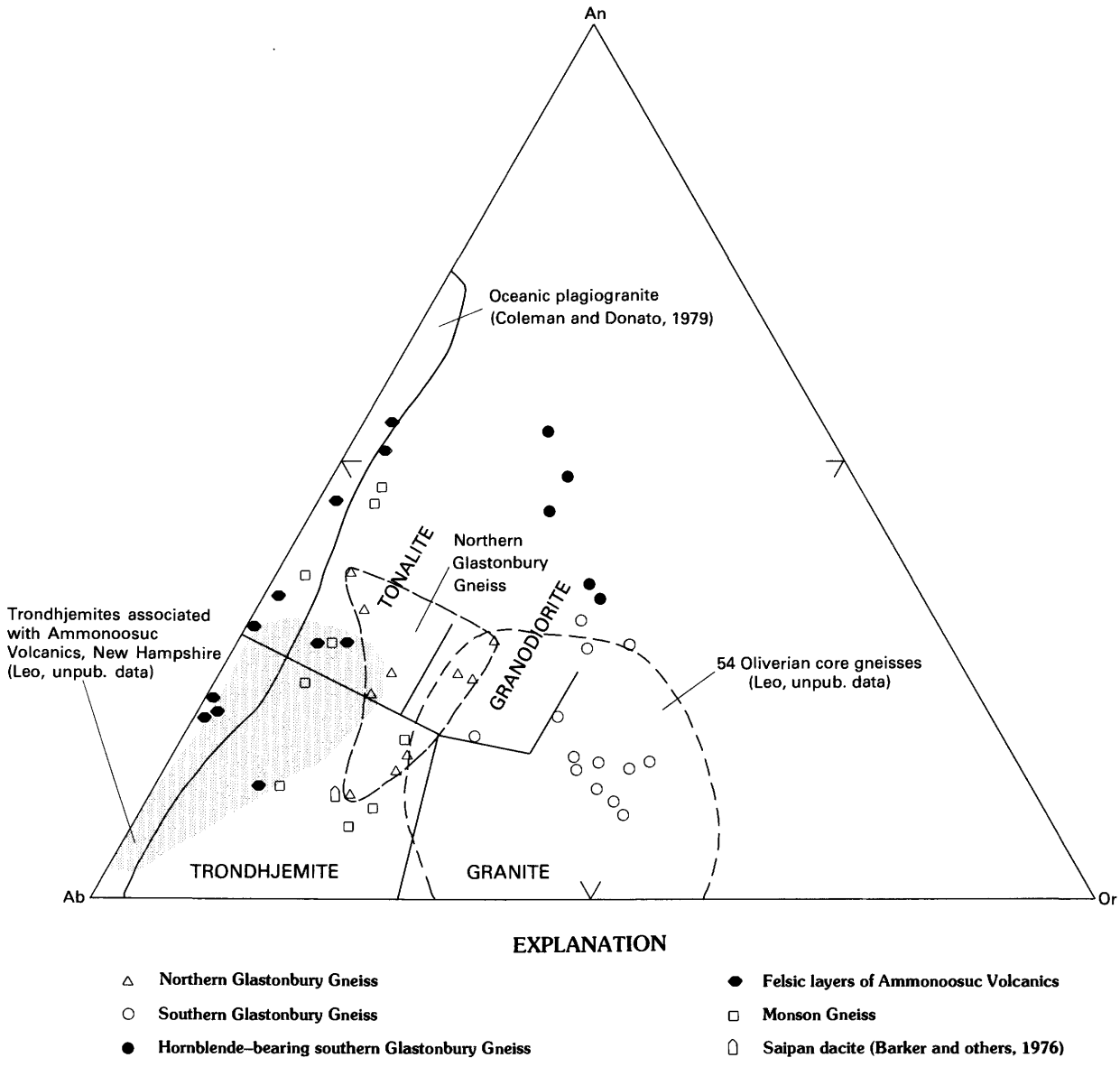
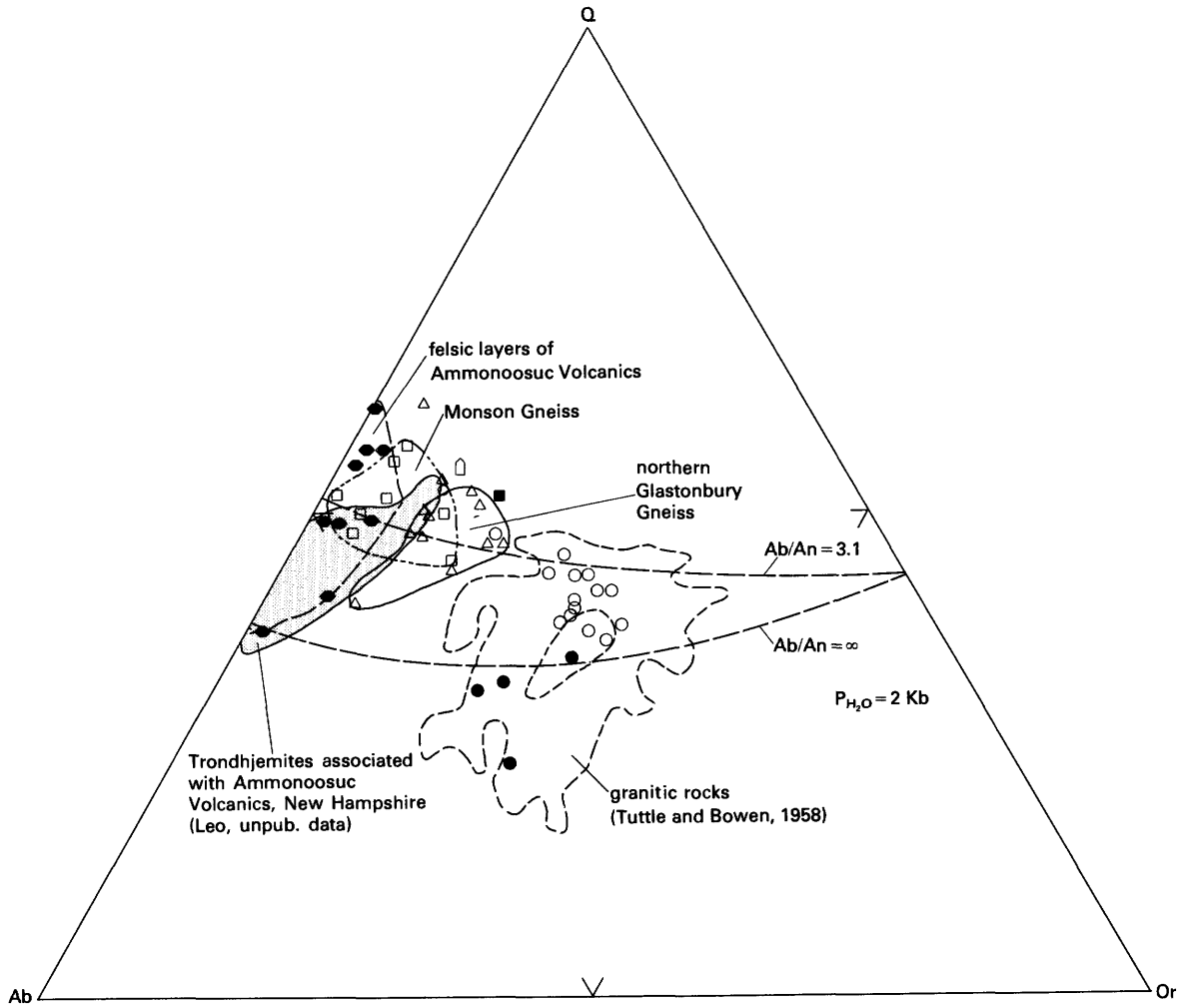


FIGURE 8.—Normative An-Ab-Or diagram using rock classification of O'Connor (1965) as modified by Barker (1979).



EXPLANATION

△ Northern Glastonbury Gneiss

○ Southern Glastonbury Gneiss

● Hornblende-bearing southern Glastonbury Gneiss

● Felsic layers of Ammonoosuc Volcanics

□ Monson Gneiss

■ Average graywacke of Pettijohn (1963, table 7, col. A)

⌂ Saipan dacite (Barker and others, 1976)

FIGURE 9.—Normative Q-Ab-Or diagram. The Q-Ab cotectic (Ab/An=∞) is shown for P_{H_2O}=2 Kb (Tuttle and Bowen, 1958, p. 75). Dashed line above the Q-Ab cotectic is projection (based on von Platen, 1965) of the quartz-plagioclase cotectic at Ab/An=3.1, the average normative plagioclase composition of the northern Glastonbury Gneiss. Field labeled "Granitic rocks" includes most of the analyzed rocks containing 80 percent or more Q+Ab+Or in Washington's tables (Tuttle and Bowen, 1958, p. 128, fig. 63). Small field surrounded by short dashes near center of diagram is granite minimum of Tuttle and Bowen (1958).

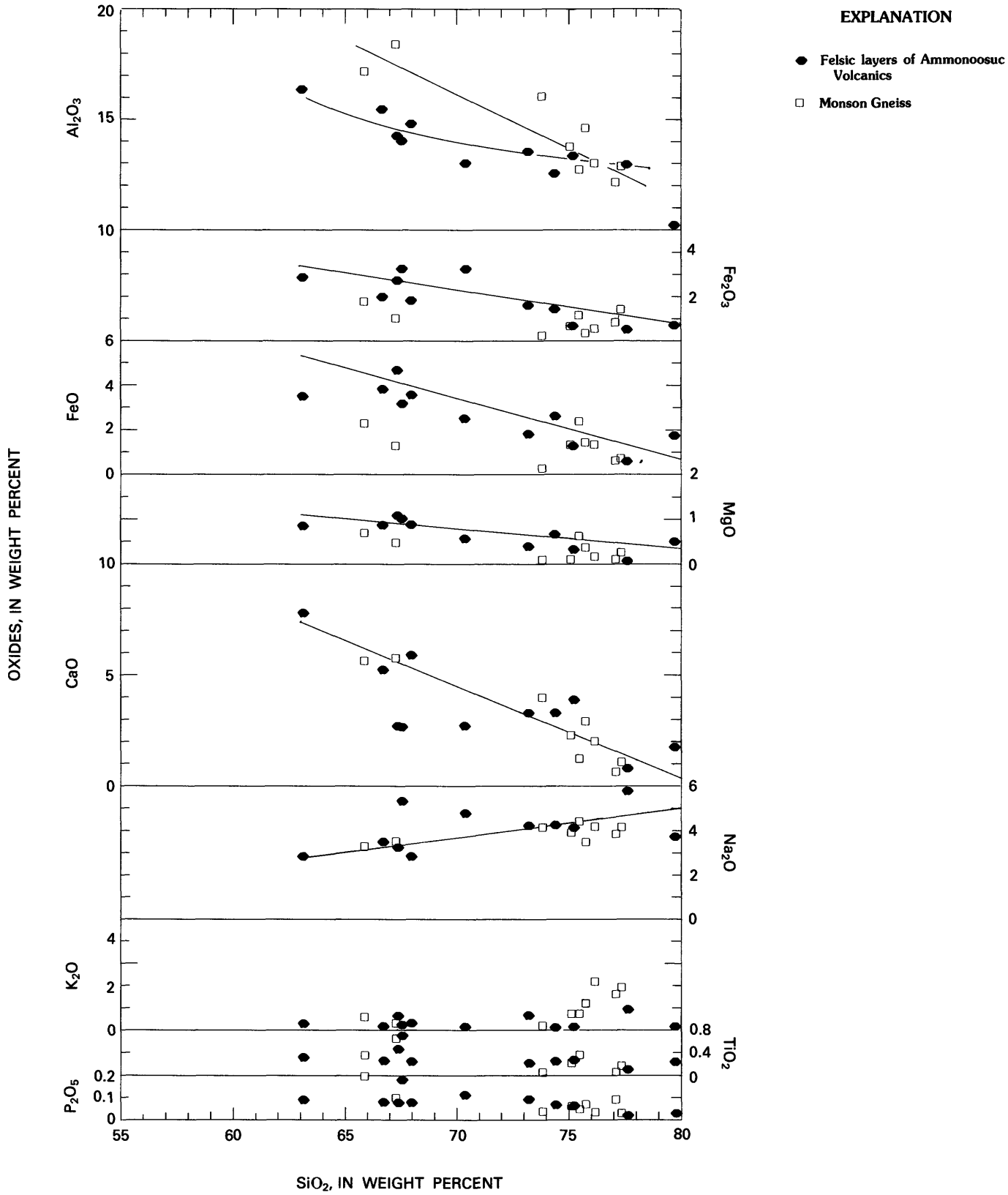


FIGURE 10.—Variation diagrams for major elements versus SiO_2. *A*, Felsic layers of Ammonoosuc Volcanics and Monson Gneiss; *B*, northern and southern Glastonbury Gneiss. Trend lines in *A* are drawn on felsic Ammonoosuc and in *B*, on southern Glastonbury; lines are fitted visually. Only 16 southern Glastonbury samples are plotted because of overlap of two points.

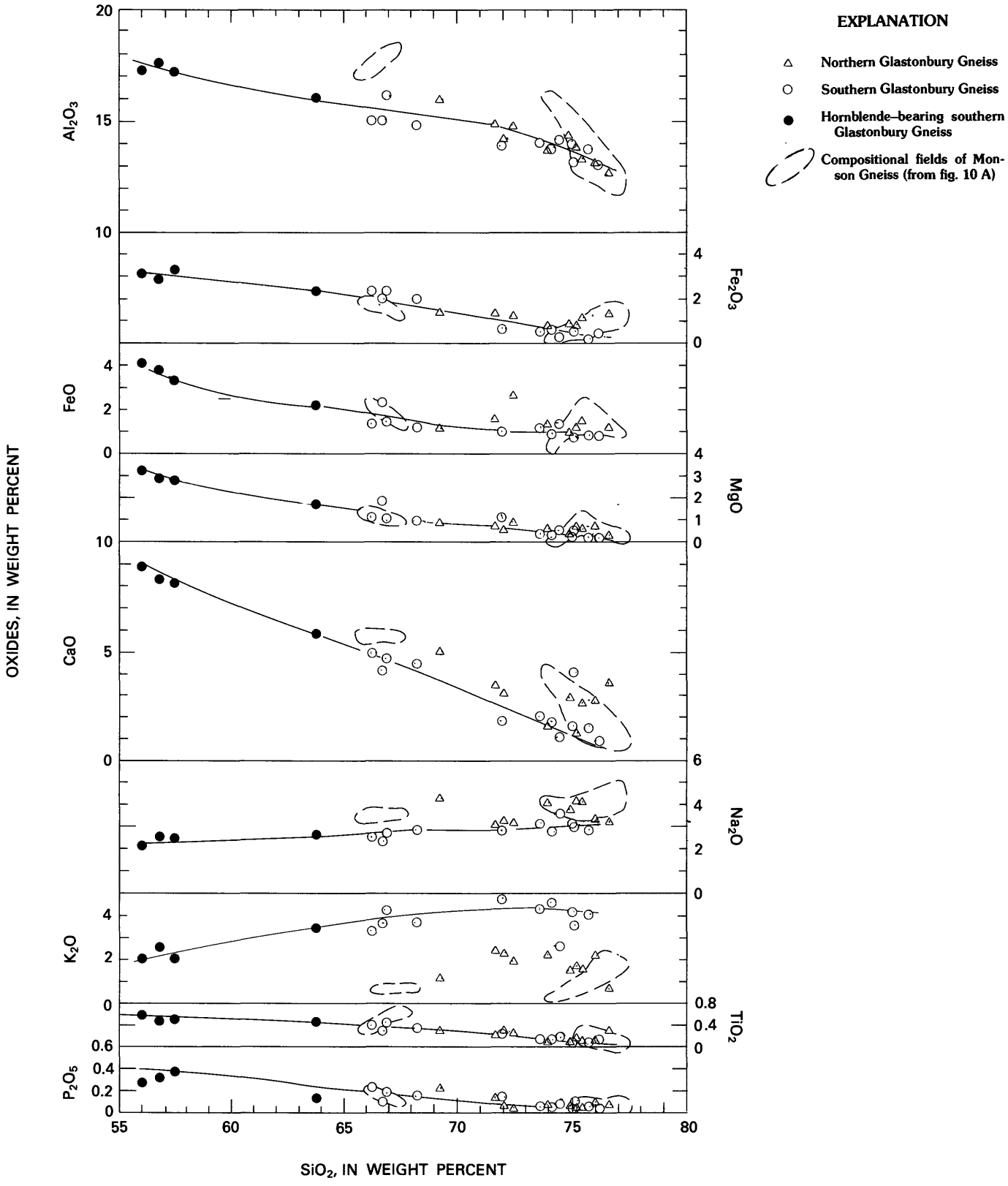


Figure 10—Continued

scattered pockets throughout the protolith. As argued below, the low K content of the model protolith (Monson lithology) would have limited the amount of melt, at geologically reasonable temperatures, to perhaps 20 percent, producing a crystal mush instead of a mostly liquid magma. Such a mush should be capable of moving through the crust (Robertson and Wyllie, 1971). The northern Glastonbury Gneiss is thought to reflect the inhomogeneous character of this mush, notably variable K content, that characterized the partial-melting process.

The southern Glastonbury Gneiss shows the smoothest variation trends that can be extended to include the hornblende-bearing marginal phase in the Middle Haddam quadrangle (figs. 2 and 10*B*). These trends appear to reflect moderate differentiation of a relatively calc-alkaline magma very likely unrelated to the northern Glastonbury. K_2O values correspond to the granite-granodiorite range (4.28 percent average for 14 hornblende-free samples, 3.66 percent average for 18 samples including hornblende-bearing rocks). In contrast to the Monson and the Ammonoosuc, Ti and P for both northern and southern Glastonbury have relatively smooth variation trends, in accord with a magmatic origin.

TRACE ELEMENTS

Trace elements for Monson Gneiss and Glastonbury Gneiss are listed in table 2, but trace elements were not analyzed for Ammonoosuc samples. Elements are listed along the general lines recommended by Taylor and White (1966) on the basis of their geochemical association.

TRACE ELEMENTS OTHER THAN RARE EARTHS

Trace elements, even nominally stable ones such as Th, Zr, Hf, Co and Cr, show some unsystematic variations. Th, Co, and Sc plotted against SiO_2 (fig. 11) display little regularity in the Monson and the northern Glastonbury samples, rather, the data points occupy irregular but partly overlapping fields. By contrast, the southern Glastonbury shows distinctly systematic variations of Co and Sc as well as linear variation in Th/SiO_2 at lower SiO_2 values. Similar plots for Zr, Cr, and Hf (not shown here) are analogous. The trace-element variations further point up the inhomogeneous character of the Monson and the northern Glastonbury, as compared to the southern Glastonbury. A plot of K vs. Rb/Sr (fig. 12) shows reasonably linear correlations analogous to those of other variation diagrams. Two southern Glastonbury points, however, fall far out of the field encompassing the remaining points. Inasmuch as these elements are among the most mobile during alteration or metamorphism, the significance of this distribution cannot be assessed.

RARE-EARTH ELEMENTS

Rare-earth element (REE) patterns for the analyzed rocks are shown in figure 13. The patterns for the Monson and the northern Glastonbury show major variations and consequently are hard to interpret in a coherent way. To test the possibility that some of the irregularities could be related to the relatively high margin of error (a maximum of 10 percent for any determination) inherent in the instrumental neutron-activation technique, all the samples were resubmitted for a second run; however, in spite of some relatively minor and systematic variations, the form of the patterns changed little. Moreover, the much more uniform patterns for the southern Glastonbury Gneiss increase the likelihood that the variations for other samples are real.

Monson Gneiss

The Monson patterns define two more or less distinct groups: slightly light-REE-enriched but otherwise fairly flat patterns with overall high REE abundances and pronounced negative Eu anomalies (solid lines, fig. 13*A*); and much more fractionated, heavy-REE-depleted patterns with negligible Eu anomalies (dashed lines, fig. 13*A*). The first and second groups are generally similar to patterns for low-alumina (<15 percent Al_2O_3) trondhjemites and high-alumina (>15 percent Al_2O_3) trondhjemites, respectively (Barker and others, 1976). The Al_2O_3 contents of the Monson samples are mostly in accord with these categories (fig. 13*A*). Although the Monson Gneiss is not a trondhjemite in the strict sense, its overall composition is trondhjemitic-tonalitic (fig. 8), and the REE patterns confirm the high/low-alumina trondhjemite relationship. The Al_2O_3-poor Monson patterns, moreover, are similar to patterns for felsic Ammonoosuc Volcanics from New Hampshire (Leo, unpub. data).

These two distinctive REE patterns are most readily explained by assuming at least two different sources. The low-alumina type could have been derived from a source in which plagioclase was residual, producing the negative Eu anomalies and the relative enrichment in heavy REE. The high-alumina type, by contrast, could be derived from a source in which hornblende or, less likely, garnet was a residual phase. It may be noted that the modal analyses of the samples in question (table 1) show only small differences in plagioclase content. In any case, the distinct gap in heavy REE contents makes it unlikely that the two Monson types are related by differentiation.

TABLE 2.—*Minor and trace elements in northern and southern Glastonbury Gneiss and Monson Gneiss*

[Data for all elements except Rb with asterisks and all Sr obtained by instrumental neutron-activation analysis carried out by Louis J. Schwarz under general direction of Jack J. Rowe and Philip A. Baedecker. Values are averages of 2 to 3 replicate runs and may be considered accurate to 10 percent. Sr data without asterisks obtained by atomic absorption spectroscopy (limit of error approx. 10 percent) by Robin Moore and Violet Merritt. Rb and Sr data with asterisks and Rb-Sr isotopic data (partly repeated in table 4) obtained by D. G. Brookins by isotope dilution analysis (see Lee and Brookins, 1978, for details of analytical procedure). n.d., not determined; —, (1) result inconclusive, (2) calculation not made because data lacking, or (3) not applicable. Field numbers, sample descriptions and locations in Appendix.]

	Northern Glastonbury Gneiss							
Analysis No.	1	2	2a	4	5	7	7a	10
Large cations								
K	19,100.	17,400.	n.d.	4,700.	14,100.	19,700.	n.d.	9,100.
Rb	83.	76.	83.5	20.	48.2*	82.0*	56.0*	52.1*
Sr	95.	83.	80.0*	150.	128.*	136.*	196.*	281.*
Ba	445.	387.	n.d.	150.	388.	840.	n.d.	1,040.
Cs	2.1	2.6	n.d.	1.5	1.3	1.0	n.d.	1.5
K/Rb	230.	229.	—	235.	293.	240.	n.d.	175.
K/Ba	42.9	45.0	—	31.3	36.3	23.4	n.d.	8.8
Rb/Sr	0.87	0.91	1.04	0.13	0.38	0.60	0.29	0.19
Ba/Sr	4.7	4.7	—	1.0	3.0	6.2	—	3.7
$^{87}Sr/^{86}Sr$	—	—	0.7297	—	0.7124	0.7205	0.7148	0.7107
$^{87}Rb/^{86}Sr$	—	—	3.02	—	1.09	1.76	.83	0.54
High-valence and ferromagnesian elements								
Th	6.6	8.3	n.d.	1.3	4.1	13.3	n.d.	13.2
Zr	113.	74.	n.d.	56.	n.d.	142.	n.d.	393.
Hf	2.8	2.3	n.d.	1.7	5.4	3.8	n.d.	7.9
Zr/Hf	40.3	32.2	n.d.	32.9	43.9	37.4	n.d.	49.7
Ta	0.31	0.36	n.d.	<0.20	0.10	0.45	n.d.	0.30
Co	1.8	5.0	n.d.	1.6	1.6	4.0	n.d.	2.9
Cr	4.	5.	n.d.	6.	9.	18.	n.d.	4.
Sc	7.3	11.7	n.d.	12.9	12.0	11.7	n.d.	4.5
Rare-earth elements								
La	15.	19.	n.d.	5.	14.	42.	n.d.	50.
Ce	36.	32.	n.d.	11.	25.	79.	n.d.	59.
Nd	14.	15.	n.d.	n.d.	10.	30.	n.d.	20.
Sm	2.6	3.3	n.d.	1.6	2.9	6.5	n.d.	3.2
Eu	0.38	0.47	n.d.	0.84	0.80	1.11	n.d.	1.10
Gd	2.0	2.3	n.d.	1.4	2.1	4.3	n.d.	2.0
Tb	0.34	0.56	n.d.	0.19	0.41	0.77	n.d.	0.23
Yb	2.2	2.5	n.d.	1.2	1.9	3.0	n.d.	1.0
Lu	0.32	0.38	n.d.	0.16	0.27	0.42	n.d.	0.17
La/Yb	6.8	7.6	n.d.	4.2	7.4	14.0	n.d.	50.

TABLE 2.—*Minor and trace elements in northern and southern Glastonbury Gneiss and Monson Gneiss*—Continued

	Southern Glastonbury Gneiss							
Analysis No.	11	11A	12	13A	13B	13C	13D	18
				Large cations				
K	29,000.	n.d.	29,900.	n.d.	n.d.	n.d.	n.d.	35,700.
Rb	144.*	128.*	115.	43.6*	168.*	140.*	142.*	103.*
Sr	113.*	167.*	250.	250.*	264.*	270.*	210.*	139.*
Ba	1,130.	n.d.	1,360.	n.d.	n.d.	n.d.	n.d.	1,820.
Cs	5.5	n.d.	14.6	n.d.	n.d.	n.d.	n.d.	5.4
K/Rb	201.	n.d.	260.	—	—	—	—	347.
K/Ba	25.7	n.d.	22.0	—	—	—	—	19.6
Rb/Sr	1.27	0.77	0.46	0.17	0.64	0.52	0.68	0.74
Ba/Sr	10.0	—	5.4	—	—	—	—	13.
$^{87}Sr/^{86}Sr$	0.7263	0.7228	—	0.7163	0.7195	0.7191	0.7185	0.7205
$^{87}Rb/^{86}Sr$	3.68	2.22	—	1.66	1.18	1.50	1.53	2.14
				High-valence and ferromagnesian elements				
Th	24.3	n.d.	28.7	n.d.	n.d.	n.d.	n.d.	15.5
Zr	259.	n.d.	304.	n.d.	n.d.	n.d.	n.d.	95.
Hf	5.8	n.d.	7.2	n.d.	n.d.	n.d.	n.d.	2.6
Zr/Hf	44.7	n.d.	42.2	n.d.	n.d.	n.d.	n.d.	35.4
Ta	0.41	n.d.	1.41	n.d.	n.d.	n.d.	n.d.	0.42
Co	1.3	n.d.	5.4	n.d.	n.d.	n.d.	n.d.	1.6
Cr	1.3	n.d.	5.4	n.d.	n.d.	n.d.	n.d.	3.
Sc	7.4	n.d.	16.1	n.d.	n.d.	n.d.	n.d.	4.7
				Rare-earth elements				
La	53.	n.d.	53.	n.d.	n.d.	n.d.	n.d.	38.
Ce	89.	n.d.	88.	n.d.	n.d.	n.d.	n.d.	57.
Nd	31.	n.d.	35.	n.d.	n.d.	n.d.	n.d.	17.
Sm	5.2	n.d.	6.8	n.d.	n.d.	n.d.	n.d.	3.3
Eu	0.72	n.d.	1.07	n.d.	n.d.	n.d.	n.d.	0.52
Gd	4.0	n.d.	3.9	n.d.	n.d.	n.d.	n.d.	2.0
Tb	0.69	n.d.	0.73	n.d.	n.d.	n.d.	n.d.	0.39
Yb	3.3	n.d.	2.5	n.d.	n.d.	n.d.	n.d.	1.8
Lu	0.55	n.d.	0.42	n.d.	n.d.	n.d.	n.d.	0.28
La/Yb	16.	n.d.	21.	n.d.	n.d.	n.d.	n.d.	21.

TABLE 2.—*Minor and trace elements in northern and southern Glastonbury Gneiss and Monson Gneiss*—Continued

Southern Glastonbury Gneiss								
18A	19	49	50	51	25	26	28	Chondrite normalizing values[1]
Large cations								
n.d.	39,800.	n.d.	n.d.	n.d.	28,200.	21,600.	16,600.	—
119.*	129.	112.	140.*	138.*	93.	70.	60.	—
302.*	160.	424.*	254.*	309.*	300.	360.	110.	—
n.d.	1,190.	n.d.	n.d.	n.d.	1,340.	1,180	1,090.	—
n.d.	6.0	n.d.	n.d.	n.d.	1.8	7.7	3.2	—
—	309.	—	—	—	303.	309.	277.	—
—	33.4	—	—	—	21.0	18.3	15.2	—
0.39	0.81	0.26	0.55	0.45	0.31	0.19	0.55	—
—	7.4	—	—	—	4.5	3.3	9.9	—
0.7161	—	0.7142	0.7193	0.7187	n.d.	n.d.	n.d.	—
1.14	—	0.77	1.60	1.29	n.d.	n.d.	n.d.	—
High-valence and ferromagnesian elements								
n.d.	45.3	n.d.	n.d.	n.d.	14.9	11.0	9.4	—
n.d.	240.	n.d.	n.d.	n.d.	203.	195.	162.	—
n.d.	5.2	n.d.	n.d.	n.d.	5.6	4.5	3.9	—
n.d.	46.2	n.d.	n.d.	n.d.	36.3	43.3	41.5	—
n.d.	2.0	n.d.	n.d.	n.d.	0.84	0.66	0.38	—
n.d.	3.5	n.d.	n.d.	n.d.	9.7	16.7	16.7	—
n.d.	10.	n.d.	n.d.	n.d.	27.	32.	18.	—
n.d.	8.7	n.d.	n.d.	n.d.	23.0	35.0	33.6	—
Rare-earth elements								
n.d.	41.	n.d.	n.d.	n.d.	42.	46.	37.	0.330
n.d.	85.	n.d.	n.d.	n.d.	74.	81.	67.	0.880
n.d.	30.	n.d.	n.d.	n.d.	36.	40.	30.	0.600
n.d.	6.3	n.d.	n.d.	n.d.	7.1	7.9	6.5	0.181
n.d.	0.88	n.d.	n.d.	n.d.	1.21	1.35	1.25	0.069
n.d.	4.8	n.d.	n.d.	n.d.	4.3	5.4	3.8	0.249
n.d.	0.55	n.d.	n.d.	n.d.	0.77	0.84	0.67	0.047
n.d.	3.5	n.d.	n.d.	n.d.	2.6	2.6	2.4	0.200
n.d.	0.59	n.d.	n.d.	n.d.	0.40	0.38	0.37	0.034
n.d.	11.	n.d.	n.d.	n.d.	16.	17.	15.	—

[1]Chondrite normalizing values from Haskin and others (1968).

TABLE 2.—*Minor and trace elements in northern and southern Glastonbury Gneiss and Monson Gneiss*—Continued

	Monson Gneiss								
Analysis No.	30	31	32	33	34	35	36	37	Chondrite normalizing values[1]
Large cations									
K	6,100.	13,900.	7,700.	18,300	1,800.	4,700.	5,800.	4,500.	—
Rb	32.	39.	52.	70.	4.4	16.	32.	28.	—
Sr	160.	28.	75.	80.	400.	400.	160.	440.	—
Ba	358.	488.	230.	343.	170.	368.	424.	250.	—
Cs	0.6	0.2	0.4	1.2	0.1	0.8	0.4	0.4	—
K/Rb	191.	356.	148.	261.	409.	294.	181.	161.	—
K/Ba	17.0	28.5	33.5	53.3	10.6	12.8	13.7	18.0	—
Rb/Sr	0.20	1.4	0.69	0.88	0.01	0.04	0.20	0.06	—
Ba/Sr	2.2	17.4	3.1	4.3	0.43	0.92	0.65	0.57	—
$^{87}Sr/^{86}Sr$	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—
$^{87}Rb/^{86}Sr$	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—
High-valence and ferromagnesian elements									
Th	2.3	6.4	5.2	5.1	1.4	4.1	7.1	1.5	—
Zr	204.	145.	278.	165.	72.	75.	185.	123.	—
Hf	5.3	4.5	7.6	4.8	1.7	1.4	4.7	2.8	—
Zr/Hf	38.5	32.2	36.6	34.4	42.3	53.6	39.4	43.9	—
Ta	0.10	0.51	0.27	0.35	—	0.20	0.20	0.12	—
Co	3.7	0.4	2.1	0.9	0.6	8.5	5.4	16.9	—
Cr	3.	—	10.	—	9.8	8.6	—	8.5	—
Sc	2.9	11.5	9.7	8.0	0.58	8.4	2.2	8.3	—
Rare-earth elements									
La	3.	23.	19.	9.	11.	18.	9.	11.	0.330
Ce	5.	46.	39.	26.	19.	32.	29.	19.	0.880
Nd	—	27.	17.	7.	4.	13.	8.	5.	0.600
Sm	0.6	7.8	6.0	1.7	0.9	2.1	1.4	1.7	0.181
Eu	0.53	0.71	1.08	0.25	0.43	0.52	0.53	0.53	0.069
Gd	0.6	6.2	5.6	1.5	0.5	1.2	0.8	1.1	0.249
Tb	0.09	1.49	1.10	0.28	—	0.16	0.11	0.16	0.047
Yb	0.5	7.1	4.8	4.8	—	0.5	0.5	0.5	0.200
Lu	0.09	1.05	0.73	0.77	—	0.08	0.08	0.07	0.034
La/Yb	6.0	3.2	4.0	1.9	—	36.	18.	22.	—

[1]Chondrite normalizing values from Haskin and others (1968)

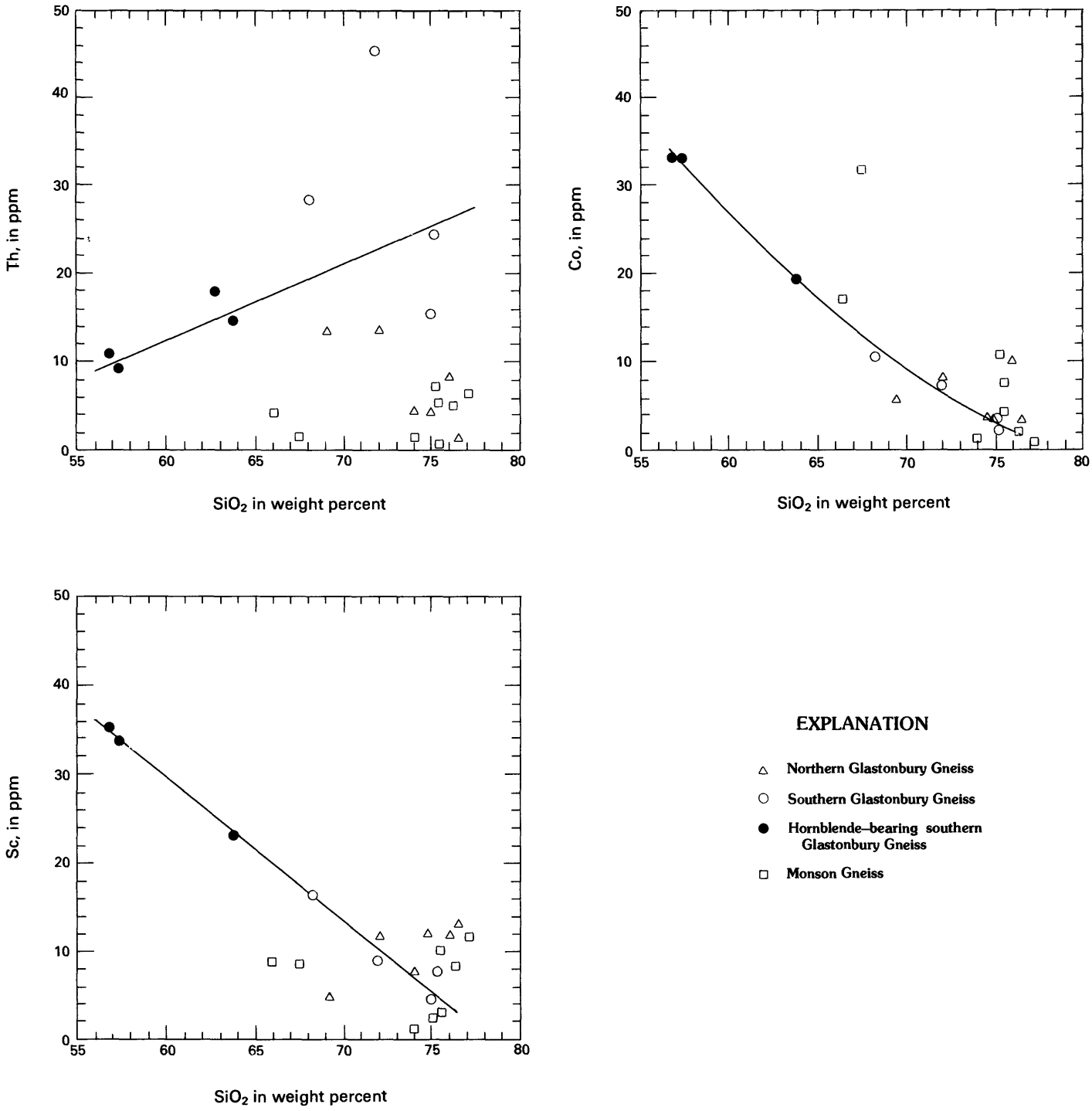


FIGURE 11.—Variation diagrams for Th, Co, and Sc versus SiO_2 for Monson Gneiss and Glastonbury Gneiss. Trend lines are drawn on southern Glastonbury Gneiss.

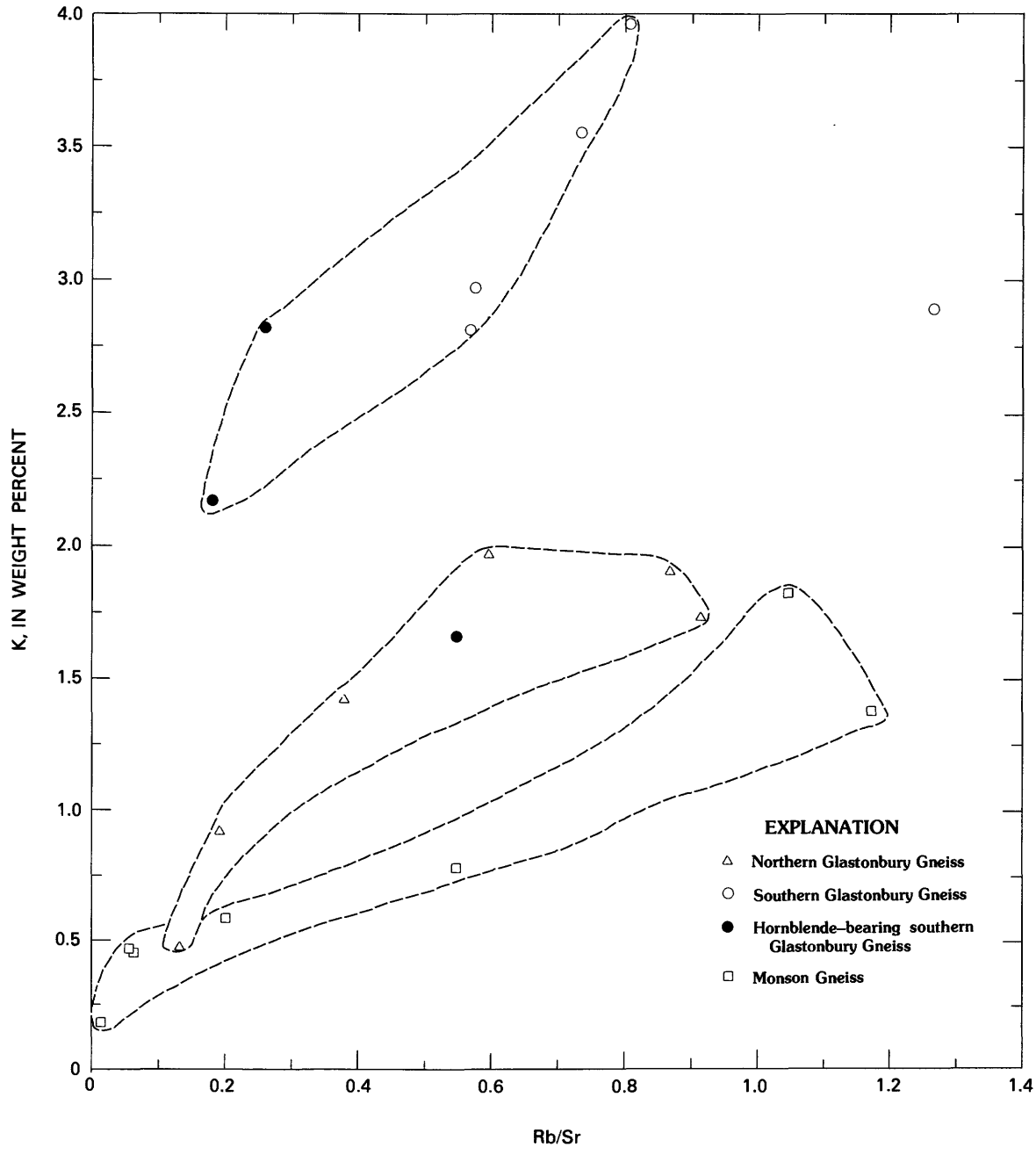


FIGURE 12.—Variation diagram for K versus Rb/Sr. Dashed lines enclose most samples of each lithology, but two points fall far outside their fields.

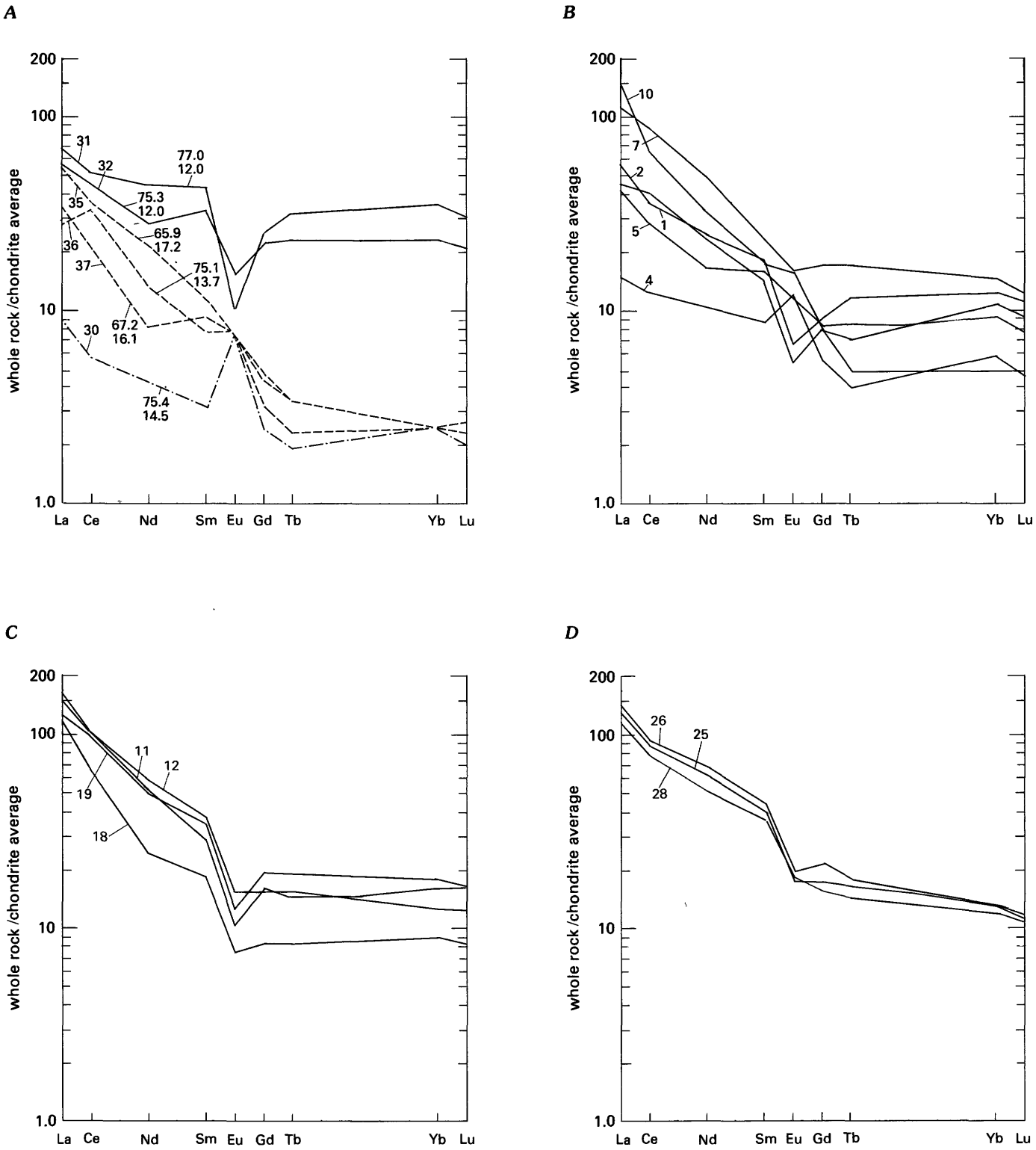


FIGURE 13.—Rare-earth-element patterns. Analysis numbers (tables 1 and 2) are shown near left-hand margins. *A*, Monson Gneiss. See text for discussion. Values are given for SiO_2 content (upper numbers) and for Al_2O_3 content (lower numbers). *B*, Northern Glastonbury Gneiss. *C*, Hornblende-free southern Glastonbury. *D*, Hornblende-bearing southern Glastonbury. Chondrite normalizing values are from Haskin and others (1968).

The solitary pattern (no. 30, dash-dot line, fig. 13*A*) showing overall REE depletion and a strong positive Eu anomaly fits neither of the two foregoing categories and thus suggests yet a third source. The pattern suggests a cumulate of K-feldspar or plagioclase, but again the modal analysis does not particularly bear this out. In the absence of a stratigraphy of the Monson Gneiss and of any knowledge of source areas, such hypothetical sources must remain speculative. It is presently unknown what further variations in REE patterns might be shown by additional samples. It is certain only that the Monson patterns cannot be accounted for by a single homogeneous source.

Northern Glastonbury Gneiss

Patterns for the northern Glastonbury Gneiss (fig. 13*B*) are moderately to strongly fractionated with respect to light REE, are flat across the heavy REE, and show variable Eu anomalies ranging from moderate negative to moderate positive. The lack of consistency probably reflects both different sources (see above) and inhomogeneity of the partly melted crystal mush prior to its solidification. Because of these irregularities, correlation of these patterns with those of the Monson Gneiss, the hypothetical protolith, cannot be attempted in a rigorous manner. In a general way it can be stated that differentiation of high-alumina source rocks (nos. 35, 36, and 37, fig. 13*A*) could yield rocks with the northern Glastonbury patterns, whereas the already highly differentiated Monson (nos. 31, 32, fig. 13*A*) could not. On the other hand, addition of a melt phase rich in K-feldspar component to the more differentiated Monson type should result in an overall slight depletion in all REE's except Eu, thus producing patterns something like numbers 2 and 5 (fig. 13*B*). Such addition also should produce relative enrichment in K-feldspar in the resulting northern Glastonbury. There is, indeed, some indication of such correlation (tables 1 and 2). However, because geological control is effectively absent, this is almost tantamount to saying that the REE patterns reflect the major-element chemistry. At best, the REE data are ambiguous regarding the relationship between the Monson and northern Glastonbury Gneisses.

Southern Glastonbury Gneiss

The REE patterns for hornblende-free southern Glastonbury Gneiss (fig. 13*C*) show relatively high abundances, strongly fractionated light REE, slightly fractionated heavy REE, and negative Eu anomalies. Patterns for the hornblende-bearing marginal phase (fig. 13*D*)are closely similar to patterns of hornblende-free rocks except for a smaller Eu anomaly, a difference that is consistent with the presence of hornblende, other things being equal (Arth and Barker, 1976). The negative Eu anomalies in all the patterns could be related to residual plagioclase; alternately, they could be due to predominantly divalent Eu in the magma (Nagasawa and Schnetzler, 1971).

The greater uniformity and consistency of these patterns reinforce the idea that the southern Glastonbury is a moderately differentiated intrusion with an origin distinct from that of the northern Glastonbury or Monson Gneiss.

ISOTOPIC AGES

The age of emplacement of the Glastonbury Gneiss has remained problematic despite considerable previous efforts to establish a chronology for the rocks of the Bronson Hill anticlinorium. Difficulties associated with sample selection in a polydeformed terrane make some of the earlier work obsolete, and we summarize here only the more significant results directly bearing on this study. Throughout this paper all radiometric ages are given in terms of the decay constants recommended by the International Union of Geological Sciences Subcommission on Geochronology (Steiger and Jäger, 1977). This adoption of the new constants has necessitated the conversion of much of the published literature but permits a more straightforward comparison between dating methods.

A minimum age for the Glastonbury is provided by a 350 m.y. Rb-Sr whole-rock isochron age on folded pegmatite dikes that cut across the gneiss and its adjacent country rock in the Middle Haddam and Glastonbury quadrangles in Connecticut (Brookins and Methot, 1971). One can argue from structural evidence to the north in central Massachusetts that the Belchertown pluton must also postdate the Glastonbury, that is, the Belchertown pluton deforms the north end of the Glastonbury dome (Leo and others, 1977). Here U-Pb zircon data have been used by Ashwal and others (1979) to assign the Belchertown a 380 ± 5 m.y. (Middle Devonian) intrusion age. A tighter constraint on the younger age limit can only be made by inferences based on the state of deformation of the gneiss dome. Even so, although the Glastonbury would seem to have fully participated in the dynamothermal metamorphism of the Acadian orogeny fixed at 380 m.y. to 405 m.y. ago (Naylor, 1971; Lyons and Livingston, 1977), field relationships do not unequivocally resolve between an early Acadian or a Taconic time of origin for this igneous rock.

As an older age limit, the Glastonbury Gneiss intrudes the Ammonoosuc Volcanics, which has been dated at 450 ± 15 m.y. by the Rb-Sr whole-rock isochron method

on samples from several localities along the Bronson Hill anticlinorium (Brookins, 1968). Brookins and Hurley (1965) earlier had reported a 430±15 m.y. age for samples of the Middletown Gneiss (Ammonoosuc equivalent) from the Middle Haddam and Glastonbury quadrangles, but Brookins and Methot (1971) later implied that the Ammonoosuc results should be used for the Middletown Gneiss, too. Brookins and Methot (1971) also report an Rb-Sr whole-rock isochron age of 470±15 m.y. for the Monson Gneiss, supporting our contention that no significant time gap separates this unit from the overlying Ammonoosuc Volcanics. A similar conclusion is reached based on new U-Pb zircon data included in this paper.

Brief mention should be made of a previously published age of 348±10 m.y. for the southern Glastonbury Gneiss (Brookins and Hurley, 1965), which was slightly revised to 354±10 m.y. by Brookins and Methot (1971). The former result is considered suspect primarily because it includes a probable pegmatite-gneiss mixed sample (R3372, see table 4). At the Spinelli quarry the country rock of the pegmatite has in part been contaminated by reaction between the pegmatite and wall rock. the uncontaminated wall rock is a foliated, partially chloritized biotite-quartz-feldspar rock now known to be chemically quite different from sample R3372. The revised isochron age of Brookins and Methot (1971) is still weighted heavily by three samples (R4792a, b, and c, see table 4), which are also probably not truly representative of southern Glastonbury Gneiss as they contain higher Rb/Sr and $^{87}Sr/^{86}Sr$ ratios than other samples included in the present study. Reexamination of the collection site reveals that the three anomalous samples were obtained close to granite dikes possibly produced by Acadian anatexis.

A major emphasis of this paper is the chemical and mineralogical distinction between the northern and southern Glastonbury Gneiss, which may imply fundamental differences in modes of origin. Thus, the possibility of different ages for the two parts of the Glastonbury also presents itself. In order to examine this possibility and to shed additional light on the Monson anatectic model, we undertook a further geochronologic investigation by the U-Th-Pb zircon and Rb-Sr whole-rock isochron methods.

The U-Th-Pb zircon analytical procedure is identical to that reported recently by Ashwal and others (1979), and it need not be repeated here. Difficulty in determining the concentration of thorium mentioned in that paper has been resolved, however, and we consider all concentration data for U, Th, and Pb in the present study to be accurate to ±1 percent (two sigma). Rb-Sr analytical methods are described in detail by Lee and Brookins (1978).

Representative samples of the northern Glastonbury Gneiss (GWL357A), the southern Glastonbury Gneiss (GWL368A), and two localities of the Monson Gneiss (GWL358A and Pec657) were collected for zircon age determination. Petrographic descriptions together with location information for these samples are given in the Appendix. The U-Th-Pb analytical data determined for two size fractions of each sample—four size fractions in the case of GWL368A—are presented in table 3 and are shown on a concordia diagram in figure 14. Also included in table 3 and figure 14 are data for two size fractions of a third sample of Monson Gneiss from near Orange in northern Massachusetts taken from Zartman and Naylor (in press).

The U-Pb analyses for the Glastonbury display minor discordance and, the $^{207}Pb/^{206}Pb$ ages permit no distinction between the two samples. Commonly employed models for interpreting such isotopic systematics would lead to a time of intrusion essentially equal to the average $^{207}Pb/^{206}Pb$ age of 456±10 m.y. The scatter in plotted error envelopes on the concordia diagram, however, somewhat exceeds that expected solely from analytical uncertainty for a precisely colinear array. This scatter could indicate a mixed zircon population, in which case a more complicated interpretation of the primary crystallization age may be required. Because the average $^{207}Pb/^{206}Pb$ age lies near the oldest limit permitted by the intrusive relationship of the Glastonbury into the Ammonoosuc Volcanics, it is appropriate to consider whether a component of older inherited zircon was present in the magma at the time of crystallization. In this regard the four closely clustered points with $^{206}Pb/^{238}U$ ages of about 430 m.y. do place a restriction on the position of the end members of possible mixed zircon populations. If for example, we appeal to an inherited zircon as might be contributed by the extensive Proterozoic Z terrain to the south and east (fig. 1), the minimum age of crystallization allowed by a two-component mixing line would be about 420 m.y. Without definitive evidence either to support or to reject this hypothesis of inherited zircon in the Glastonbury, we proceed to consider the Monson Gneiss data, which provide additional insight into the chronology of both units.

In general appearance, the U-Pb analyses for the Monson closely resemble those of the Glastonbury in that they also display only minor discordance with similar $^{207}Pb/^{206}Pb$ ages among the three samples. The obvious difference between the two sets of data is that the averge $^{207}Pb/206Pb$ age of 435±6 m.y. for the Monson is younger than that of the Glastonbury, a situation at odds with the field relationships that require the reverse order of emplacement. The possibility mentioned in the preceding paragraph of older inherited zircon in the Glastonbury remains as one means of resolving this

TABLE 3.—*Uranium-thorium-lead isotopic ages of zircon from the Glastonbury and Monson Gneisses*

[Field numbers, sample descriptions, and locations in Appendix.]

Mesh size	Concentration (ppm)			Isotopic composition of lead (atomic percent)				Age, in millions of years			
	U	Th	Pb	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{208}Pb}{^{232}Th}$
Northern Glastonbury Gneiss [2]											
−100+150	754	261	54.0	0.0670	83.68	5.671	10.58	428	432	456	374
−200+270	978	376	67.0	.0873	82.25	5.901	11.76	401	410	463	339
Southern Glastonbury Gneiss [51]											
−100+150	539	289	39.8	.0323	80.70	4.975	14.29	429	431	445	405
−200+270	781	459	57.2	.0118	81.46	4.764	13.76	431	436	467	374
−270+325	839	532	61.6	.0125	81.05	4.724	14.21	430	433	453	358
−325+400	1042	663	74.1	.0148	81.14	4.755	14.10	417	422	451	341
Monson Gneiss [31]											
−150+200	1304	396	81.1	.0108	88.32	5.062	6.602	398	404	434	287
−250+325	1365	370	87.8	.0043	88.76	4.996	6.240	414	417	436	325
Monson Gneiss [52]											
−100+150	1241	485	80.2	.0030	86.65	4.843	8.501	407	409	428	314
−200+250	1069	368	70.4	.0023	88.01	4.920	7.066	420	422	433	302
Monson Gneiss from near Orange, Mass.[2]											
−100+150	383	137	24.3	.0079	85.29	4.861	9.843	393	399	438	381
−270+325	455	156	30.3	.0167	84.81	4.967	10.20	409	414	440	419

[1]Decay constants: $\lambda_{^{238}U}=1.55125\times10^{-10}$ yr^{-1}; $\lambda_{^{235}U}=9.8485\times10^{-10}$ yr^{-1}; $\lambda_{^{232}Th}=4.9475\times10^{-11}$ yr^{-1}; $^{238}U/^{235}U=137.88$. Isotopic composition of common lead assumed to be $^{204}Pb:^{206}Pb:^{207}Pb:^{208}Pb=1:18.20:15.60:38.10$.

[2]Sampe from Zartman and Naylor (in press).

enigma. However, we are faced with an apparent age of the Monson that lies at the youngest limit permitted by its stratigraphic position underneath the Ammonoosuc Volcanics. While the Monson data show less scatter in $^{207}Pb/^{206}Pb$ ages than the Glastonbury data, the hint of a trend does emerge with the three Monson localities becoming progressively younger southward. The age discrepancy between the Monson and Glastonbury might thus be alternatively explained by preferential metamorphic overprinting of the Monson zircons, in the form of either episodic disturbance of preexisting grains or new growth. The weakness in this hypothesis is that the reason for such greater response of the Monson zircons to subsequent metamorphism as compared to the Glastonbury is not apparent. Can we simply appeal to variations in physiochemical conditions when even adjacent localities, such as numbers 2 and 31 (fig. 2), maintain the age distinction? Likewise, different susceptibilities related to different uranium contents are not obviously supported by the analyses. Again, further speculation is not warrented without additional work except to point out that zircon with $^{207}Pb/^{206}Pb$ ages considerably older than Ordovician has been found at a number of localities flanking the southern Bronson Hill anticlinorium (Naylor, 1975; Zartman, unpub. data). The survival of such ages makes it unlikely that the Monson is much older than indicated by existing U-Pb zircon and Rb-Sr whole-rock results.

For our purposes, the anomalous age relationship revealed by the present study can, most likely, be resolved by postulating either (1) a small component of old inherited zircon in the Glastonbury or (2) preferential Acadian or Alleghanian metamorphic overprinting of the zircon in the Monson. Despite the ambiguity that

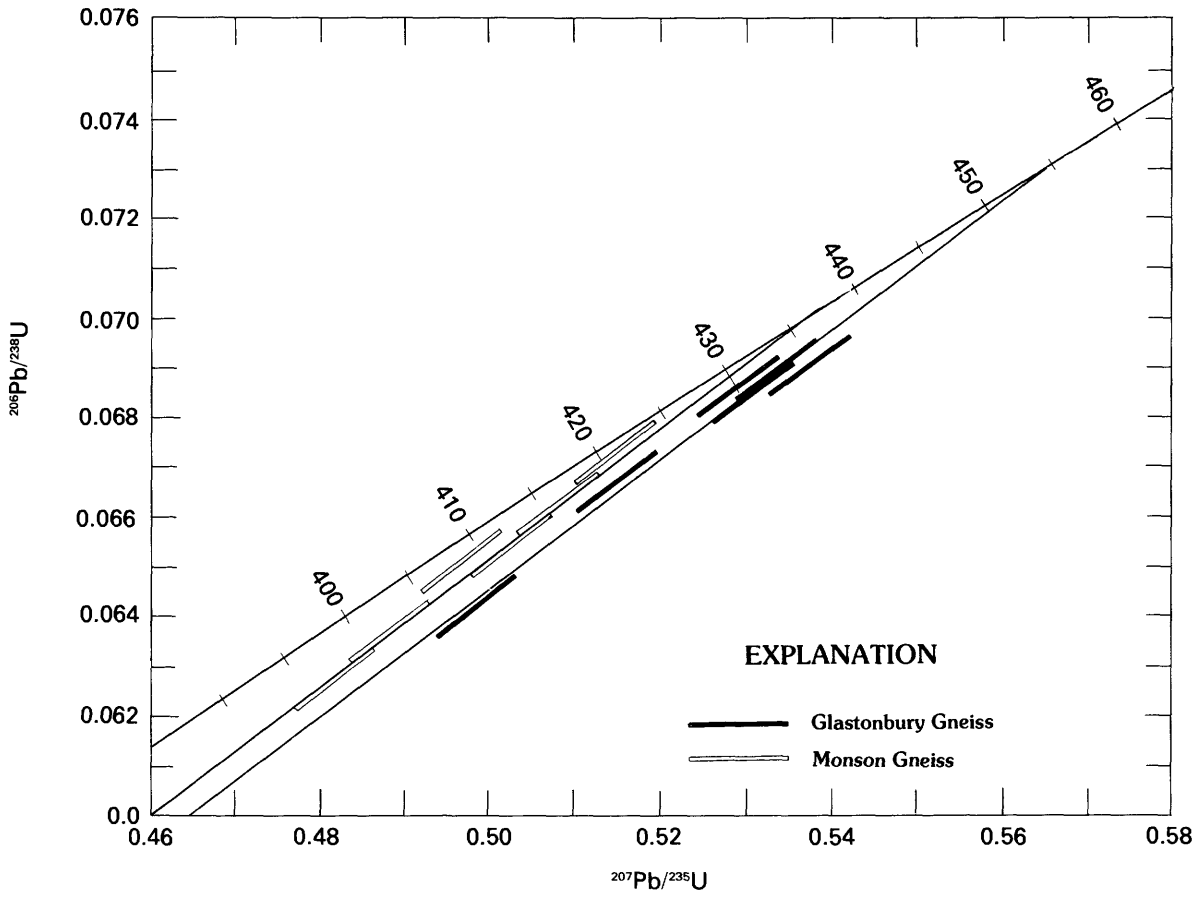


FIGURE 14.—Concordia diagram for zircon from the Glastonbury and Monson Gneisses. Linear regression lines constrained to pass through origin are shown for each unit.

exists around making precise age assignments within the 470 to 420 m.y. (Middle Ordovician to Early Silurian) interval, we feel confident to interpret the Glastonbury Gneiss as a Taconic intrusion not recognizably younger than the mantling strata into which it was emplaced.

We turn now to the considerably more complex Rb-Sr whole-rock results. The Rb-Sr data for the Glastonbury are presented in table 4 and plotted as either northern or southern gneiss on an isochron diagram in figure 15. We include on the isochron diagram results on normal varieties of the gneiss from previous studies (Brookins and Hurley, 1965; Brookins and Methot, 1971; Brookins 1980) and on seven new determinations of material especially collected for the present study. Excluded from the diagram are the four samples (R3372, R4792a,b,c) discussed above that largely controlled earlier attempts to date the Glastonbury but probably represent chemically altered or even foreign rock. By inspection, it is obvious that there is too much scatter even in this selected suite of samples to attempt any age interpretation.

The southern Glastonbury is represented by 19 samples (11, 11a, 13a, 13b, 13c, 13d, 18, 18a, 49, 50, 51, R1132b, R1132d, R1136a, R1066a, R1066b, R1066c, R4998, R4999), for which a York (1966) regression yields an apparent age of 309 ± 84 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7108 ± 0.0022. Apart from the dubious worth of attempting a linear regression through such scattered data, the resultant age is too low for a rock that has been involved only in Acadian deformation and metamorphism.

A regression of the five samples from the northern Glastonbury (2a, 5, 7, 7a, and 10) yield an apparent age of 536 ± 130 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7066 ± 0.0034. Clearly, such a result is also uninterpretable in terms of an emplacement age because the gneiss intrudes the Middle Ordovician Ammonoosuc Volcanics. Although the limited sampling of the northern

TABLE 4.—*Rubidium-strontium isochron ages of whole rocks from the Glastonbury Gneiss*

[Field numbers, sample descriptions and locations of samples 2A to 51 in Appendix.]

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age[1] (m.y.)	
Northern Glastonbury Gneiss						
2a	83.5	80.0	3.02	0.7297		
5	48.2	128.	1.09	.7124	536±130	
7	82.0	136.	1.76	.7205	0.7066±0.0034	
7a	56.0	196.	.83	.7148		
10	52.1	281.	.54	.7107		
Southern Glastonbury Gneiss						
11	144.	113.	3.68	.7263		
11a	128.	167.	2.22	.7228		
13a	43.6	250.	1.66	.7163		
13b	168.	264.	1.18	.7195		
13c	140.	270.	1.50	.7191		375±80
13d	142.	210.	1.53	.7185		0.7093±0.0020
18	103.	139.	2.14	.7205		
18a	119.	302.	1.14	.7161		
49	112.	424.	.77	.7142		
50	140.	254.	1.60	.7193	309±84	
51	138.	309.	1.29	.7187	0.7108±0.0022	
R1132b	—	—	1.41	.7164		
R1132d	—	—	1.55	.7178		
R1136a	—	—	2.90	.7230		
R1066a	—	—	1.84	.7170		
R1066b	—	—	1.47	.7159		
R1066c	—	—	1.77	.7167		
R4998	—	—	1.30	.7169		
R4999	—	—	.56	.7095		
Questionable Southern Glastonbury Gneiss (see text)						
R3372	—	—	27.90	.8458		
R4792a	—	—	13.26	.7743		
R4792b	—	—	17.43	.7975		
R4792c	—	—	6.80	.7440		

[1]Decay constant: $\lambda_\beta = 1.42 \times 10^{-11}$ yr^{-1}; ages calculated from least squares regression method of York (1966). See graphical representation of these data in figure 15.

Sample numbers with an R prefix refer to data previously published by Brookins and Hurley, 1965; Brookins and Methot, 1971; and Brookins, 1980. Other samples were especially collected for the present study.

Glastonbury makes it difficult to compare the isotopic systematics with the more extensively studied southern Glastonbury, the data do largely overlap in Rb/Sr ratio and strontium isotopic composition. The big difference in calculated ages would seem to merely reflect the strong control of the most radiogenic samples on the regressions.

Finally, a regression involving all 24 samples from both varieties of Glastonbury yields an apparent age of 375 ±80 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7093±0.0020. While this age could be accommodated within the geologically imposed constraints, the large uncertainty caused by the badly scattered and rather unradiogenic data casts serious doubt upon such a combined isochron plot as well. Especially in the light of the more precise U-Pb zircon results, which suggest that the Glastonbury was emplaced sometime between 420 and 470 m.y. ago, we believe that the Rb-Sr whole-rock systems violate one or more of the basic assumptions of the isochron method.

An Early Silurian to Middle Ordovician age for the Glastonbury translates into an initial $^{87}Sr/^{86}Sr$ ratio range of 0.7046 to 0.7128 if the scatter on the isochron diagram is caused solely by variability in initial isotopic composition. Although the parent magma may well have originated by rapid, high-level generation from a diverse upper crustal terrane, this extremely heterogeneous strontium probably would not be available from only slightly older island arc rocks, such as represented by the immediately adjacent Ammonoosuc Volcanics

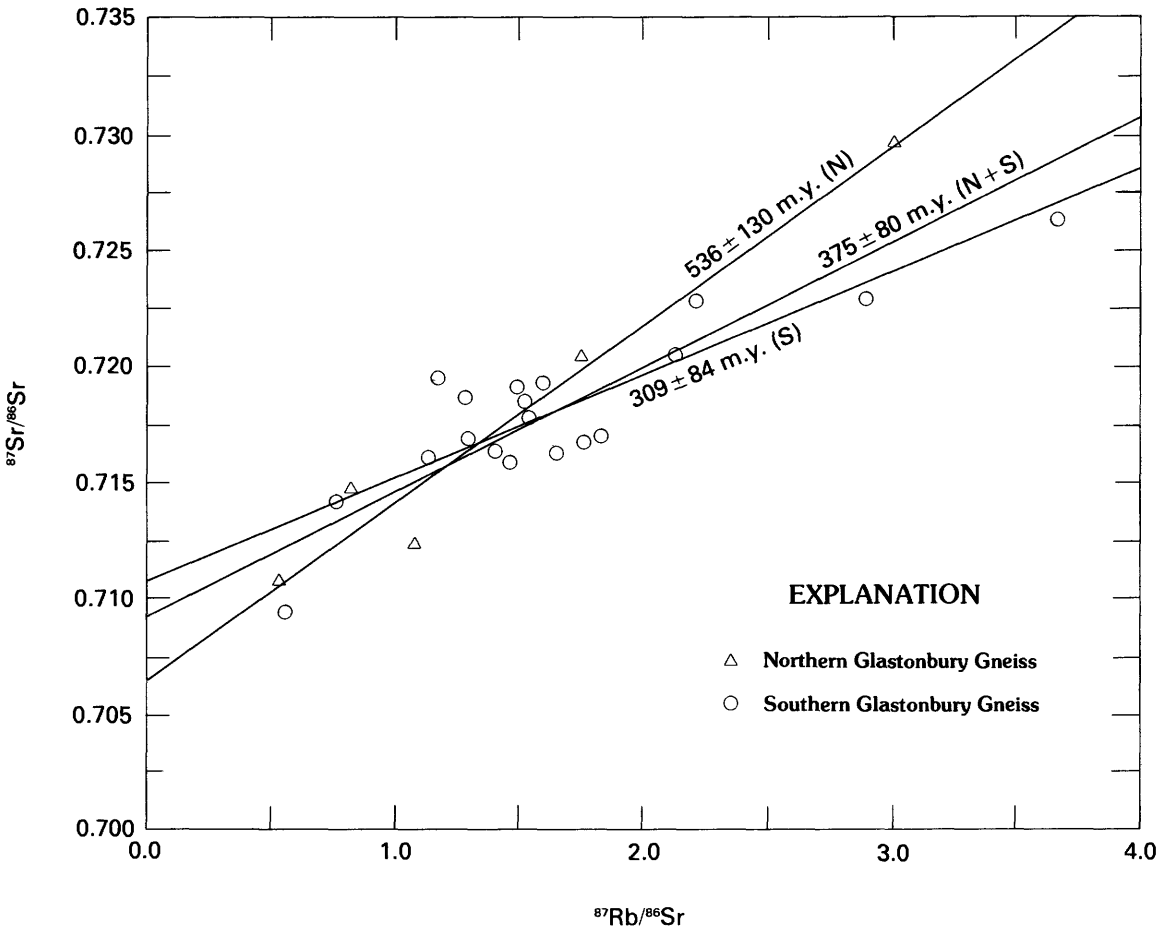


FIGURE 15.—Rb-Sr whole-rock isochron diagram for the Glastonbury Gneiss. Linear regression lines are shown for the northern (N), southern (S), and composite (NS) gneiss.

and Monson Gneiss. Initial isotopic variability is usually associated with substantially older and, therefore, isotopically evolved source material. The identification of more ancient basement rock in the vicinity would strengthen the case for this interpretation.

The scatter in the data may also result from open-system conditions superimposed at a later time, and this hypothesis is especially attractive where the geology reveals subsequent metamorphism, as along the Bronson Hill anticlinorium. Here the local redistribution or even metasomatic addition and (or) removal of rubidium and strontium in the rocks during the Acadian orogeny is a distinct possibility. Mounting evidence that southern New England was also involved in the late Paleozoic Alleghanian orogeny cannot be ignored in the interpretation of radiometric systematics. In fact, a valid objection to the Acadian orogeny as the only disturbing event is the short time interval thereby implied between the emplacement and the metamorphic ages. If a redistribution of Rb and Sr initiated in the Acadian were further accentuated during the Alleghanian, however, the scatter observed on the isochron diagram seems entirely plausible.

DISCUSSION

As stated in the introduction, the Glastonbury dome is stratigraphically and structurally analogous to the Oliverian domes of New Hampshire. The one respect in which the Glastonbury dome differs most markedly from other Oliverian domes is in the petrologic character and apparent origin of the northern, potassium-poor gneiss.

A gray gneiss with relatively low K_2O content (2 to 3.5 percent) forms a border phase to granitic gneiss in several domes (for example, Jefferson dome, Leo, unpub. data; Lebanon dome, Lyons, 1955; fig. 1). Relatively homogeneous trondhjemitic gneiss intrudes Ammonoosuc Volcanics as dikes and small plugs in several Oliverian domes and constitutes the entire core of at least three of the small domes in southwestern New Hampshire and adjacent Vermont (Leo and Gromet, 1981

and Leo, unpub. data). Such trondhjemitic rocks, which are very similar to felsic Ammonoosuc Volcanics (Leo, unpub. data), may constitute part of a primitive island-arc assemblage of mantle origin. By contrast, the northern Glastonbury Gneiss with its odd, unsystematic variations in texture, in bulk composition, and in trace-element abundances; its compositional overlap with Monson Gneiss and relative lack of overlap with the northern trondhjemites; and field relations that locally suggest a transition from plastically deformed Monson Gneiss, implies a mode of origin distinct from that of the other Oliverian core gneisses. In the present section some of the peculiar problems related to the genesis of the northern Glastonbury are discussed.

NORTHERN GLASTONBURY GNEISS

The proposed origin of the northern Glastonbury by anatexis of a Monson-like lithology is supported by field relations, textures, and, to some extent, by major- and trace-element chemistry. Other aspects that must be considered include the following: (1) what is known about the possible attainment of pressures and temperatures adequate to initiate melting of Monson lithology?, and (2) what does this scenario imply regarding heat flow and metamorphism along the southern part of the Bronson Hill anticlinorium in Middle Ordovician to Early Silurian time? These questions are considered in turn below.

ANATEXIS OF MONSON LITHOLOGY

In addressing this question, it should be noted that the Monson sequence is not unique as a potential protolith for the northern Glastonbury Gneiss, inasmuch as rocks stratigraphically underlying the Monson are lithologically comparable. The pre-Monson section in southern Connecticut includes the New London Gneiss and the Mamacoke Formation (Goldsmith, 1966); in the Haddam area, the Monson is underlain by the Haddam Gneiss (Eaton and Rosenfeld, 1972). However, there are difficulties in relating these older rocks to the northern Glastonbury Gneiss, to wit: (1) such rocks are known only in central and southern Connecticut, well to the south of the latitude of the northern Glastonbury (where the bottom of the Monson section is not exposed); and (2) no transition from pre-Monson rocks to Glastonbury has been demonstrated, and existence of such a transition can only be speculative.

In the absence of evidence to the contrary, we believe it unlikely that the Monson or underlying rocks already were recrystallized gneiss prior to Middle Ordovician to Early Silurian (that is, Taconic) metamorphism. The point is significant because of the water needed for anatexis to proceed at geologically reasonable temperatures, in particular in view of the low potassium content of the Monson rocks. The water content of the felsic tuffs and volcaniclastic sediments constituting the primary Monson sequence might have been of the order of 2 to 3 percent, whereas that of the Monson Gneiss averages about 0.5 percent (table 1).

The depth of burial of the base of the Monson section at the onset of Middle Ordovician metamorphism can only be approximated. Apparent thicknesses of the units, based on present exposures, are unlikely to be equivalent to original thicknesses, in view of changes related to original compaction followed by intense deformation including tectonic thinning, notable in the Acadian (Robinson and Hall, 1980). In the aggregate, these processes probably have led to a net reduction of thicknesses. Estimated thicknesses of presently exposed sections at the approximate latitudes of Palmer, Mass. and Ellington, Conn. (fig. 2), are as follows (data from Leo and others, 1977; Geologic Map of Massachusetts, in press; and M. H. Pease, Jr., written commun., 1980):

	Palmer, Mass.	*Ellington, Conn.*
Monson Gneiss (minimum thickness; base not exposed)	4.0 km	1.5 km
Ammonoosuc Volcanics	1.5 km	1.0 km
Partridge Formation	0.05 km	—
Northern Glastonbury Gneiss	3.5 km	9.0 km
Total	9.1 km	11.5 km
Average	10.3 km	

If a conservative 20 percent is added to these totals to compensate for tectonic and compactional thinning, the minimum estimated thickness to the base of the exposed section is 12 to 13 km. Such a depth corresponds to approximately 3 kbar.

The experimental studies of H. G. F. Winkler and his coworkers (summarized in Winkler, 1974) and P. J. Wyllie and his coworkers (e.g., Robertson and Wyllie, 1971) provide much insight on the anatexis of K-poor quartzo-feldspathic rocks under varying conditions of water pressure. Winkler and his coworkers demonstrated that in a water-saturated system with P_{H_2O}=P total=2kbar, micacecous quartz-plagioclase gneisses lacking K-feldspar began to melt below 700 °C (Winkler, 1974, p. 300). Breakdown of micas (muscovite or biotite) contributed an Or component to the melt. Somewhat comparable results were reported by Piwinskii and Wyllie (1968) working with water-saturated systems between 1 kbar and 3 kbar. The rock most closely comparable to Monson Gneiss was a tonalite (their sample 1213) with 63 percent SiO_2, 12 percent modal quartz, 16 percent biotite, and 15 percent hornblende. In a 2-kbar system this rock began to melt at 730 °C and yielded 8

percent liquid at 750 °C. The melt fraction is referred to as "granitic," but no specific composition is given. At 3 kbar, melting began at 700 °C, and 20 percent liquid had formed at 750 °C. A temperature of 750 °C is not unreasonable for the upper amphibolite facies, although attainment of such a temperature at 13 km depth implies a higher than normal heat flow (approximately 60 °C per km).

It appears, then, that anatectic development of the northern Glastonbury magma is compatible with P-T conditions at the base of the Monson section in Middle Ordovician time, assuming an essentially closed and water-saturated system with $P_{H_2O}=P$ total (type IV system of Robertson & Wyllie, 1971). Such a system, however, in which available water can range between 6 and 15 percent, may have only limited application to anatexis in the crust where the water content is unknown, but likely lower. A possibly more realistic model is the type III system of Robertson and Wyllie (1971). This system is defined as an assemblage of silicate minerals with or without hydrous phases plus a vapor phase but without sufficient water to saturate the completely melted assemblage at the existing pressure. Under these conditions, melting, which begins a few degrees above the solidus, is limited by the amount of available pore water that is dissolved in the melt (about 13 percent melt per 1 percent of pore water; Robertson and Wyllie, 1971, p. 270). Subsequent melting proceeds along a saturation boundary, defined by the amount of water required to saturate the combined crystals and liquid at any given temperature. The result is a much higher liquidus temperature than that of a water-saturated system, especially so in the case of K-poor rocks. However, assuming a pore fluid of about 2 percent and a limited amount of melt formed during anatexis (20 to 30 percent), the situation would differ little from the water-saturated system (type IV of Robertson and Wyllie, 1971). In either case, the melt thus formed should be sufficient to produce a crystal mush consisting of the K-enriched liquid plus crystals which for the rocks under consideration would be dominantly quartz and plagioclase. Such a mush could rise in the crust prior to consolidation, provided the liquid fraction was either water unsaturated or significantly hotter than the solidus temperature, or both (Robertson and Wyllie, 1971, p. 271; Winkler, 1974, p. 306-307). Assuming incomplete homogenization of the mush, the resulting intrusive rock could be expected to resemble the northern Glastonbury Gneiss prior to its subsequent recrystallization in Acadian time.

MIDDLE ORDOVICIAN TO EARLY SILURIAN HEAT FLOW AND METAMORPHISM

Temperatures in the range of 700 to 750 °C at a depth of 12 to 13 km imply a thermal gradient of the order of 60 °C/km. Such a thermal gradient is considerably higher than average values (20 to 30 °C/km), but might be expected during a regime of active subduction with associated island-arc plutonism and volcanism such as is now considered to characterize the early development of the Bronson Hill anticlinorium (see below).

Devonian (Acadian) metamorphism of this general intensity has been widely documented. Progressive regional metamorphism in southwestern New Hampshire, summarized by Turner (1968, fig. 8.4 and p. 362), involved temperatures in excess of 700 °C at pressures of about 3 kbar. Similar temperatures and somewhat higher pressures (>5 kbar) have been documented in the Quabbin reservoir area of central Massachusetts (Tracy and others, 1976; Tracy, 1978) and in southeastern Connecticut (Lundgren, 1966). Localized to widespread anatexis has occurred in each of these areas.

Direct evidence of high-grade Middle Ordovician to Early Silurian (Taconic) metamorphism is harder to find, in large part because such evidence has been mostly obliterated by Acadian metamorphism. Nevertheless, occasional relics of sillimanite-orthoclase or sillimanite-muscovite grade found within kyanite-grade rocks may bear evidence of a Taconic metamorphism (Leo and others, 1977; Tracy and Robinson, 1980). Sillimanite-grade metamorphism of Taconic age in northern Vermont has been confirmed by $^{40}Ar/^{39}Ar$ dating of muscovite (Lanphere and Albee, 1974).

The discussion thus far has centered on an anatectic model of origin for the northern Glastonbury Gneiss, but some alternative hypotheses must be considered. One possibility is that the gneiss crystallized from a trondhjemitic magma derived by partial melting or fractional crystallization of basaltic source rocks in the oceanic crust or the upper mantle. Such an origin has the advantage of being less circumscribed by limitations on pressure and temperature. Trondhjemites, tonalites, and genetically related low-K dacites have received much study in recent years (Barker, 1979), and the distinctive mode of genesis of these rocks is by now fairly well understood. Trondhjemites as parts of island-arc assemblages have been documented by Barker and others, 1976; Payne and Strong, 1979; Barker and others, 1979; Bryan, 1979; Gill and Stork, 1979. The northern Glastonbury Gneiss would appear to fit into this context, inasmuch as trondhjemite in the northern Oliverian domes is regarded as part of a bimodal Ammonoosuc assemblage with some characteristics of an oceanic setting and others developed in a complex volcanic arc in a continental-margin environment (Leo and Gromet, 1981; Leo, unpub. data).

The principal arguments against considering the northern Glastonbury of deep-seated magmatic origin

are based on the same characteristics that seem to support the crystal-mush hypothesis: the unsystematic variations in major- and trace-element abundances are REE patterns, plus the relatively high K and Rb contents compared to most mantle-derived trondhjemites. These features are incompatible with an origin involving separation of an essentially homogeneous and largely liquid magma from a mantle source. The trondhjemites of New Hampshire are distinct in this regard from the northern Glastonbury in that they appear to be more homogeneous, are consistently lower in K and Rb, and have more uniform REE patterns (Leo, unpub. data).

Admittedly, these criteria are somewhat subjective as a basis for a major genetic distinction. Moreover, the possibility cannot be ruled out that some of the chemical variation in the northern Glastonbury may be due to post-intrusion alteration and (or) mobilization of unstable cations. A potentially more definitive criterion for a mantle origin could be provided by $^{87}Sr/^{86}Sr$ initial ratios. Bona fide trondhjemites consistently show low initial ratios characteristic of most mantle-derived rocks; although Sr evolution through geologic time gradually raises the $^{87}Sr/^{86}Sr_0$, trondhjemites of early to middle Paleozoic age should show initial ratios of less than about 0.704 (Peterman, 1979). Unfortunately, the Sr-isotopic data for the Glastonbury Gneiss are too ambiguous to permit a meaningful evaluation of the initial strontium composition.

Collins (1954) proposed a metasomatic origin involving large-scale conversion of Ammonoosuc Volcanics and the overlying Silurian-Devonian sedimentary rocks in the Ellington quadrangle by "fluids" bearing silica and alkalies. However, our own field observations, supported by recent work in the Ellington quadrangle (M. H. Pease, oral commun., 1978) and in the Hampden quadrangle to the north (Peper, 1977; fig. 2), lend little support to this idea. In particular, large-scale metasomatism of the kind envisaged by Collins, which reflected then-current ideas of granite petrogenesis, is incompatible with the intrusive character of the gneiss, its lack of gradation to adjacent rocks, and the total absence of relict compositional layering.

SOUTHERN GLASTONBURY GNEISS

The southern Glastonbury Gneiss, with its relatively smooth variation trends and uniform REE patterns (figs. 10–13) and associated mafic border phase, appears to be a relatively uncomplicated calc-alkaline granite intrusion. The only incongruous aspect of the southern gneiss is the notable variation in grain size and textures throughout the pluton (fig. 7). This is further discussed below.

The compositional fields of the southern and northern Glastonbury, although rather broad, show no appreciable overlap (fig. 6). Considering the similar ages of the two gneiss bodies it must be concluded that the calc-alkaline magma that crystallized to form the southern Glastonbury was generated concurrently but spatially separate from the crystal mush thought to have produced the northern Glastonbury.

The source of protolith for the southern Glastonbury Gneiss is even more speculative than in the case of the northern gneiss. The composition of the southern gneiss virtually precludes its being derived from a Monson lithology, unless the latter grades to more calc-alkaline compositions towards the south. However, there is no indication that this is the case; rather, Monson Gneiss and underlying units continue as K-poor, volcanigenic gneisses along the length of the Bronson Hill anticlinorium and into southern Connecticut (Herz, 1955; Goldsmith, 1966; Snyder, 1970; Lundgren and others, 1971).

The most plausible kind of calc-alkaline source for the southern Glastonbury would be granite of pre-Middle Ordovician age, that is, part of the basement upon which the Monson assemblage was deposited. K-rich metasedimentary rocks could also have been involved. Granites that are potential source rocks are exemplified by the Sterling Plutonic Group which appears to be older than the Monson although its exact age is unknown (Goldsmith, 1966; Dixon and Lundgren, 1968). The nearest mapped exposures of these granitic rocks are in the core and on the west flank of the Willimantic dome (Goldsmith, 1963), some 15 to 20 km east of the southern part of the Glastonbury dome (fig. 1). Although the region is structurally complex and shows no evidence of older granite at depth beneath the Glastonbury dome, it appears likely that suitable rocks were available. Regarding the conditions of melting of such source rocks, it may be assumed that, relative to the Monson sequence, they were (1) more potassic, (2) deeper seated (a pressure range of perhaps 3 to 5 kbar), and (3) crystalline and not unconsolidated like the Monson sequence, hence containing less water. The first two conditions would lower the temperature at which a given amount of melt would form, whereas the third would raise it. Experimental evidence (summarized by Wyllie, 1979, p. 511–513) suggests that in an undersaturated granite system at 3 to 5 kbar and 700 to 750 °C, anatectic melting would proceed quite readily.

PLATE-TECTONIC SETTING OF THE GLASTONBURY DOME

Recent attempts to place early to middle Paleozoic development of the northern Appalachians in a plate-tectonic framework consider the Bronson Hill anticlinorium the locus of a Middle Ordovician island arc

over a subduction zone. In the earliest comprehensive regional analysis (Bird and Dewey, 1970), the subduction zone was considered to dip westward. More recent models (Osberg, 1978; Robinson and Hall, 1980) involve an eastward-dipping subduction zone, which more logically fits the distribution of lithologic and tectonic features and which is also in accord with more extensively documented plate-tectonic regimes in Newfoundland (Strong and others, 1974).

Tectonic and geometric considerations aside, the rationale for the island-arc model is found in the widely distributed Ammonoosuc Volcanics and the associated plutons (Oliverian core gneisses). Recent work on this assemblage in New Hampshire and northern Massachusetts (Aleinikoff, 1977; Leo, 1980a,b, and unpub. data) indicates that the mafic component of the Ammonoosuc is low-K, oceanic tholeiite, and contains negligible andesite. Thus the Ammonoosuc has moderate analogs in relatively primitive, essentially oceanic arcs characteristic of the early period of arc construction (Kuno, 1966). The source of the felsic Ammonoosuc, mostly K-poor keratophyres, is less clear. Available data suggest that these rocks were not derived by differentiation of the tholeiites but reflect a different (mantle?) source. The same is presumably true of the trondhjemitic plutons of southwestern New Hampshire and trondhjemite associated with Ammonoosuc Volcanics elsewhere along the Bronson Hill anticlinorium. The calc-alkaline Oliverian plutons, of which the southern Glastonbury Gneiss is reasonably representative, show evidence of being derived from sialic crust. A problem as yet incompletely understood is the apparent juxtaposition of oceanic and continental crust, with virtually simultaneous generation of magma from both sources, in Middle Ordovician time (Leo, 1980a).

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APPENDIX

Sample field numbers, descriptions, and locations for tables 1–4

[Except as noted on table 4; analysis no. as used in tables 1–4. See figure 2.]

NORTHERN GLASTONBURY GNEISS

[Inasmuch as Glastonbury Gneiss is invariably quartzo-feldspathic and contains biotite, lesser muscovite, and epidote, these features are not repeated in the remaining descriptions. Specimens of Monson Gneiss and felsic layers of Ammonoosuc Volcanics likewise are quartzo-feldspathic. Other distinguishing features of these rocks are included in descriptions as appropriate.]

1. 73–GWL–34–1. Lineated, faintly foliated quartzo-feldspathic gneiss with blotchy, elongated biotite-epidote aggregates; scattered small garnets. Chilson Road, 65 m south of intersection with Three Rivers Road, Ludlow quadrangle.

2. 74–GWL–357–1. Equigranular gneiss with crenulated foliation. Large cut on Massachusetts Turnpike (I–90) just east of Kelly Hill Street overpass, about 3 km west of center of Palmer, Palmer quadrangle.

2A. 74–GWL–357–2. Similar to no. 2 except somewhat less foliated and richer in epidote. Same location as no. 2.

3. 71–GWL–35–1/2. Similar to no. 1, garnet free. Southwest corner of Pulpit Rock Pond, southeast corner of Ludlow quadrangle.

4. 367. Inequigranular, nearly unfoliated felsic gneiss. About 1 km northeast of Hampden, Hampden quadrangle.

5. 620. Fine-grained, pin-striped, and delicately foliated gneiss. East side of Chapin Road, 0.8 km east southeast of summit of Pine Mountain, east-central part of Hampden quadrangle.

6. H7–A. Fine-grained, pin-striped gneiss. East side of Crow Hill, 2.5 km north northeast of West Stafford, Stafford Springs quadrangle.

7. 74–GWL–361. Fine-grained, delicately foliated gneiss; center of eastern gneiss body. Hillock south of airstrip, 1.7 km east southeast of West Stafford, Stafford Springs quadrangle.

7A. 74–GWL–361–2. Generally similar to, and from same location as no. 7.

8. P9–32. Delicately foliated gneiss with scattered garnets. Knob at 209 m level, east side of unnamed ridge, 0.7 km north northeast of north end of Bradway Pond and 1.3 km southeast of West Stafford.

9. P9–26. Fine- to medium-grained, well-foliated gneiss. Quarry on south side of Cooper Road, 1.5 km southeast of West Stafford.

10. 73–GWL–329–2. Strongly lineated, micaceous gneiss, somewhat darker than average. Outcrops on north side of Shenipsit Lake Road about 3 km east of Ellington, Conn.

SOUTHERN GLASTONBURY GNEISS

11. 73–GWL–330. Medium-grained, strongly lineated and weakly foliated rock with blotchy biotite aggregates and porphyroblasts of quartz and K-feldspar. Roadcut north side of Connecticut Route 15–Route I–86, 1.5 km south of Rockville, Rockville quadrangle.

11A. 73–GWL–330–3. Generally similar to no. 11. Location 50 m west along roadcut from no. 11.

12. 73–GWL–331–1. Rather massive gneiss with crenulated foliation, prominent biotite and K-feldspar porphyroblasts up to 1.5 cm long. Near east end of roadcut, north side of Connecticut Route 15 (I–84) directly east of Wyllys Street overpass and approximately 0.8 km east of Highland Street exit, Rockville quadrangle.

13. 73–GWL–331–2. Somewhat more mafic appearing gneiss near center of same roadcut as no. 12. About 160 m west of no. 12.

13A–13D. 73–GWL–331–3 to 73–GWL–331–6. From same location as no. 13, samples showing a range of slight compositional variations, but all generally similar to nos. 12 and 13.

14. 2309. 1.2 km southwest of Birch Mountain, northwest corner of Marlborough quadrangle. Descriptive data not available.[2]

15. 2392. 0.8 km east of Buckingham Reservoir, northwest part of Marlborough quadrangle. Descriptive data not available.[2]

16. 2379. "Schistose facies" of Herz (1955); 0.6 km southwest of Buckingham village, Glastonbury quadrangle. Descriptive data not available.[2]

17. 2424. Northwest side of Goodale Hill Road, 0.6 km southwest of Diamond Lake, west edge of Marlborough quadrangle. Descriptive data not available.[2]

18. 74–GWL–359. Inequigranular, poorly foliated, quartz-microcline-plagioclase-biotite gneiss. Washed outcrop at site of Hebron Ave. gravel pit, about 0.5 km south of Connecticut Route 94, west edge of Marlborough quadrangle.

18A. 74–GWL–359–2. Generally similar sample as no. 18, same location.

19. 73–GWL–334. Light-gray, fine-grained, delicately laminated gneiss; "flaser facies" of Herz (1955). Goodale Hill Road, about 1.6 km east of East Glastonbury, Glastonbury quadrangle.

20. 796B. "Eastern border facies" of Herz (1955); roadcut on Connecticut Route 2, eastbound (south) side, about 0.2 km west of Hollow Brook crossing, southeast part of Glastonbury quadrangle.[3]

21. 1680. Biotite-epidote granodiorite gneiss; 0.5 km east northeast of intersection of Thompson Hill and Cotton Hill Roads, north-central part of Middle Haddam quadrangle.[3]

22. 1702. Biotite granodiorite gneiss; 0.3 km northeast of Raccoon Hill, northeast part of Middle Haddam quadrangle.[3]

23. 1704. Biotite granodiorite gneiss; 0.3 km east of Raccoon Hill, 0.5 km south southwest of preceding location.[3]

24. 1594. Biotite granite gneiss; quarry, east slope of Larson Hill, 0.5 km southeast of intersection of Stewart Hill and Great Hill Roads, central part of Middle Haddam quadrangle.[3]

25. 1728. Fine-grained, moderately foliated quartz-plagioclase-K-felspar-biotite-hornblende-epidote gneiss. 0.4 km east of South Road and 1 km north northeast of intersection of South Road and Cox's Road, north-central part of Middle Haddam quadrangle.[3]

26. 804. Gneiss similar to no. 25, but with better foliation and somewhat higher color index. Slope west of South Road, approx. 310-ft level, about 0.5 km west of no. 25.[3]

27. 809. Generally similar rock to no. 26. Ridge 0.3 km west southwest of no. 26.[3]

28. 1716. Fine-grained gneiss with crenulated foliation generally similar to nos. 26 and 27. 0.5 km east of summit of Strickland Hill and 0.3 km north of Cox's Road, about 250-ft level, Middle Haddam quadrangle.

49. 74–GWL–367–3. Fine- to medium-grained, gray to pink, slightly porphyritic, biotite-rich gneiss. South side of Connecticut Route 2, approx. 5 km southeast of Glastonbury, point where powerline crosses road, Glastonbury quadrangle.

50. 74–GWL–368–2. Gray porphyritic gneiss with ovoid, abraded K-feldspar porphyroblasts. West side of Connecticut Route 2, 1.0 km southeast of no. 49, Glastonbury quadrangle.

51. 74–GWL–371–2. Fine- and even-grained, faintly foliated gneissic granite (fig. 7*D*). Tower Hill quarry, 300 m south of New London Turnpike, approx. 5 km southeast of Glastonbury, Glastonbury quadrangle.

[2]Collected by G. L. Snyder.

[3]Collected by G. P. Eaton.

MONSON GNEISS

29. 212. Delicately foliated and crenulated gneiss with cataclastic texture. Large overhanging outcrop 0.75 km south southwest of summit of Pattaquattic Hill, northeast part of Palmer quadrangle.

30. 768. More homogeneous and evenly foliated gneiss than no. 24, base of cliff east of jeep trail, 0.6 km northeast of intersection of Warren and Gates Streets, central part of Palmer quadrangle.

31. 74-GWL-358-1. Weakly foliated and compositionally laminated felsic gneiss with blotchy mica aggregates on foliation plane. North side of cut on Massachusetts Turnpike (I-90) just east of Breckenridge St. overpass, 2.5 km north northeast of center of Palmer, Palmer quadrangle.

32. 807. Granular, sugary-textured rock with scattered feldspar megacrysts; possible relict tuffaceous textures. West slope of small hill about 0.4 km north northwest of intersection of Smith and Mason Streets, 0.7 km west of Thompson Lake, east-central part of Palmer quadrangle.

33. M-CC. Fine-grained, delicately foliated gneiss. Roadcut, west side of access road to Children's Colony, Monson State Hospital, 0.9 km south southwest of intersection of Hospital and upper Palmer Roads, Palmer quadrangle.

34. A-14. Very leucocratic, sugary-textured, faintly foliated rock. Flynt quarry, east side of upper Palmer Road, about 2.0 km north northwest of center of Monson, Monson quadrangle.

35. MQ-2. Relatively mafic, even-grained, and nearly homogeneous rock. Same locality as no. 34.

36. P8-270. Fine- to medium-grained, well-foliated gneiss. Headwaters of Bonemill Brook, 0.8 km southeast of Tolland Ave., Stafford Springs quadrangle.

37. P8-272. Finely foliated, hornblende-bearing gneiss, 100 m upstream from no. 36.

52. (Table 3 only). Pec 657. Homogeneous, fine-grained gneiss with moderate foliation and faint compositional banding. South exit ramps from I-86 to Connecticut Route 195; northwest corner of South Coventry quadrangle.

FELSIC LAYERS OF AMMONOOSUC VOLCANICS

38. 71-GWL-17-1. Fine-grained, sugary-textured, leucocratic granofels, 0.6 km northeast of intersection of Glendale and Ridge Roads, about 2 km east southeast of North Wilbraham, Ludlow quadrangle.

39. 71-GWL-35-4/6. Fine-grained, finely laminated biotitic granofels. South side of Massachusetts Turnpike, 1.1 km east of Chicopee River, Ludlow quadrangle.

40. 71-GWL-43-1/4. 2 cm felsic layer interbedded with hornblende-plagioclase amphibolite. 0.4 km east of fire lookout tower, Minechoag Mountain, approx. 490-ft elevation, Ludlow quadrangle.

41. 71-GWL-41-4/1. Finely foliated, crenulated hornblende-biotite-garnet-bearing gneiss. 30 m east of Glendale Road-Crane Hill Road intersection, 2.6 km southeast of North Wilbraham, Ludlow quadrangle.

42. 71-GWL-41-4/3. Gneiss generally similar to no. 41. About 10 m north of Glendale Road-Crane Hill Road intersection.

43. 357. Fine-grained, closely foliated, hornblende-bearing gneiss. Same unit as nos. 41 and 42.

44. 71-GWL-45-2/4. Medium-grained, garnetiferous granofels interlayered with amphibolite. Peak west of Ridge Road, 0.4 km southwest of Crane Hill Road-Glendale Road intersection.

45. 71-GWL-46-4/1. Fine-grained, leucocratic, speckled granofels associated with amphibolite. Eastern slope of small peak north of no. 44, 0.2 km northwest of Glendale-Crane Hill Road intersection.

46. 71-GWL-43-1/1. Fine-grained, thin-bedded, gray-brown cummingtonite-hornblende-bearing granofels. Same as no. 40.

47. 71-GWL-66-2/4. Felsic layer in Ammonoosuc generally similar to no. 46, but contains cummingtonite-anthophyllite. About 300 m east southeast from fire lookout tower, Minechoag Mountain, Ludlow quadrangle.

48. H7-B. Fine-grained,sugary-textured, finely striped leucocratic tremolite-actinolite-bearing granofels. Just west of no. 6, Stafford Springs quadrangle.