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Glastonbury Gneiss Body, a Modified Oliverian Dome, and Related Rocks in South-central Massachusetts and North-central Connecticut: Petrology, Geochemistry, and Origin

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with a Section on Rb-Sr Geochronology

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To title page

A petrogenetic study of an Acadian gneiss body

based on new chemical and strontium-isotope data

Resume for <u>New Publications of the Geological Survey</u>

The Glastonbury Gneiss body, trending about 65 km along the axis of the Bronson Hill anticlinorium in south-central Massachusetts and north-central Connecticut, consists of a northern, silicic and potash-poor gneiss partly of trondhjemitic composition and a southern, differentiated calc-alkaline granitic gneiss. The northern Glastonbury is believed to be the product of Acadian anatexis of mid-Ordovician metavolcanic rocks, whereas the southern gneiss may reflect remobilization of a more potassic crust. A number of major- and trace-element analyses are presented for the Glastonbury Gneiss and associated metavolcanic rocks. An Rb-Sr whole-rock isochron age of 383 ± 41 m.y., with $^{87}Sr/^{86}Sr_o = 0.7093$, has been determined for the Glastonbury. The Glastonbury Gneiss is analogous to Oliverian domes at deeper, hotter crustal levels.

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ABSTRACT

The Glastonbury Gneiss crops out in a long, narrow belt trending north-northeast for about 65 km through Connecticut and Massachusetts along the west side of the Bronson Hill anticlinorium. The Glastonbury is overlain by Paleozoic rocks of the New Hampshire sequence, ~~and~~ it intrudes the Ordovician Ammonoosuc Volcanics and may intrude the overlying Collins Hill Formation. Structurally and stratigraphically the Glastonbury is generally comparable to the domes of the Oliverian Plutonic Series in New Hampshire. The northern part of the Glastonbury body typically consists of leucocratic, granoblastic, granitic-looking gneiss that appears compositionally homogeneous in outcrop but proves to be chemically and modally inhomogeneous over short distances. Strong foliation and/or lineation with accompanying cataclastic (?) textures are typical. The gneiss is metatrondhjemite in part, consisting dominantly of quartz and calcic oligoclase (generally less than 10 percent K-feldspar) and additionally contains biotite, epidote, muscovite, and minor accessories; it approaches the composition of Monson Gneiss and felsic layers in Ammonoosuc Volcanics and is quite distinct from calc-alkaline granitic rocks. By contrast, gneiss in the southern part of the body is consistently more potassic, with calc-alkaline compositions ranging from granite to ~~quartz~~ granodiorite. It also shows textural and structural variations, likewise possibly of cataclastic origin.

The origin of the Glastonbury rocks is evidently complex. The northern gneiss is believed to have consolidated from a crystal mush produced by anatexis in a water-deficient system. The postulated gneiss protolith (Monson Gneiss and, possibly, underlying units), is similar to other major gneiss units in the northern and central Appalachians (for example, the James Run Formation in eastern Maryland) and has a composition comparable to that of marine volcanic-volcaniclastic sediments of eugeosynclinal environments, as well as that of some Archean trondhjemites. The southern granitic gneiss appears to represent a distinct calc-alkaline intrusion, but its trace-element characteristics are clearly related to those of the northern Glastonbury and the Monson Gneiss. Petrologically the Glastonbury Gneiss and associated volcanic rocks may be compatible with the plate-tectonic regime of Bird and Dewey (1970). A composite Rb-Sr whole-rock isochron for the entire Glastonbury body shows much scatter (Brookins, this volume) but suggests a composite age of 383 $\pm$ 41 m.y. at the 1σ confidence level. Because of the scatter, the validity of the isochron age is somewhat doubtful. Indeed, the possibility of two or more "ages cannot be discounted, and an isochron through the northern Glastonbury points only yields 548 $\pm$ 90 m.y. (1σ confidence level). On the other hand, geologic considerations suggest a most probable time of intrusion around 400-380 m.y., thus within the uncertainty of the composite isochron age.

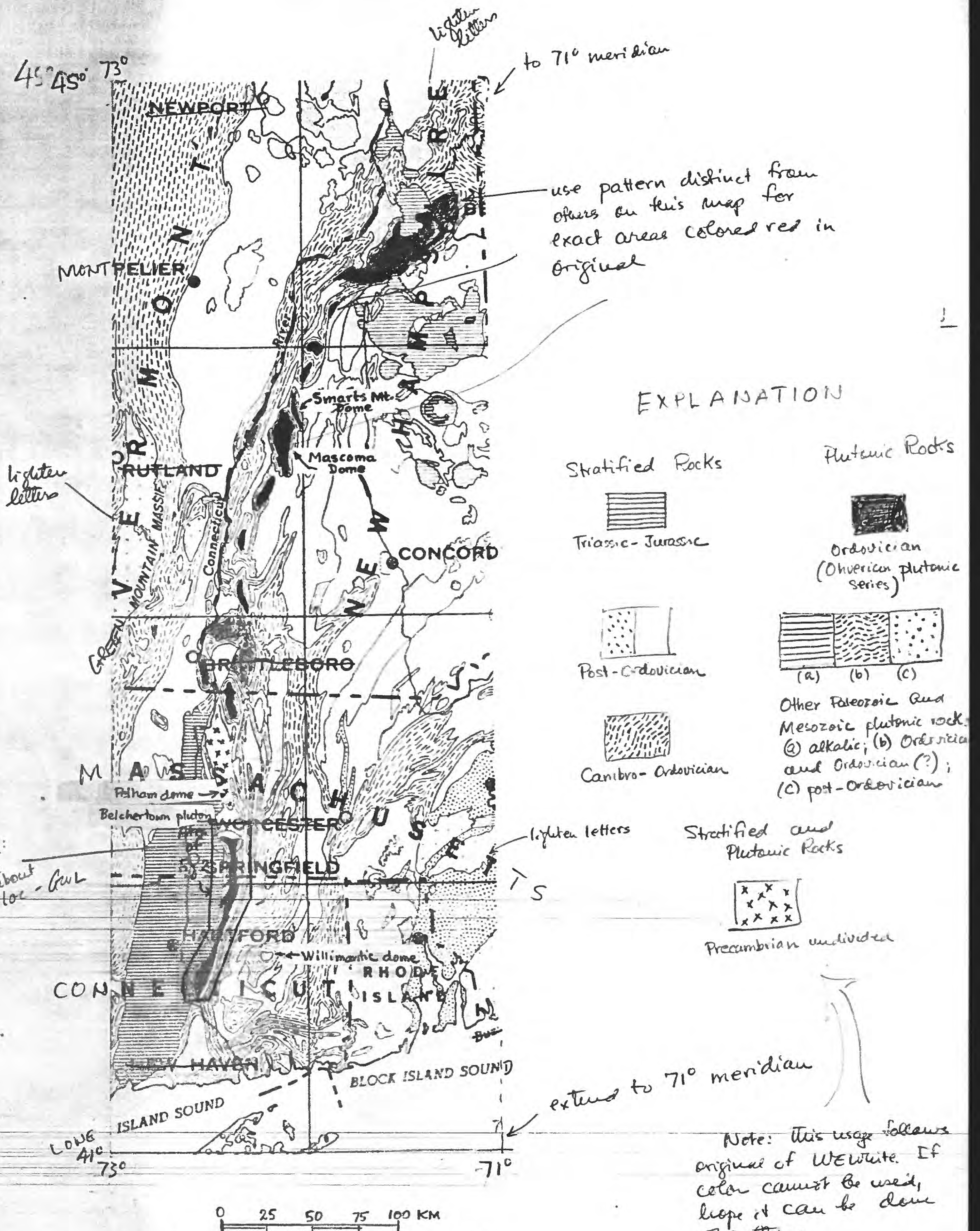
The northern and southern gneisses of the Glastonbury body are lithologically comparable to the stratified and unstratified core gneiss, respectively, of a typical Oliverian dome such as the Mascoma dome of New Hampshire (Naylor, 1969). In the latter, however, potash-poor, volcanigenic stratified core gneiss is clearly distinct from crosscutting, relatively homogeneous granitic rocks (unstratified core gneiss) of the associated pluton. The origin proposed here for the Glastonbury gneiss body, implies as unusually high heat flow in Early Devonian time to bring about palingenesis at moderate depths of burial. In the Mascoma and other Oliverian domes of Ordovician age, by contrast, there is no indication of anatexis and mobilization of pre-existing rocks.

Introduction

The Glastonbury gneiss body is a narrow, elongate structure which extends from just south of the Belchertown batholith in central Massachusetts to the vicinity of Middletown, Connecticut (figs. 1 and 2).

Figures 1 and 2 near here.

The Glastonbury body constitutes a part of the Bronson Hill anticlinorium (Billings, 1956; Thompson and others, 1968), a complexly folded and deformed sequence of Paleozoic metasedimentary, metavolcanic, and plutonic rocks trending south-southwest from northwestern New Hampshire to Long Island Sound (fig. 1). The stratified rocks are intruded by ~~a variety of~~ igneous plutons which have been assigned to several magma series on the basis of composition, degree of deformation, and apparent age (Billings, 1937, 1956). The Oliverian plutonic series, recognized on the basis of field relations and metamorphic recrystallization to be among the oldest, comprises a number of gneiss domes mantled by the dominantly mafic Ammonoosuc Volcanics of Early to Middle Ordovician age. The Glastonbury gneiss body resembles the Oliverian domes in that 1) it also is mantled by Ammonoosuc Volcanics (and, at its southern end, by Collins Hill Formation, which overlies the Ammonoosuc Volcanics or their equivalent, the Middletown Formation) and intrudes these strata along much of the western side of the dome; and 2) it is pervasively metamorphosed at middle amphibolite facies grade. On this basis, the Glastonbury body has gneerally been regarded as an Oliverian dome.


45° 45° 73°
NEWPORT
MONTPELIER
RUTLAND
GREEN MOUNTAIN MASSIF
Connecticut
River
Smarts Mt. Dome
Mascoma Dome
CONCORD
BRATTLEBORO
VERMONT
NEW HAMPSHIRE
MASSACHUSETTS
Pelham dome
Belchertown pluton
WORCESTER
SPRINGFIELD
HARTFORD
Willimantic dome
RHODE ISLAND
CONNECTICUT
NEW HAVEN
BLOCK ISLAND SOUND
LONG ISLAND SOUND
41° 73°
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lighten letters
to 71° meridian
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EXPLANATION
Stratified Rocks
Plutonic Rocks
Triassic-Jurassic
Ordovician (Oliverian plutonic series)
Post-Ordovician
(a) (b) (c)
Other Paleozoic and Mesozoic plutonic rocks: (a) alkalic; (b) Ordovician and Ordovician (?); (c) post-Ordovician
Cambro-Ordovician
Stratified and Plutonic Rocks
Precambrian undivided
Note: this usage follows original of WEWhite. If color cannot be used, hope it can be done w/ patterns.

Figure 1.--Geologic setting of the Oliverian domes (adapted from map by Walter S. White, _in_ Zen and others, 1968).

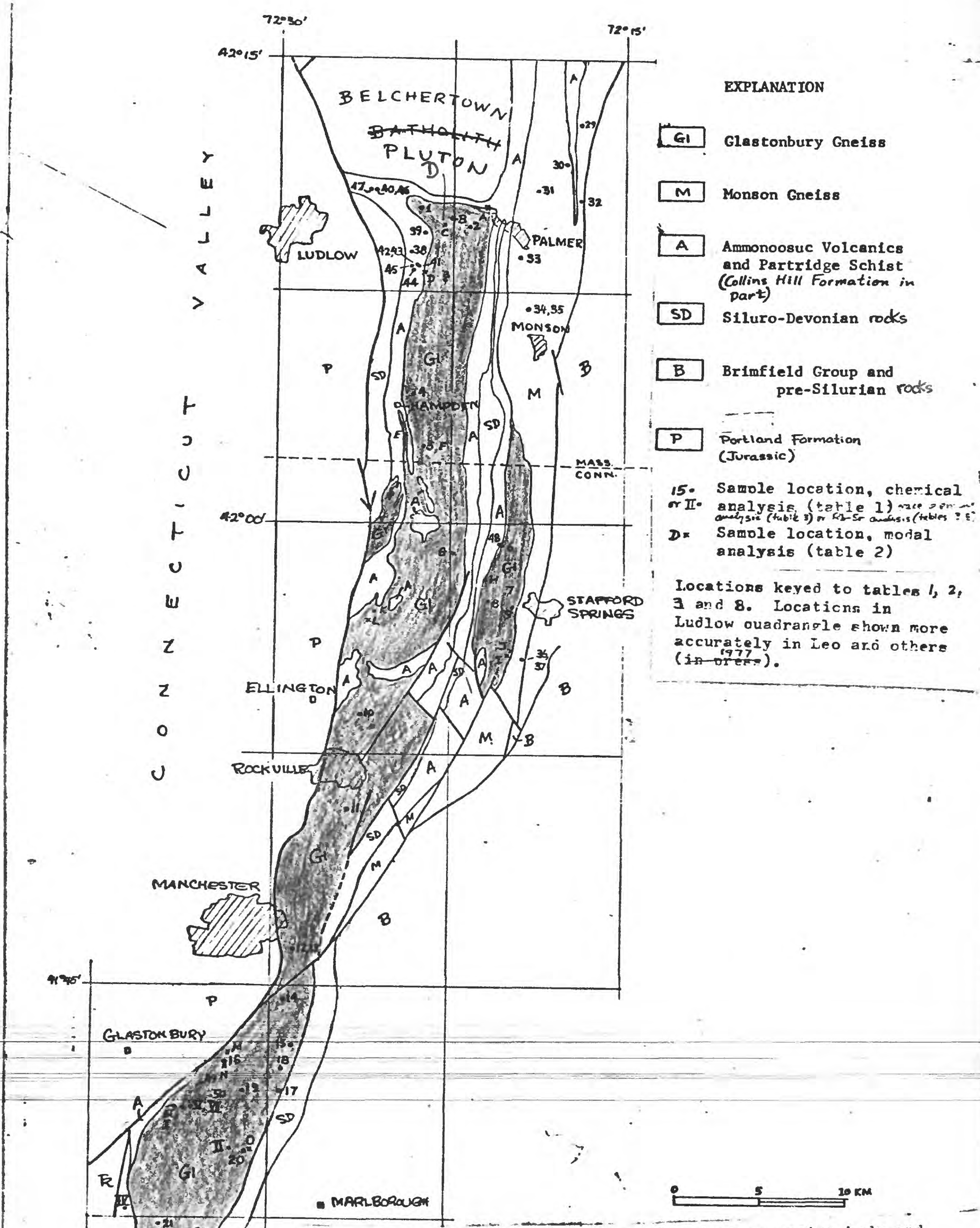

Fig. 2. Geologic sketch map of the Glastonbury gneiss body and adjacent lithologic units. Compiled from published sources (Collins, 1954; Aiken, 1955; Herz, 1955; Snyder, 1970) and from various unpublished data, mainly of M. H. Pease and J. D. Peper, U. S. Geological Survey.

Figure 2.--Geologic sketch map of the Glastonbury gneiss body and adjacent lithologic units. Compiled from published sources (Collins, 1954; Aitken, 1955; Herz, 1955; Snyder, 1970) and from various unpublished data, mainly of H. H. Pease and J. D. Peper, U. S. Geological Survey.

On the other hand, there are some significant petrologic differences between the core rocks of the Glastonbury body and those of Oliverian domes as presently known. Naylor (1968, 1969) has described two kinds of felsic rocks which constitute the core of the Mascoma dome in northwestern New Hampshire which is regarded as typical of Oliverian domes in general. Unstratified core rocks, constituting a pluton which makes up about one-fourth of the core of the dome, are massive and homogeneous and range in composition from granite to quartz monzonite. Stratified gneiss, constituting the remainder of the core of the dome, consists dominantly of quartz and plagioclase with subordinate K-feldspar and accessory minerals. The stratified core gneiss is assumed to be of volcanic origin, and is cut by the unstratified core rocks, which may also intrude mantling Ammonoosuc Volcanics.

Rocks of the Glastonbury body likewise show a bimodal character, but the stratified gneiss typical of the Oliverian domes is lacking. Instead, weakly to conspicuously foliated but unstratified gneiss constitutes all of the core. Despite much textural and compositional variation on a local as well as a regional scale, the Glastonbury Gneiss can be divided grossly into two portions on the basis of the lithology. Rocks in the northern part of the body, extending roughly to the south edge of the Ellington quadrangle (fig. 2) characteristically are quartz-

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Figure 2 near here.

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plagioclase gneiss containing less than 10 percent K-feldspar and approaching trondhjemite in composition. The southern part of the body, by contrast, consists of weakly foliated to unfoliated granitic rocks with a much higher content of K-feldspar than the northern rocks, locally as conspicuous prophyroblasts.

The Glastonbury Gneiss poses several problems in petrogenesis and age relationships to which this paper is addressed.

1) The variable, but generally potash-poor and silica-rich composition of the northern gneiss is distinct from that of magmatic intrusions on the calc-alkaline differentiation trend, but more nearly resembles the composition of the adjacent Monson Gneiss. Although primary textures have been obliterated by Acadian metamorphism, the lack of recognizable compositional layering in the northern gneiss, coupled with its demonstrably intrusive relationship to the Ammonoosuc Volcanics, indicates that the gneiss was intruded as a magma (more specifically, as will be argued, a water-undersaturated crystal mush). A major purpose of this paper is to show that the northern Glastonbury could have originated by early Acadian anatexis of the Monson Gneiss (and/or underlying rocks of generally similar composition. In support of this thesis, a number of new analyses of Glastonbury Gneiss, Monson Gneiss, and felsic layers of Ammonoosuch Volcanics are presented.

2) The scatter in the age data (fig. 14), further discussed by Brookins (this volume) leaves the true time of intrusion of the Glastonbury Gneiss in some doubt, and also leaves open the question whether or not there is a distinct age difference between the chemically (and genetically?) distinct northern and southern parts of the gneiss body. Regarding the first point, the whole-rock Rb-Sr isochron age of 383 $\pm$ 41 m.y. represents the 67 percent (1σ) confidence level. In view of the non-linear array of data on the isochran diagram (fig. 14), however, the

uncertainty might better be stated at the 95 percent (2σ) confidence level, i.e., 383 $\pm$ 82 m.y. (J. A. Arth, pers. commun., 1977). This uncertainty is greater than that defined by geologic-stratigraphic controls, as summarized below. Regarding the possibility of more than one Glastonbury age, a least-squares regression through the 5 data points for the northern Glastonbury Gneiss only (fig. 14) suggests an age of 548 $\pm$ 90 m.y. at the 1σ confidence level. Although this "age" is improbably high in terms of presently known ages and geologic relationships in the region as a whole, and its validity cannot be assessed without further data for the northern Glastonbury Gneiss, it does point up the uncertainties in the Rb-Sr systematics, and suggests the possibility that the northern Glastonbury is, indeed, older than the southern.

Geologic considerations based on presently available field evidence and geochronologic data for other units place some constraints on the age of intrusion of the Glastonbury Gneiss. A U-(Th)-Pb zircon date of 380 $\pm$ 5 m.y. (early Middle Devonian) for the Belchertown pluton north of the Glastonbury body (see fig. 1) has recently been determined by R. E. Zartman (Leo and others, 1977). The Belchertown is younger than the Glastonbury, for the following reasons: 1) the north end of the Glastonbury in the core of the Minechoag anticline (Leo and others, 1977) is seemingly deformed by the Belchertown pluton, and 2) the Belchertown is significantly less metamorphosed (virtually undisturbed igneous-textured core grading to recrystallized gneissic margins) than the thoroughly recrystallized Glastonbury Gneiss. Thus, 380 m.y. represents a valid minimum age for the Glastonbury. A maximum age, meanwhile, is imposed by the 460 $\pm$ 10 m.y. age for the Ammonoosuc Volcanics (Brookins, 1968) assuming that determination to be representative; the Ammonoosuc is intruded by northern Glastonbury Gneiss. A more doubtful maximum age is the 424 ± 41 m.y. for Collins Hill Formation (Brookins and Methot, 1971; see footnote, p. 77, this paper), a unit which is apparently, but not definitely, intruded by the southern Glastonbury Gneiss (see p. 22B). Finally, conditions of temperature and pressure required to produce an anatectic melt from a Monson lithology were most likely to be attained in the early Acadian at the time of maximum burial of Ordovician rocks by the Siluro-Devonian section, approximately 400-380 m.y. ago. Thus, this most probable age of intrusion of the Glastonbury is within the margin of error of the Rb-Sr isochron age of 383 ± 41 m.y. Because of this correlation between a geologically reasonable age and the whole-rock isochron age, the latter will be referred to, as a "working age," throughout the paper; however the uncertainties inherent in the isochron age should be kept in mind by the reader.

Acknowledgments

Richard S. Naylor, Northeastern University, ~~reviewed~~ provided a perceptive review of an early draft of the manuscript. M. H. Pease and John D. Peper, U. S. Geological Survey, were most helpful in orienting me in the field; and Naylor, as well as Joseph G. Arth and Richard Goldsmith of the Survey, provided stimulating discussions on petrology and regional relationships. To these collegues I express my sincere thanks and appreciation.

Regional Geology

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 the Ammonoosuc Volcanics. The name Partridge Formation is applied principally to rocks north of the Connecticut boundary while Collins Hill is the name used for stratigraphically equivalent rocks in the Middle Haddam quadrangle. Both units consist of micaceous schists containing graphite and sulfide (commonly pyrrhotite) which results in a characteristic yellow-brown weathering crust, 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).

Ammonoosuc Volcanics and Middletown Formation

The Ammonoosuc Volcanics is a unit of volcanic, volcaniclastic, and epiclastic origin of Middle Ordovician age which is distributed along the Bronson Hill anticlinorium from Maine through Connecticut (Billings, 1937, 1956). In northwestern New Hampshire and Vermont, the Ammonoosuc concordantly overlies the Albee Formation (Billings, 1937, p. 472-475), a sequence of mostly non-volcanic, quartz-rich arenaceous and pelitic rocks. In southeastern New Hampshire, Massachusetts, and Connecticut, the Ammonoosuc is concordantly underlain by stratified Oliverian core gneisses and also the Monson Gneiss, rocks mostly of volcanic and volcaniclastic origin. This situation is ascribed by Naylor (1968, p. 234-237) to a broad facies change across a line trending northeast across northwest New Hampshire and north central Maine. Gradational contacts between Ammonoosuc Volcanics and Monson Gneiss in the Monson area have been described by Peper (1966). South of the Monson quadrangle the base of the Ammonoosuc is either faulted or intruded by the Glastonbury Gneiss.

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The Ammonoosuc shows a wide range of compositional and textural variations. Compositions vary from basalt to rhyolite, while textures indicate a variety of pyroclastic rocks ranging from volcanic conglomerate through tuffs and tuffaceous sandstone, as well as subordinate ryolitic and mafic flows (Billings, 1956, p. 17-18). Relict volcanic textures in the Ammonoosuc tend to be more apparent at the lower metamorphic grades in westernmost New Hampshire (Billings, 1956). Higher-grade rocks (above staurolite zone)which include those discussed in this report, typically are hornblende-plagioclase amphibolite and felsic gneiss and granofels. The greater part of the Ammonoosuc sequence south of the Belchertown batholith (fig. 2) consists of thin-

Figure 2 near here.

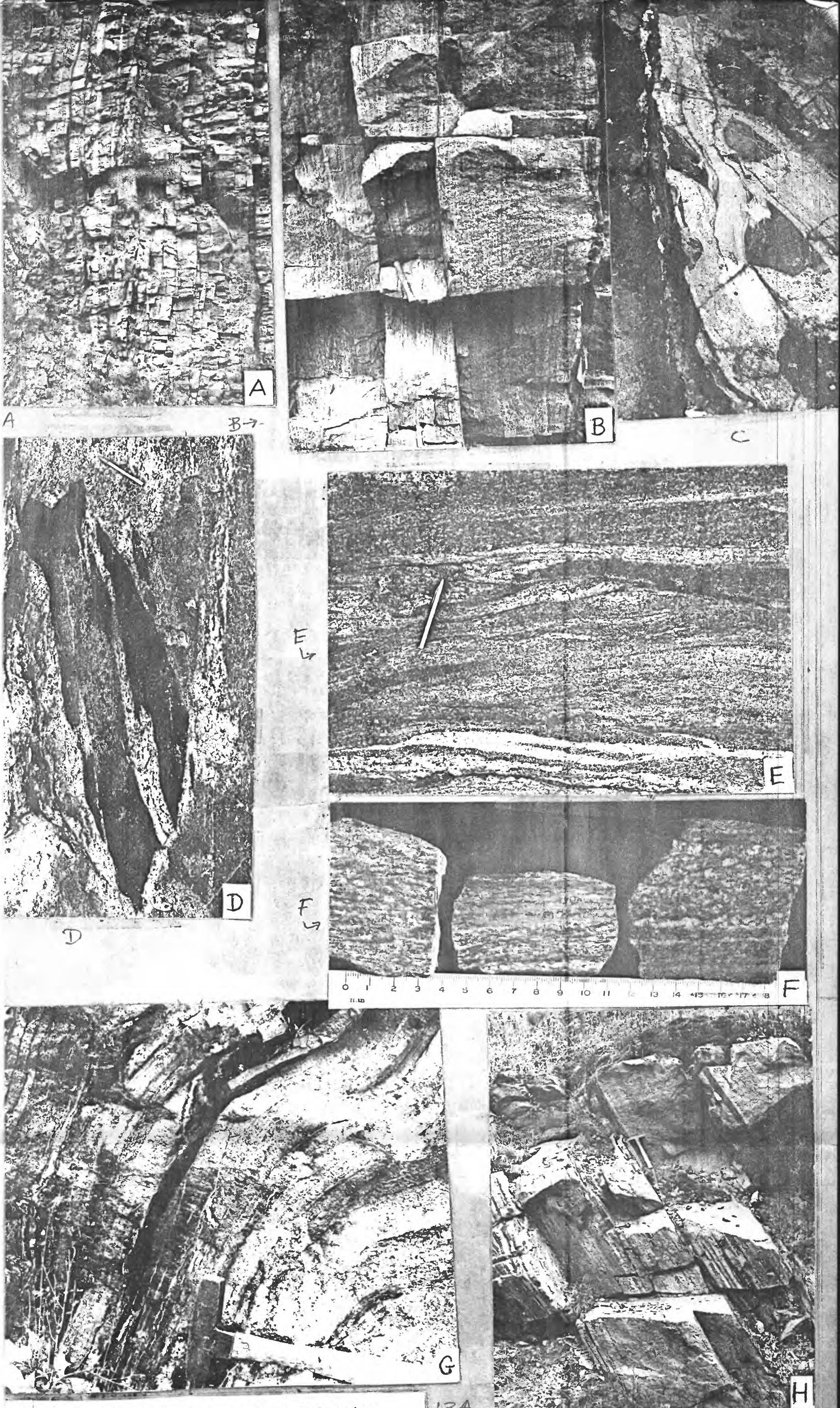
layered, typically-crinkled hornblende-plagioclase amphibolite that locally contains garnet, quartz, and epidote. Felsic granofels forms thin layers in amphibolite and ordinarily predominates towards the top of the section (Peper, 1967; Thompson and others, 1968, p. 206). In the Ludlow area, felsic gneiss gradational to amphibolite in the lower part of the section have been included with Ammonoosuc (Leo, unpub. data), although elsewhere such rocks have probably been regarded as Monson Gneiss. The felsic rocks interbedded with amphibolite typically are fine-grained, sugary-textured, and unfoliated, but possess a delicate striping due to concentration of mafic minerals along bedding planes (fig. 3, 7).

Figure 3 near here.

They consist of quartz, sodic plagioclase, and less than 15 percent of one or several of the following minerals: biotite, Ca-poor amphiboles, hornblende, garnet, epidote, and magnetite. K-feldspar is typically scarce or absent. Thin layers of rusty-weathering, felsic granofels containing acicular anthophyllite and cummingtonite (no. 38-40, table 1) are rare but distinctive; such rocks are particularly characteristic of the Ammonoosuc in the Orange area of

Table 1 near here.

northern Massachusetts and southern New Hampshire (Robinson and Jaffe, 1969).



3. Monson Gneiss and Ammonoosuc Volcanics

Figure 3.--Monson Gneiss and Ammonoosuc Volcanics.

A. Well-layered, vertically tilted Monson Gneiss, north side of cut on Massachusetts Turnpike (I-90), 0.5 km south of Palmer Center, directly east of crossing of Breckenridge Road, Palmer quadrangle (fig. 2, loc. 31).

B. Delicate compositional banding in massively layered gneiss, same location as preceding.

C. Ovoid amphibolite inclusions evidently aligned by flow of felsic Monson Gneiss. Flynt quarry, east side of upper Palmer Road, about 2 km NNW of Monson, Mass. (fig. 2, loc. 34035).

D. Detail of preceding. Note blotchy texture of felsic layer in amphibolite 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 at bottom and lower right.

E. Swirled and diffuse banding in gneiss that has apparently flowed plastically. Compare with A and B. Flynt quarry.

F. Textural variations in Monson Gneiss. Left, foliated but fairly homogeneous gneiss; center, ~~well-preserved clastic~~ probable cataclastic, ~~possibly eutaxitic~~ texture; right, compositionally layered but essentially unfoliated gneiss.

G. Typical association of mafic and felsic layers in folded Ammonoosuc Volcanics. Southeast side of Minechoag Mountain, Ludlow quadrangle, Mass. (fig. 2, loc. 47).

H. More thickly layered felsic gneiss and amphibolite of Ammonoosuc Volcanics near bottom of section. South side of Massachusetts Turnpike, 1.1 km east of Chicopee River, Ludlow quadrangle (fig. 2, loc. 39).

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Explanation for Table 1. See figure 2 for location numbers.

Glastonbury Gneiss

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

2. Equigranular gneiss with crenulated foliation. Large cut on Massachusetts Turnpike (I-90) just northeast of Kelly Hill Street overpass, ca. 3 km west of center of Palmer, Palmer quadrangle.

3. Similar to no. 1, garnet free. SW corner of Pulpit Rock Pond, SE corner of Ludlow quadrangle.

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

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

6. Fine-grained, pin-striped gneiss. East side of Crow Hill, 2.5 km NNE of West Stafford, Stafford Springs quadrangle.

1/ 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 Ammonoosuc Volcanics likewise are quartzo-feldspathic. Other distinguishing features of these rocks are used as appropriate.

7. Fine-grained, delicately foliated gneiss; center of eastern gneiss body. Hillock south of airstrip, 1.7 km ESE of West Stafford. Stafford Springs quadrangle.

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

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

10. Strongly lineated, micaceous gneiss, somewhat darker than average. Outcrops on north side of Shenipsit Lake Road about 3 km east of Ellington, Conn. (fig. 5E, F).

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

12. 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 Rte. 15 (I-84) directly east of Wyllys Street overpass and approximately 0.8 km east of Highland Street exit, Rockville quadrangle.

13. Somewhat more mafic appearing gneiss near center of same roadcut, about 160 m west of loc. 10 (fig. 5D, E).

14. 1.2 km SW of Birch Mountain, NW corner of Marlborough quadrangle, Conn.; collector, G. L. Snyder.

15. 0.8 east of Buckingham Reservoir, NW part of Marlborough quadrangle; collector, G. L. Snyder.

16. "Schistose facies" of Herz (1955); 0.6 km SW of Buckingham village, Glastonbury quadrangle; collector, G. L. Snyder.

17. Northwest side of Goodale Hill Road, 0.6 km SW of Diamond Lake, west-central part of Marlborough quadrangle; collector, G. L. Snyder.

18. Inequigranular, poorly foliated, relatively felsic gneiss. Washed outcrop at site of Hebron Ave. Gravel pit, ca. 0.5 km south of Connecticut Rte. 94, west edge of Marlborough quadrangle.

19. 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. "Eastern border facies" of Herz (1955); roadcut on Conn. Rte. 2, eastbound (south) side, about 0.2 km west of Hollow Brook crossing, SE part of Glastonbury quadrangle.

21. 0.5 km ENE of intersection of Thompson Hill and Cotton Hill Roads, north-central part of Middle Haddam quadrangle.

22. 0.3 km NE of Raccoon Hill, NE part of Middle Haddam quadrangle.

23. 0.3 km east of Raccoon Hill, 0.5 km SSW of preceding location.

24. Quarry, east slope of Larson Hill, 0.5 km SE of intersection of Stewart Hill and Great Hill Roads, north-central part of Middle Haddam quadrangle.

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

26. Similar gneiss but better foliation and somewhat higher color index. Slope west of South Road, approx. 300 ft level, about 0.5 km west of preceding location.

27. Generally similar rock to no. 26. Ridge 0.3 km WSW of loc. 26.

28. 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.

Monson Gneiss

29. Delicately foliated and crenulated gneiss ~~with possible relict eutaxitic texture (see~~ figs. 3F, ~~center~~) ~~and 4A),~~ Large overhanging outcrop 0.75 km SSW of summit of Pattaquattic Hill, NE part of Palmer quadrangle.

30. More homogeneous, evenly foliated gneiss (fig. 3~~E~~F, right). Base of cliff east of jeep trail, 0.6 km NE of intersection of Warren and Gates Streets, central part of Palmer quadrangle.

31. 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 NNE of center of Palmer, Palmer quadrangle (Fig. 3A, P).

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

33. Fine-grained, delicately foliated gneiss (see fig. 3E, left). Roadcut, west side of access road to Children's Colony, Monson State Hospital, 0.9 km SSW of intersection of Hospital and Upper Palmer Roads, Palmer quadrangle.

34. Very leucocratic, sugary-textured, faintly foliated rock. Flynt quarry, east side of Upper Palmer Road, about 2.0 km NNW of center of Monson, Monson quadrangle.

35. Relatively mafic, even-grained and nearly homogeneous rock. Same locality as preceding.

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

37. Finely foliated, hornblende-bearing gneiss, 0.1 km upstream from preceding sample.

Felsic Ammonoosuc

38. Fine-grained, sugary-textured, leucocratic granofels, 0.6 km NE of intersection of Glendale and Ridge Roads, about 2 km ESE of North Wilbraham, Ludlow quadrangle.

39. Fine-grained, finely laminated biotitic granofels. South side of Mass. Turnpike, 1.1 km east of Chicopee River, Ludlow quadrangle.

40. 2 cm felsic layer interbedded with hornblende-plagioclase amphibolite. 0.4 km east of fire lookout tower, Minechoag Mt., approx. 120 m elevation, Ludlow quadrangle.

41. Finely foliated, crenulated hornblende-biotite-garnet-bearing gneiss (Oag of Leo and others, 1977 ~~press~~ ~~in prep~~). 30 m east of Glendale Road-Crane Hill Road intersection, 2.6 km SE of North Wilbraham, Ludlow quadrangle.

42. Generally similar gneiss, same unit. About 10 m north of Glendale Road-Crane Hill Road intersection.

43. Fine-grained, closely foliated, hornblende-bearing gneiss. Same unit as preceding two samples.

44. Medium-grained, garnetiferous granofels interlayered with amphibolite. Peak west of Ridge Road, 0.4 km SW of Crane Hill Road-Glendale Road intersection.

45. Fine-grained, leucocratic, speckled granofels associated with amphibolite. Eastern slope of small peak north of preceding location, 0.2 km NW of Glendale-Crane Hill Road intersection.

46. Fine-grained, thin-bedded, gray-brown cummingtonite-hornblende-bearing granofels. Same location as no. 32.

47. Felsic layer in Ammonoosuc generally similar to preceding sample, but contains cummingtonite-anthophyllite. About 300 m ESE from fire lookout tower, Minechoag Mt., Ludlow quadrangle.

48. Fine-grained, sugary-textured, finely striped leucocratic tremolite-acti~~o~~nolite-bearing granofels. Just west of no. 5.

Felsic gneiss at the bottom of the Ammonoosuc section in the Ludlow quadrangle is generally coarser grained and more thickly layered than granofels in the upper part of the section. Associated amphibolite is subordinate in quantity, forming both sharply bounded and compositionally gradational layers (fig. 3H). The composition of the felsic gneiss is very similar to the rest of the felsic Ammonoosuc.

The Ammonoosuc Volcanics have been correlated with the lithologically similar Middletown Formation in central Connecticut (Eaton and Rosenfeld, 1960, 1972). Herz (1955) mapped Middletown along the west edge of the Glastonbury body in the Glastonbury quadrangle; 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).

~~Samples of~~ Analyzed Ammonoosuc samples ~~selected for chemical analysis~~ (Table 1) represent a varied suite of felsic rocks in terms of mineral assemblages including some hornblende-bearing rocks gradational to amphibolite (no. ~~23-25~~ 41-43, table 1). All but one of the analyzed samples are from the Ludlow quadrangle.

Monson Gneiss

The Monson Gneiss (Monson granodiorite of Emerson, 1917, p. 241-243), cropping out intermittently from southern New Hampshire to Long Island Sound, is the oldest unit of the Bronson Hill anticlinorium. As a consequence of intense deformation, mainly at its northern and southern extensions, the Monson at the present level of erosion forms broad domes or "bodies" in northern Massachusetts (main body and Tully body, Thompson and others, 1968), and in southern Connecticut (Killingsworth dome, Dixon and Lundgren, 1968, fig. 16-1, 16-2). Between these two areas the Monson Gneiss constitutes a stratigraphic layer, locally much faulted and displaced (fig. 2). Contacts with the overlying Ammonoosuc Volcanics appear to be gradational (Peper, 1966; Eaton and Rosenfeld, 1972). The stratified core gneiss of the Mascoma dome (Naylor, 1968, 1969) ~~and probably also of other Oliverian domes,~~ is at the same stratigraphic level as the Monson Gneiss and is lithologically somewhat similar.

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 (in isolated layers?) constitutes 10 percent or more. Ordinarily the gneiss shows compositional layering, ranging from distinct beds accentuated by thin, continuous amphibolite layers and showing ~~clear~~ possible relict sedimentary features (fig. 3A, B) to less distinct, massive ~~bedding~~ layering. Locally, as at Flynt quarry north of Monson (loc. ~~26-27~~ 34-35, fig. 2) the gneiss lacks ~~bedding~~ layering and shows a number of features suggestive of plastic flow. The rock is massive, faintly foliated, and compositionally inhomogeneous, traversed by felsic streaks, mafic schlieren, and localized sharp to shadowy contacts between more felsic and more mafic rock (fig. 3C, D, E). Discordant, typically ellipsoidal inclusions of amphibolite are abundant. 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 (fig. 3C, D). These features suggest that the felsic gneiss reached the condition of anatexis and plastic flow, disrupting mafic layers and carrying fragments which became flow-rounded during transport.

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Textures of the Monson Gneiss generally reflect thorough recrystallization, ~~but some possible primary sedimentary features are preserved (fig. 3 A,B)~~. Textures are generally granoblastic with more or less distinct foliation, which is parallel to original ~~bedding~~ layering where the latter is recognizable. The variation in grain size within a thin section varies 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, which are evidently the result of metamorphic recrystallization under stress, and/or cataclasis. Other plagiocalse forms large, undistrubed grains with scalloped margins which evidently are porphyroblasts (possible recrystallized clasts) (Fig. 3 F).

The sum of 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).

Glastonbury gneiss body

Regional aspects of the Glastonbury body are discussed in the Introduction. This section summarizes the structural character of the body and considers the petrography of the gneiss in more detail.

Domal character.--The Glastonbury Gneiss has some structural attributes of a dome but lacks others, and for this reason is herein referred to as a body instead of a dome. Flanking units (Ammonoosuc Volcanics in the north, Collins Hill Formation and Siluro-Devonian units in the south) wrap around the ends of the gneiss body; but foliation trend lines do not appear to close (Gordon Eaton, pers. comm., 1975). Foliation in the gneiss trends predominantly north to northeast with low to moderate northwest dips (fig. 4D), and mineral

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Figure 4 near here

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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 adjacents units are rare, but outcrop patterns are clear in a number of places. Glastonbury Gneiss intrudes Ammonoosuc amphibolite on the southeast side of Baptist Hill, Palmer quadrangle (fig. 4A). The cross-cutting relations are seen in several outcrops over a distance of about 50 m (165 ft). The contact is sharp, without any evidence of reaction or other alteration. Glastonbury gneiss from near the contact is among the least potassic encountered (table 2A). This

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Table 2 near here

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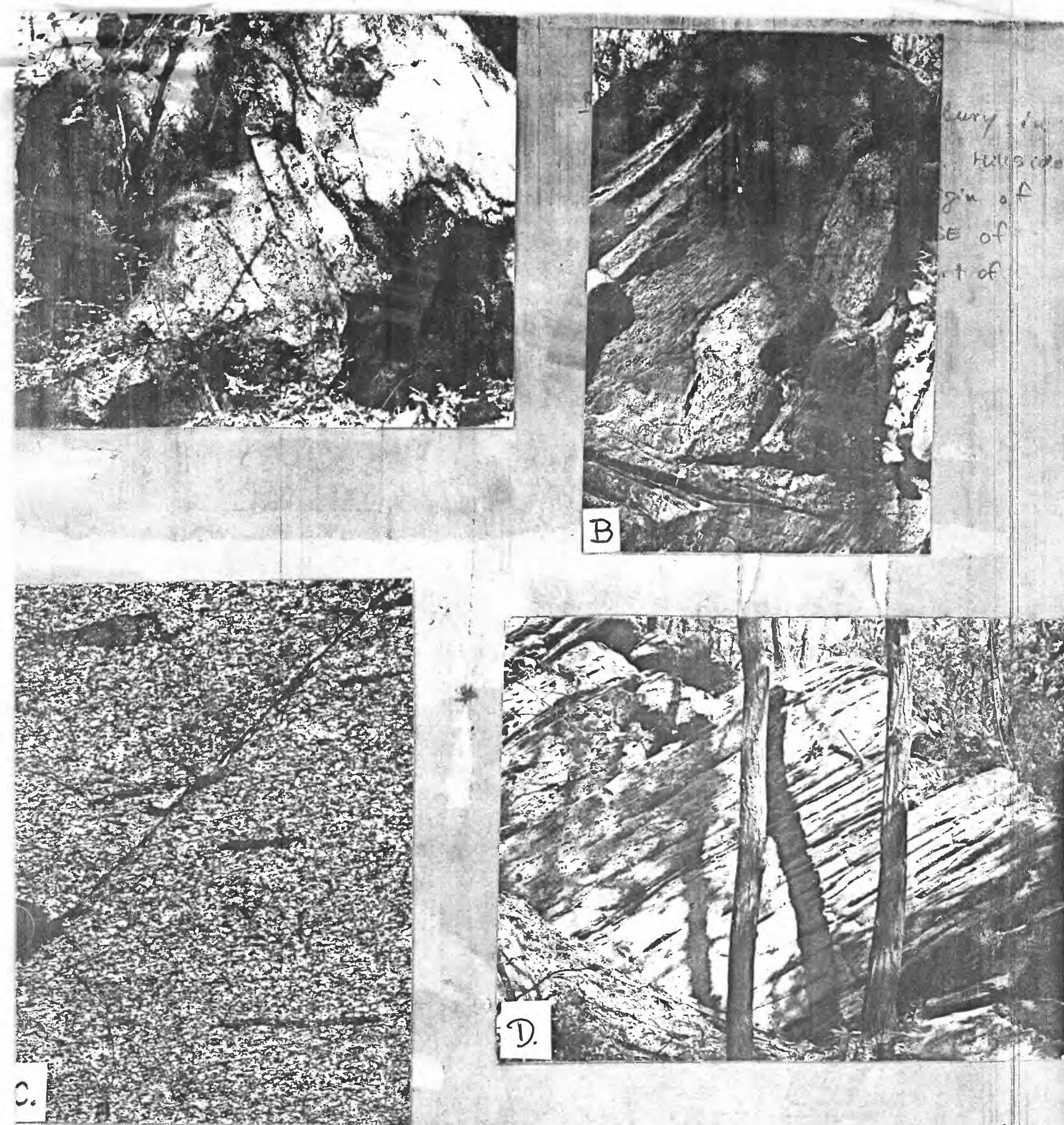
is the most clearly exposed cross-cutting contact known to the writer. A smaller-scale example of Glastonbury intruding Ammonoosuc was noted in the Hampden quadrangles (fig. 4B). Lenses of Glastonbury occur within Ammonoosuc in the southern part of the Ludlow quadrangle (Leo and others, 1977) but contact relations are not exposed.



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Fir. 4. Structures and textures in northern Glastonbury Gneiss.

Figure 4.--Structures and textures in northern Glastonbury Gneiss.

A. Intrusive contact between Glastonbury Gneiss (light gray) Ammonoosuc amphibolite. Southeast side of Baptist Hill, Palmer quadrangle (fig. 2, loc. A).

B. Folded sill of Glastonbury Gneiss (right center) in Ammonoosuc amphibolite. Hillside north of Root Road at origin of Schanade Brook, 2.4 km. ESE of North Somers, southeastern part of Hampden quadrangle.

C. Massive, well-foliated gneiss in cut, north side of Massachusetts Turnpike (I-90) just east of Baptist Hill Road crossing, 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 north of Shenipsit Lake Road, 3 km east of Ellington, Conn. (fig. 2, loc. 10).

Table 2. Additional modes of Glastonbury Gneiss
Locations on fig. 2

Loc. No.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Spec. No.	73-GWL 242	73-GWL 243	73-GWL 245	73-GWL 319-1	635	73-GWL 337-1	73-GWL 327-1	P9-39	P8-280	P8-281	73-GWL 328-6	73-GWL 328-8	73-GWL 332	73-GWL 333	73-GWL 336
Quartz	42.7	40.6	43.8	32.9	42.6	49.9	43.7	49.0	38.0	41.0	43.6	43.6	43.4	42.4	36.4
Plagioclase	53.6	40.2	45.1	47.6	36.6	34.2	28.9	25.0	31.2	37.1	41.0	38.1	33.9	30.5	30.0
K-feldspar	--	8.9	--	10.2	0.3	3.1	19.9	8.2	2.4	0.6	8.3	11.7	16.3	22.0	27.2
Biotite	2.8	7.6	7.1	7.1	15.1	10.3	5.8	11.4	15.2	15.2	5.1	4.9	5.4	4.4	4.3
Muscovite	--	0.9	1.5	0.1	--	0.4	0.9	4.2	--	--	1.0	1.1	0.2	--	1.0
Epidote	--	1.5	1.9	1.9	5.1	2.2	0.5	1.4	5.6	5.0	0.1	1.1	0.6	0.3	--
Hornblende	0.5	--	--	--	--	--	--	--	7.5	--	--	--	0.1	0.1	--
Garnet	0.1	0.1	--	0.1	--	--	0.2	tr.	--	--	0.2	0.1	--	--	--
Opaque	--	0.2	0.5	0.1	--	--	0.1	--	0.2	--	0.6	0.4	--	0.1	0.9
Remainder*	0.1	--	--	--	0.2	--	0.2	0.6	0.1	0.5	0.1	0.1	0.1	0.2	0.3

*includes sphene, apatite, zircon and carbonate.

Explanation for table 2. (See fig. 2 for locations).

A. Fine-grained, leucocratic, very faintly foliated, sugary-textured rock from intrusive Glastonbury-Ammonoosuc contact (fig. ~~5~~4A). Steep SE. slope of Baptist Hill, 0.5 km west of Mass. Turnpike bridge over Quaboag River, Palmer quadrangle.

B. Inequigranular, finely foliated gneiss. Along road south side of Baptist Hill, extreme east edge of Ludlow quadrangle.

C. Fine-grained, closely foliated gneiss from lens west of Glastonbury dome. 220 m SE. of Glendale Road-Crane Hill Road intersection, SE. quadrant of Ludlow quadrangle.

D. Medium-grained, poorly foliated gneiss. West side of unnamed creek, 0.7 km north of Massachusetts Turnpike (I-90) near east boundary of Ludlow quadrangle.

E. Compositionally homogeneous, poorly foliated, biotite-rich gneiss. ~~(fig. 5G, far right),~~ 0.5 km SW. of summit of Perkins Mountain, ~~SE. part~~ near center of Hampden quadrangle.

F. Compositionally homogeneous but strongly lineated and foliated flaser gneiss. East side of Chapin Road, 0.8 km ESE. of summit of Pine Mountain, SE. part of Hampden quadrangle.

G. Inequigranular, inhomogeneous, faintly foliated flaser gneiss. Intersection of Tetrault and Springfield Roads, NW. corner of Stafford Springs quadrangle.

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H. Fine-grained, delicately foliated, leucocratic gneiss from western margin of eastern Glastonbury gneiss body, ~~(fig. 5G, second from left)~~. Eastern outskirts of West Stafford, Stafford Springs quadrangle.

I. Relatively mafic, hornblende- and biotite-bearing, closely foliated gneiss; east margin of eastern Glastonbury Gneiss body. East side of Tolland ~~Avenue~~ Turnpike, 1.4 km northeast of Bluff Cap Road intersection, Stafford Springs quadrangle.

J. Poorly foliated, blotchy gneiss typical of northern Glastonbury. Tolland ~~Road~~ Turnpike, 0.5 km northeast of preceding ~~specimen~~ locality.

K. Gneiss of similar appearance to preceding. Approx. 1.5 km west along road from fire lookout tower on Soapstone Mt., Ellington quadrangle.

L. Similar to preceding, 0.8 km farther southwest along road.

M. Pink, dominantly fine-grained rock with scattered K-feldspar porphyroblasts up to 1 cm long; "schistose facies" of Herz (1955). Intersection of Manchester and Hebron Avenues, northeast ~~quadrant~~ part of Glastonbury quadrangle.

N. Medium-grained, poorly foliated gneiss with abundant small (< 5 mm) rounded K-feldspar porphyroblasts; "porphyritic facies" of Herz (1955). Old Eastbury Cemetery, 0.9 km SW. along road from preceding locality.

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O. Fine-grained, sugary-textured, sheared-appearing flaser gneiss; "eastern border facies" of Herz (1955). North side of Connecticut Rte. 2, approx. 120 m west of Hollow Brook crossing, SE part of Glastonbury quadrangle.

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Scattered outcrops of Glastonbury within Ammonoosuc along the western edge of the dome near the southern boudnary of the Ludlow quadrangle are interpreted as sills, although contacts are not exposed. This gneiss, too, is unusually low in potash (table 2, C).

Evidence for intrusion of Ammonoosuc Volcanics by 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 Ammonoosuc in a series of partly cross-cutting sills, creating a number of inliers and roof pendants ranging from a few meters to several kilometers in diameter; a semi-concordant inlier rifted from the Ammonoosuc section trends more than 4 km (2-1/2 mi) south from the town of Hampden (J. D. Peper, in press). Sharp contacts between Glastonbury Gneiss and Ammonoosuc amphibolite are locally exposed. Similar relationships are found in the Ellington quadrangle to the south; large blocks of amphibolite such as that at Soapstone Mountain are interpreted as roof pendants of Ammonoosuc in Glastonbury (M. H. Pease, pers. commun., 1974).

Southward from the Ellington quadrangle the Glastonbury body is mostly bounded by faults along both sides. At the southern end of the body in the Middle Haddam quadrangle, strongly foliated, hornblende- and epidote-rich Glastonbury Gneiss crops out a few meters from coarsely crystalline Collins Hill Formation rich in lime-poor amphibole. This contact could be intrusive, ~~but~~ is more equivocal than the Glastonbury-Ammonoosuc relationship described earlier; the Glastonbury-Collins Hill contact could be depositional, modified by regional metamorphism.

A lens of granitic gneiss within Collins Hill Formation in the Middle Haddam quadrangle has been tentatively identified as Glastonbury, but cannot be regarded as conclusive evidence for an intrusive contact (G. P. Eaton, oral commun., 1976).

Hence, the lower age limit of the Glastonbury is unaffected by contact relationships in the southern area. On a geologic basis it can be positively stated only that the intrusive age of the gneiss is younger than the Ammonoosuc Volcanics.

The contact between Glastonbury Gneiss and the Clough Formation of Silurian age, which flanks the Glastonbury body along its southeast side, is not exposed. Snyder (1970) mapped the Glastonbury-Clough contact as a fault which was assumed to have obliterated an intrusive contact. This (intrusive) relationship remains to be demonstrated.

Lithologic Character.--The northern Glastonbury is weakly to conspicuously foliated and typically has a well-defined lineation (fig. 4C). 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. 5).

Figure 5 near here.

Mafic inclusions are common and locally abundant; they are generally small, disc-shaped, and subparallel to foliation (fig. 4C, D). Rare tabular amphibolite bodies as much as 50 cm thick are partly concordant with the foliation and partly crosscutting. Such bodies appear to be synmetamorphic dikes, probably unrelated to the disc-shaped inclusions.

The northern part of the body is leucocratic gneiss consisting dominantly of quartz and plagioclase with subordinate K-feldspar, biotite, epidote (both in isolated grains and idiomorphic granules scattered through plagioclase), with or without minor muscovite, hornblende, garnet, and various other accessories.

The mafic minerals typically form elongate clusters that impart a streaky lineation to the rock (fig. 4D, F); elongation of quartz patches, contributes to the preferred orientation of the mineral fabric. Textures range from equigranular to highly inequigranular with large porphyroblasts of quartz and plagioclase cutting across a granoblastic matrix. The textures are metamorphic, giving no definite clues to a pre-existing igneous fabric.

Fig. 5

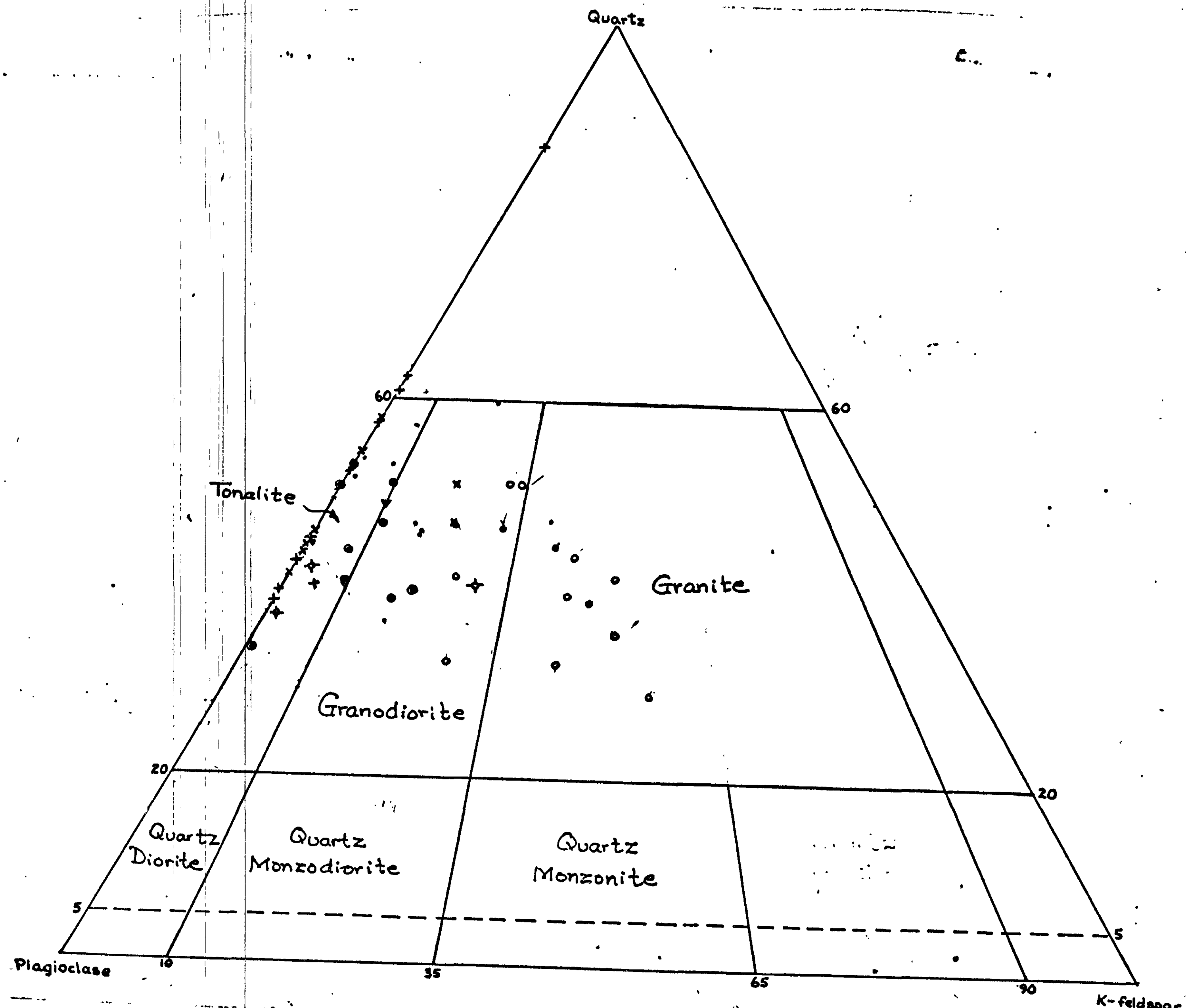
Quartz
60
60
Tonalite
Granite
Granodiorite
20
20
Quartz Diorite
Quartz Monzodiorite
Quartz Monzonite
5
5
Plagioclase
10
35
65
90
K-feldspar

Figure 5.--Modal variations in Glastonbury Gneiss, Monson Gneiss, and felsic Ammonoosuc Volcanics, ⊙ = chemically analyzed northern Glastonbury (table 1, nos. 1-10); o = chemically analyzed felsic (hornblende-free) southern Glastonbury (table 1, nos. 11-13 and 18-24; modal data for nos. 14-17 not available); ◇ = chemically analyzed intermediate to mafic (hornblende-bearing) southern Glastonbury (table 1, nos. 25-28, plotted positions misleading due to high modal biotite); · = other northern Glastonbury samples (table 2); • = other southern Glastonbury samples (table 2); x = Monson Gneiss (table 1, nos. 29-37); + = felsic layers of Ammonoosuc Volcanics (table 1, nos. 38-48). Classification according to IUGS (Geotimes, Oct. 1973, p. 26).

Modal K-feldspar in northern Glastonbury rocks ranges from 0 to 19.9 percent, with a median value of 4.5 percent (fig. 6) The K-feldspar has the grillwork twinning of microcline and generally occurs in small interstitial grains, locally in elongated patches and only uncommonly as a late constituent (replacing plagioclase and/or quartz). ~~metasomatic mineral~~. 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 near the center. ~~(fig. 6)~~.

Figure 6 near here

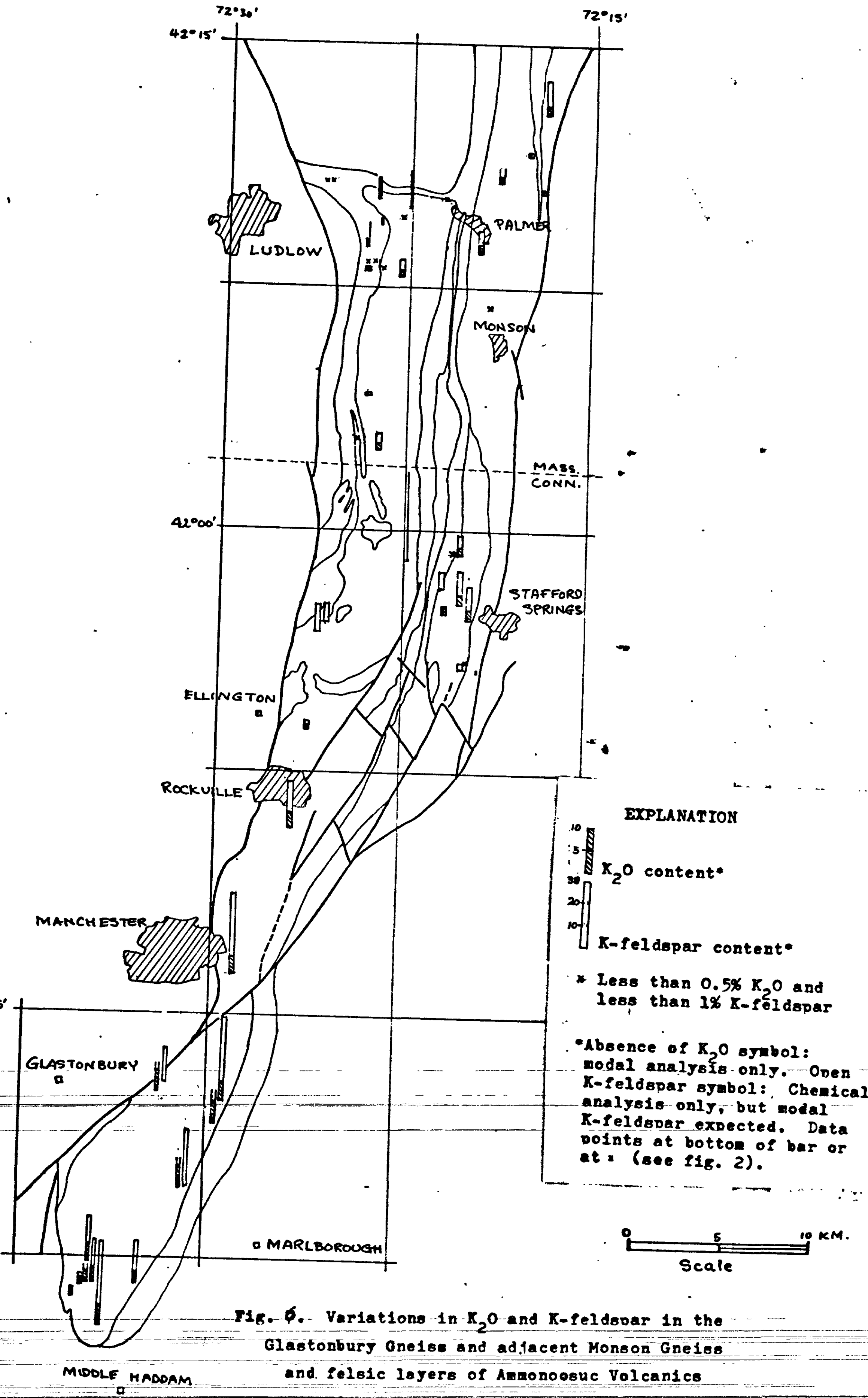

Fig. 6. Variations in K_2O and K-feldspar in the Glastonbury Gneiss and adjacent Monson Gneiss and felsic layers of Ammonoosuc Volcanics

Figure 6.--Variations in the content of K_2O and K-feldspar in the Glastonbury gneiss ~~dome~~ body.

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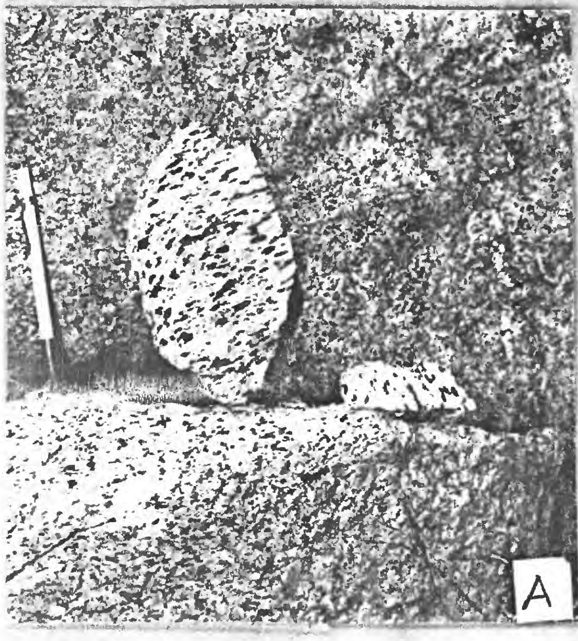
Southward from the Ellington quadrangle the Glastonbury Gneiss shows gradual and pervasive changes in texture and composition (cf. Herz, 1955; Snyder, 1970; Eaton and Rosenfeld, 1974). The most consistent compositional change is the greater proportion of potassic feldspar (the range in 12 point-counted sections is 0 to 33 percent, tables 1 and 2; fig. 6), and a roughly proportional decrease in quartz and plagioclase. Along the southwest side of the Glastonbury body in the Middle Haddam quadrangle, there is a progressive change in composition from granite to granodiorite and tonalite, with the appearance of hornblende and increasing amounts of biotite and epidote (table 1). The granodiorite lies on a calc-alkaline differentiation trend (fig. 5, 8, 9), hence it is quite distinct from any of the northern Glastonbury Gneiss. Rare-earth element contents (fig. 11C) show a close affinity between the hornblende-bearing rocks and more felsic southern Glastonbury Gneiss.

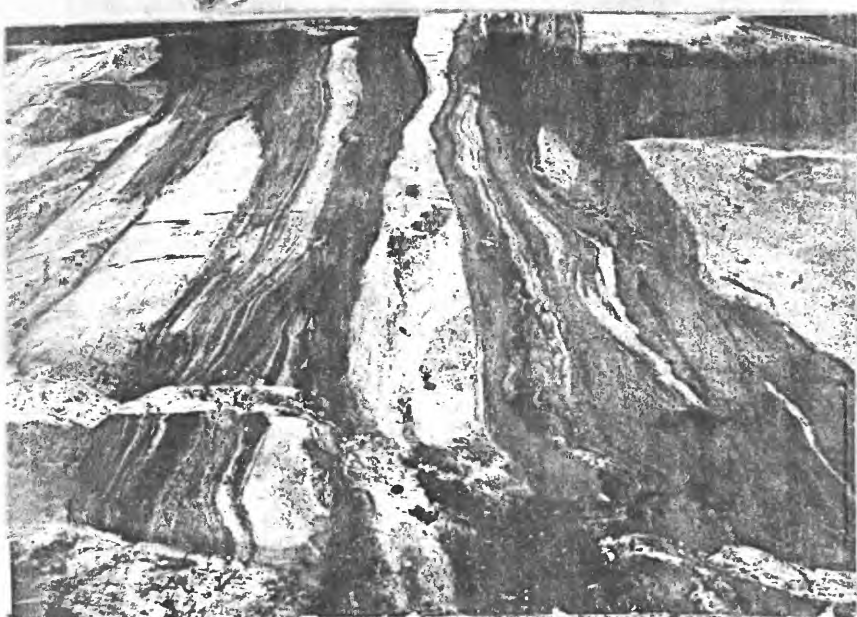
Comparable compositional variations in the Glastonbury quadrangle were noted by Herz (1955). Compositional variations in the gneiss in the Marlborough quadrangle have been described as imperceptibly gradational (Snyder, 1970). Mafic layers or schlieren with abrupt contacts against felsic gneiss (fig. 7c) are assumed to be inclusions, quite likely of Middletown Formation (Ammonoosuc equivalent).

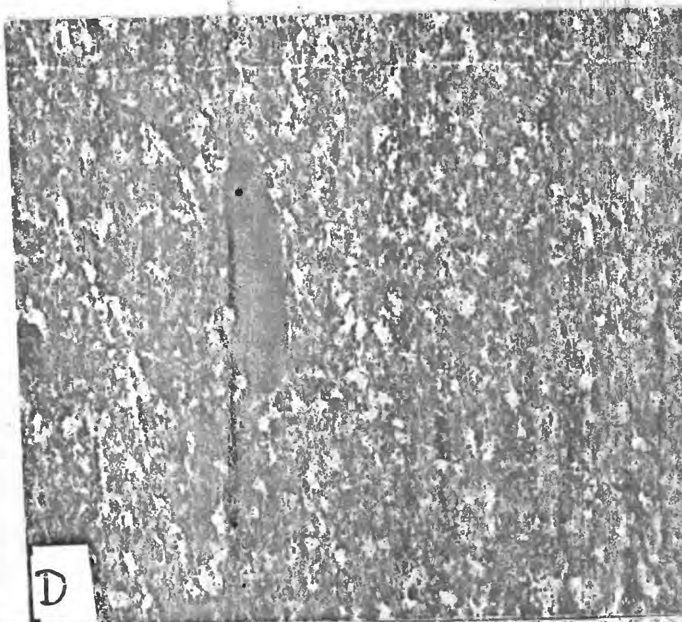
Fig. 7 near here.



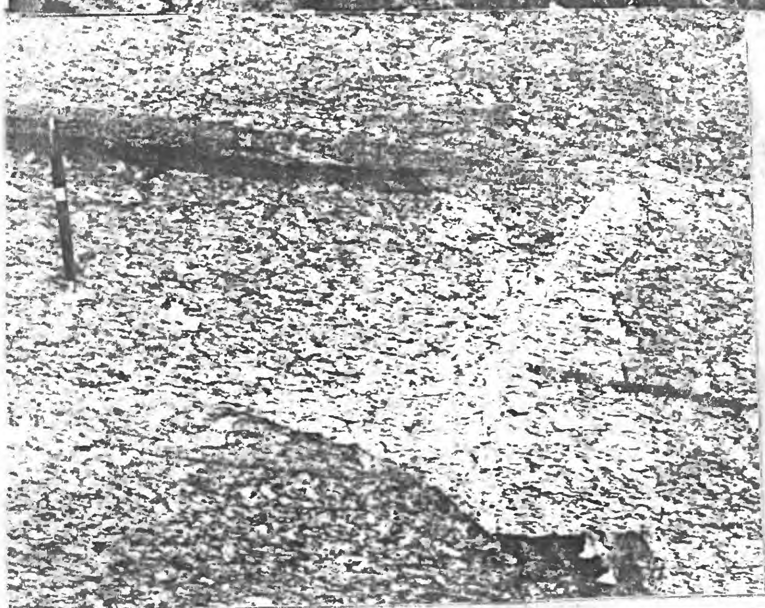
A

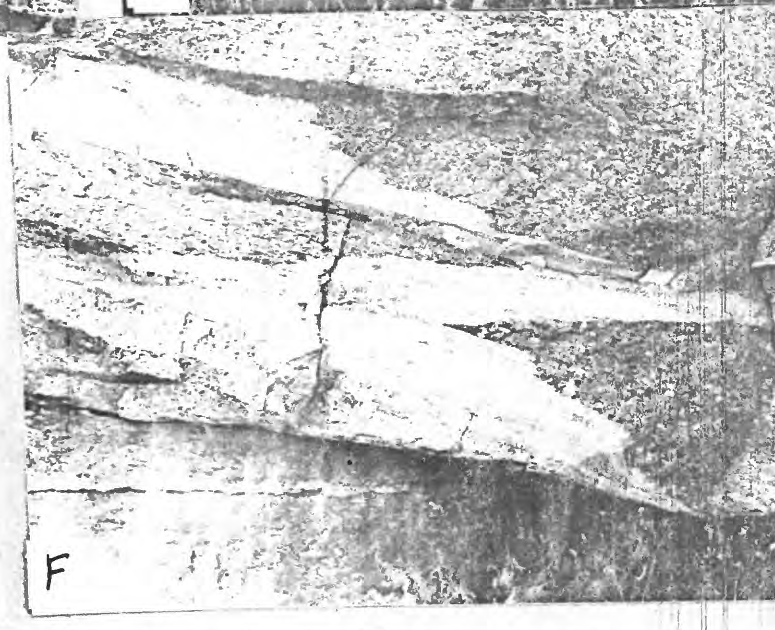
B



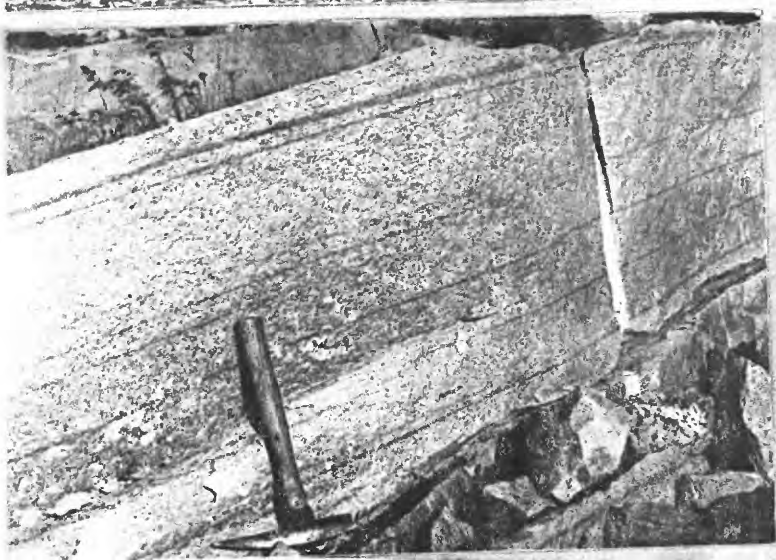


D





F



E.

G

Figure 7.--Structures and textures in southern Glastonbury Gneiss.

A. Flaser gneiss with blotchy biotite aggregates. Roadcut north side of Connecticut Rte. 15 --Rte. I-86, 1.5 km south of Rockville (fig. 2, loc. 9).

B. Massive Glastonbury Gneiss, approximate center of roadcut on north side of Connecticut Route 15 (I-84) directly east of Wyllys Avenue overpass and approximately 0.8 km east of Highland Street exit (fig. 2, loc. 12, 13). Shows indistinct foliation, conspicuous K-feldspar porphyroblasts, and angular amphibolite inclusions.

C. Partly assimilated, plastically deformed mafic layers, assumed to be Middletown, parallel to strong regional foliation in otherwise homogeneous granitic-Glastonbury gneiss. Pegmatite (foreground) cuts dike and gneiss. Hebron Avenue gravel pit south of Connecticut Rte. 94, west side of Marlborough quadrangle (fig. 2, loc. 18).

D. Granitic gneiss with small elongated mafic inclusions subparallel to foliation. Same locality.

E. Porphyroblastic, plastically sheared gneiss with highly stretched mafic inclusions. West side of Connecticut Rte. 2, 0.7 km north of Quarry Street overpass, Glastonbury Quadrangle.

F. Disrupted aplite dike, same locality. Note variations in abundance of porphyroblasts.

G. Faint, continuous mafic septa in otherwise homogeneous, equigranular gneiss. Tower Hill quarry, south of New London Turnpike 0.9 km NW of intersection with Quarry Street, Glastonbury Quadrangle.

The range of textural variations in the southern gneiss likewise appears considerably greater than in the northern rocks. 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. 7A); 10 km to the south the rock is comparatively massive and contains prominent microcline porphyroblasts (loc. 12, 13; fig. 7E, F). In the Glastonbury quadrangle, roadcuts along Ct. Rte. 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 faintly foliated, porphyroblastic, fine-grained granitic gneiss; somewhat coarser grained, better-foliated gneiss with ovoid microcline prophyroblasts up to 2 cm long which is gradually to abruptly transitional to much finer-grained, nonporphyritic gneiss (fig. 7F, G); and gneiss with ellipsoidal microcline augen (this type is probably sheared porphyritic gneiss). Eastwards into the Glastonbury body the rocks are generally more homogeneous and less strongly foliated; thin, continuous mafic bands in otherwise massive gneiss (fig. 7C) appear to be rare. Three texturally distinct gneisses from the Glastonbury quadrangle have fairly similar compositions (no. 16, 19 and 20, fig. 2 and table 1).

Textural variations at the south end of the Glastonbury body 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 body is relatively massive with faint but distinct regional foliation. Hornblende-biotite bearing gneiss is increasingly foliated towards the southwest margin ~~(fig. 7I)~~. There is little indication of compositional layering.

Mafic inclusions of two general types are locally abundant: (a) angular, irregular-shaped, and sharply bounded (fig~~s~~. 7C), and (b) ellipsoidal, more or less stretched parallel to foliation, and sharply bounded to shadowy and diffuse (figs. 7E, F); the latter probably were produced by shearing of originally angular inclusions. Pegmatites are abundant, especially along an axial line of the gneiss body in the Glastonbury quadrangle (Herz, 1955).

Microtextures in the southern Glastonbury gneiss are generally comparable with those in the northern rocks except that microcline is more abundant, both as small interstitial grains and as large, ragged, cross-cutting plates. The patchy microcline porphyroblasts replace plagioclase along margins and contain partly resorbed plagioclase remnants ~~(fig. 6F, G)~~. 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 Glastonbury rocks. As in the northern gneiss, epidote and biotite are ubiquitous and seemingly stable, suggesting that conditions of metamorphism were similar throughout the ~~entire~~ gneiss body.

Chemistry

Major elements

Monson and Ammonoosuc.--As expected from the mineralogy of Monson and Ammonoosuc samples, bulk compositions, with few exceptions, are characterized by low K_2O and moderate but variable Na_2O and CaO (table 1), thus they cluster along the Q-Ab boundary (fig. 8A). The

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Figure 8 near here.

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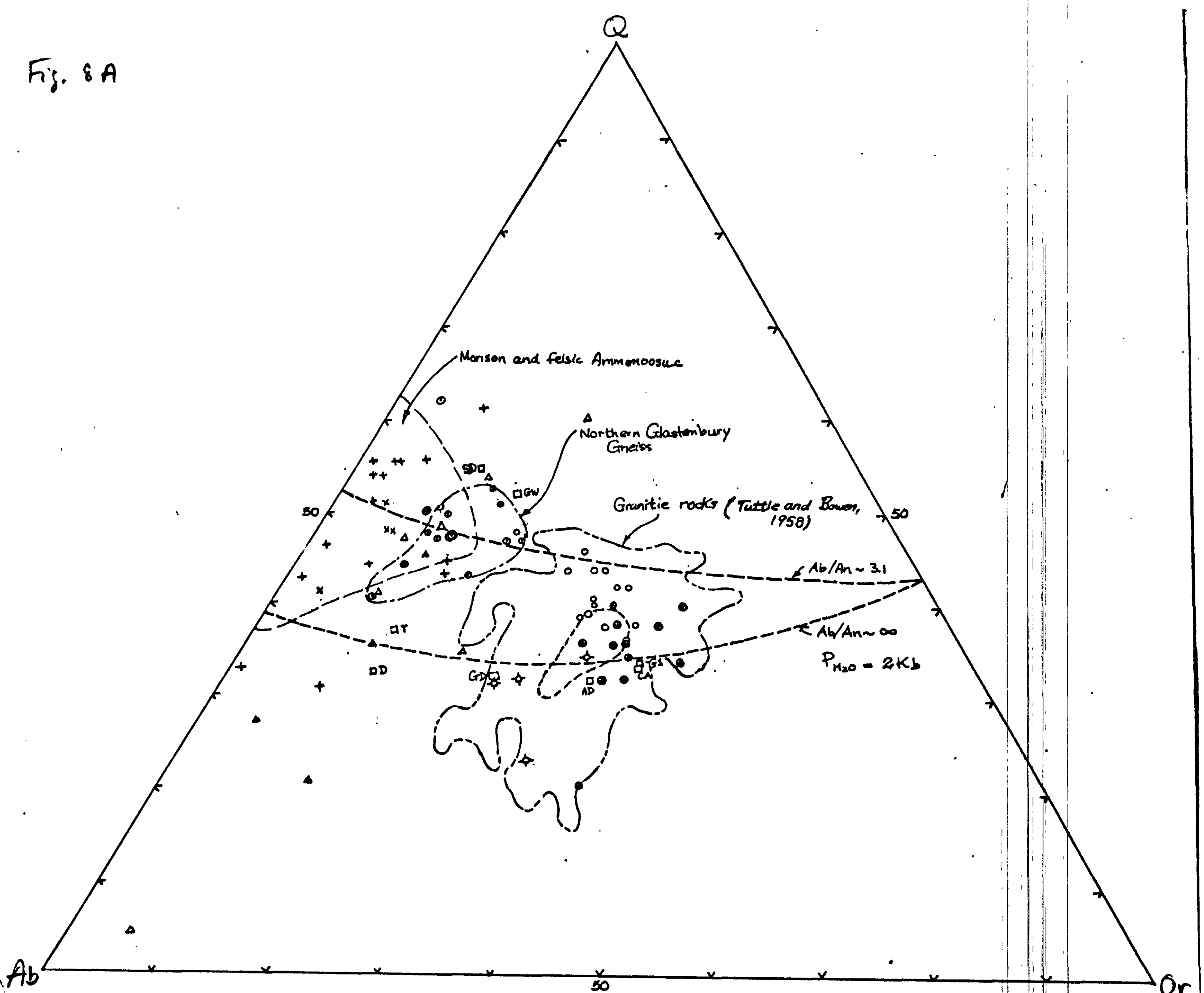
range of K_2O for 20 analyses is 0.03 to 2.2 percent, with a median value of 0.55 percent, while Na_2O has a range of 2.8 to 5.8 percent with a median of 4.0 percent, and CaO ranges from 0.65 to 7.9 percent with a median of 2.8 percent. The Ab/An ratio shows a remarkable range of 0.8 to 12.1. The low ratio is for a hornblende-bearing rock and the high one is for meta-rhyolite(?), but even if these limiting compositions are eliminated the Ab/An ratio still ranges from 1.1 to 10.5. Such variation just among the relatively felsic rocks must reflect a mixed provenance for the original sedimentary and volcanic rocks.

Fig. 8A



Q
Ab
Or
50
50
50
Monson and felsic Ammonoosuc
Northern Glastenbury Gneiss
Granitic rocks (Tuttle and Bowen, 1958)
Ab/An ~ 3.1
Ab/An ~ ∞
P_{H_2O} = 2Kb
GW
SD
T
D
GD
AD
CA
GS

Fig. 8A

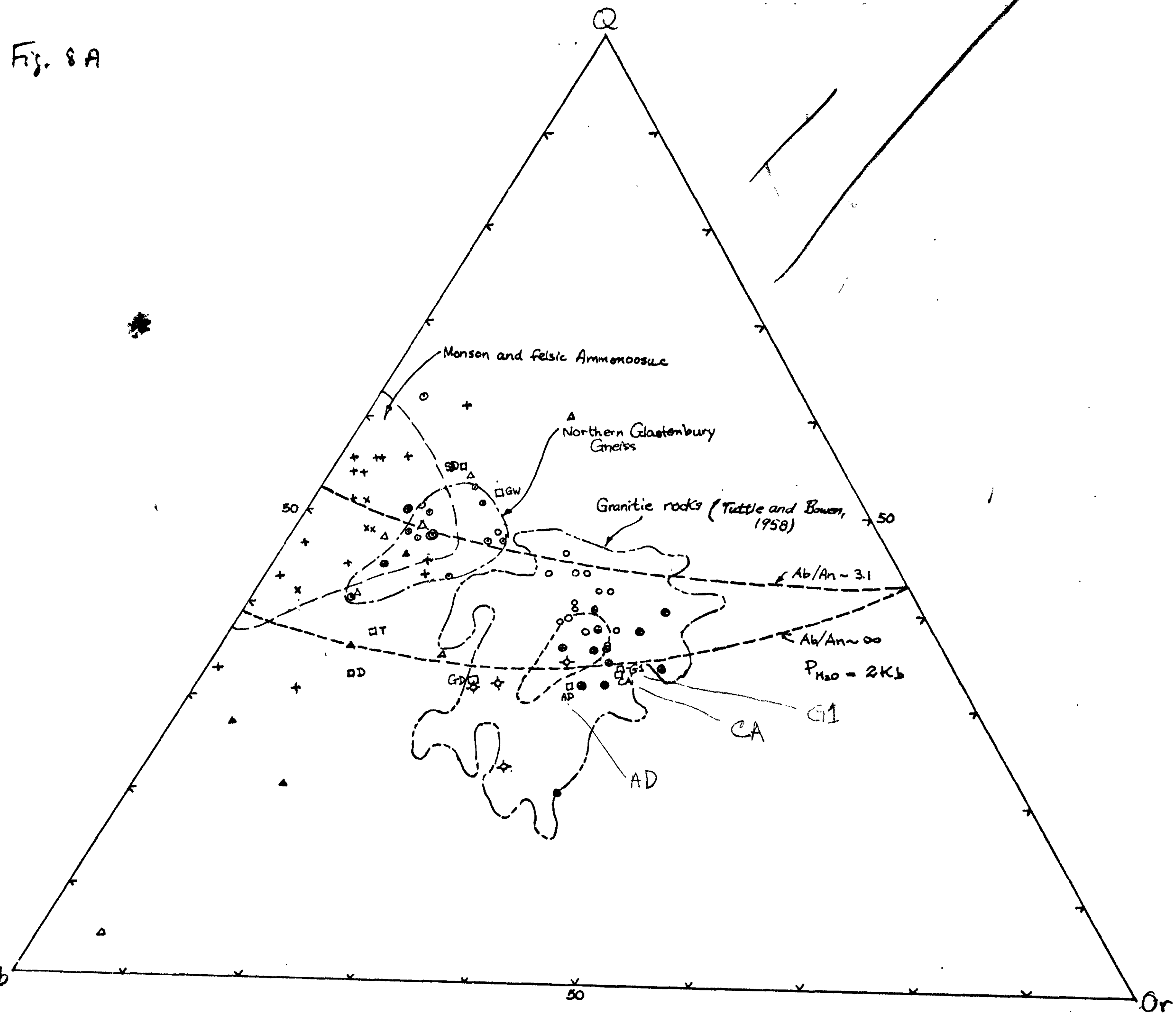

Q
Ab
Or
50
50
50
Monson and felsic Ammonoosuc
Northern Glastenbury Gneiss
Granitic rocks (Tuttle and Bowen, 1958)
Ab/An ~ 3.1
Ab/An ~ ∞
P_{H_2O} = 2Kb
GW
SD
T
D
GD
AD
CA
G1

Figure 8.-- Normative Q - Ab - O diagrams. 8A: Glastonbury Gneiss, Monson Gneiss and felsic Ammonoosuc volcanics and comparable rocks. Notation for northern and southern Glastonbury as in fig.5; points on fig. 5 corresponding to table 2 not shown. Monson and Ammonoosuc shown by a field only. Other notation: ◎ = average of analyses of northern Glastonbury (table 1, nos. 1-10); ⊕ = Oliverian core rocks (Billings and Wilson, 1964, table 8; two points near northern Glastonbury field are from Mascoma and Smarts Mountain domes (see text)); x - Relay quartz diorite of Hopson (1964, p. 159) and other Relay rocks (Higgins, 1972, p. 1007, fig. 14); + = other James Run rocks (Higgins, 1972, p. 1006, footnote 4); △ = volcanic marine sediments of the Upper Eocene Ohanapecosh Formation, Washington (Hopson, 1964, and R. S. Fiske, unpub. data); ▲ = tuffs and flows associated with the Ohanapecosh sediments; □ with letters: Nockold's (1954) average calk-alkaline granite (CA); adamellite (AD), granodiorite (GD), tonalite (T), and dacite (D); SD, average dacite of Saipan (Schmidt, 1957, Table 5, col. 12); GI, G-1 granite; GW, average graywacke of Pettijohn (1963, table 7, Col. A). Dashed line above the Q-Ab cotectic (Ab/An=∞) 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. Field labeled "Granitic rocks" includes most of the analyzed rocks in Washington's tables containing 80% or more Ab + or + Q (Tuttle and Bowen, 1958, p. 128, fig. 63). Small field surrounded by short dashes near center of diagram is granite mimimum of Tuttle and Bowen (1958).

8B: Compositional fields of various trondhjemites in relation to northern Glastonbury Gneiss, Monson Gneiss, and felsic Ammonoosuc volcanics. 1): composition of melt at 720°C and P_{H_2O} = 2 Kb from gneiss consisting of quartz (21%), plagioclase (45%; An21) and biotite (30%); 2): composition of melt at 760°C and P_{H_2O} = 2 Kb from gneiss consisting of quartz (38%), plagioclase (28%; An_{13}) and biotite (34%). Point 1 represents 50% melt, point 2, 60%. After Winkler, 1974, p. 300, fig. 18-9.

The traditional view of the origin of the Monson and Ammonoosuc, based on appearance, composition, and stratigraphic correlation, is that they are dominantly volcanogenic sediments comprising more or less pure tuffs together with tuffaceous sandstones, siltstones, or graywackes, and subordinate intercalated lava flows. This view is supported by the present analyses, which resemble those of certain other volcanic sediments, both metamorphosed and unmetamorphosed. A striking compositional similarity is apparent between the Monson-Ammonoosuc and rocks of the James Run Formation (fig. 8A) described as "closely associated, approximately contemporaneous metavolcanic and metavolcaniclastic rocks (and also including) metamorphosed epiclastic rocks" (Higgins, 1972, p. 1001); other compositionally comparable rocks are the plutonic or hypabyssal trondhjemite of Rio Brazos, N. M., and the metavolcanic Twilight Gneiss in southwestern Colorado (fig. 8B), both of Precambrian age (Barker and others, 1976). However, trace element contents and strontium isotope data of these gneisses differ significantly from the Monson as well as the northern Glastonbury, as will be discussed in a later section.

The composition of these various crystalline rocks overlaps with that of the unmetamorphosed, fine- to coarse-grained volcanic sediments, tuff-breccias, and associated lava flows of the Eocene Ohanapecosh Formation in the Mount Rainier area of Washington (Hopson, 1964; R. S. Fiske, 1963 and unpub. data). Although the Ohanapecosh rocks are mostly more mafic than the Monson-Ammonoosuc assemblage here used, the comparison would doubtless be closer if mafic Ammonoosuc compositions had been included. The Ohanapecosh Formation has been interpreted (Fiske, 1963) as a sequence of subaqueous pyroclastic flows related to underwater eruptions, interbedded with turbidity-current and ashfall flows and local subaerial lava flows. Metamorphism of the finer-grained facies (dominantly waterlaid ashfall tuffs) of the Ohanapecosh could result in a lithology similar to the Monson Gneiss or the Ammonoosuc Volcanics. As will be discussed subsequently, the Monson-Ammonoosuc (-Partridge) sequence is regarded as the product of ensialic island-arc volcanism, an environment which differs somewhat from that of the Ohanapecosh volvanics which presumably reflect continental-margin volcanism above a subduction zone involving no island arc. In any case, this type of assemblage is rather common in eugeosynclinal environments, and metamorphic equivalents are probably not rare in ancient crystalline terrains.

Oliverian rocks.--Oliverian granitic rocks (Billings and Wilson, 1964) shown on fig. 8A, nominally are igneous, plutonic types, with the possible exception of two samples described as "gneiss". There is no assurance that the analyzed samples are representative of the domes from which they were collected; in particular, it is not definitely known whether a given analysis represents the inner, unstratified core rock (generally granite to granodiorite) or the outer, stratified core gneiss (generally potash-poor; Naylor, 1969).

Nevertheless, of the 14 Oliverian analyses plotted on figure 8, 11 fall within the field that characterizes magmatic, calc-alkaline granitic rocks (Tuttle and Bowen, 1958) and four analyses are within the innermost contour near the ternary eutectic. This distribution of compositions strongly suggests that the Oliverian rocks concerned are ~~magmatic,~~ calc-alkaline plutons more nearly comparable with plutonic New England granites (Chayes, 1952) than with the Glastonbury.

Two Oliverian analyses, one from the Mascoma Dome and the other from Smarts Mountain (Hadley, 1942, p. 140, table 11), fall well outside the calk-alkaline granite field, but resemble northern Glastonbury and some Monson Gneiss (fig. 8A). The Mascoma sample, described as oligoclase granodiorite (Hadley, 1942, p. 140) is located within the stratified core gneiss of Naylor (1969, p. 407), and its composition is similar to other rocks in that category (Naylor, 1969, p. 418, fig. 8b). The Smarts Mountain "granodiorite" appears to be representative of the entire, relatively homogeneous Smarts Mountain dome (Hadley, 1942, and personal commun., 1974). Both rocks ~~plot close to the~~ are compositionally trondhjemites ~~field~~ (fig. ~~8~~ 8B) as recognized and discussed by Hadley (1942, p. 140-141).

Glastonbury Gneiss.--As expected from the diverse petrography, analyses of Glastonbury Gneiss show a range of compositions and limited bimodal character. The northern Glastonbury compositions, with one especially silica-rich and potash-poor exception (table 1, no. 4), fall into a fairly small field which partly overlaps with that of the Monson and Ammonoosuc (fig. ~~8~~ 8A). On the average the northern Glastonbury is somewhat more potassic than these, with a K_2O range for ten samples (1 - 10, table 1) from 0.5 to 2.4 percent and a median value of 1.8 percent compared to a median of 0.55 percent for combined Monson and Ammonoosuc. The compositional field is close to trondhjemite. ~~as will be discussed below.~~ The Ab/An ratio shows a rather broad range (1.6 to 6.2), with an average value of 3.1.

By contrast, analyses of felsic (i.e., hornblende-free) southern Glastonbury Gneiss (table 1, nos. 11-24) mostly plot within the field of calc-alkaline granitic rocks (fig. 8A), with a concentration of points not far from the Q-Ab-Or eutectic. Compositions are generally comparable with Oliverian core rocks. More mafic (i.e., hornblende-bearing) Glastonbury Gneiss from the southwestern end of the body (table 1, nos. 25-28) has plausible igneous compositions although departing from tonalites (T, figs. 8A and 9), and Nockolds, 1954, p. 1015). The overall differention trend, if it is one, of the southern Glastonbury thus is not typical, but does approximate a well-established intrusive sequence in the Sierra Nevada (fig. 9). Fig. 9 ~~and 10~~ further emphasizes the distinction between northern and southern Glastonbury, as well as the affinity between the northern Glastonbury and the Monson Gneiss.

Figure 9 ~~and 10~~ near here.

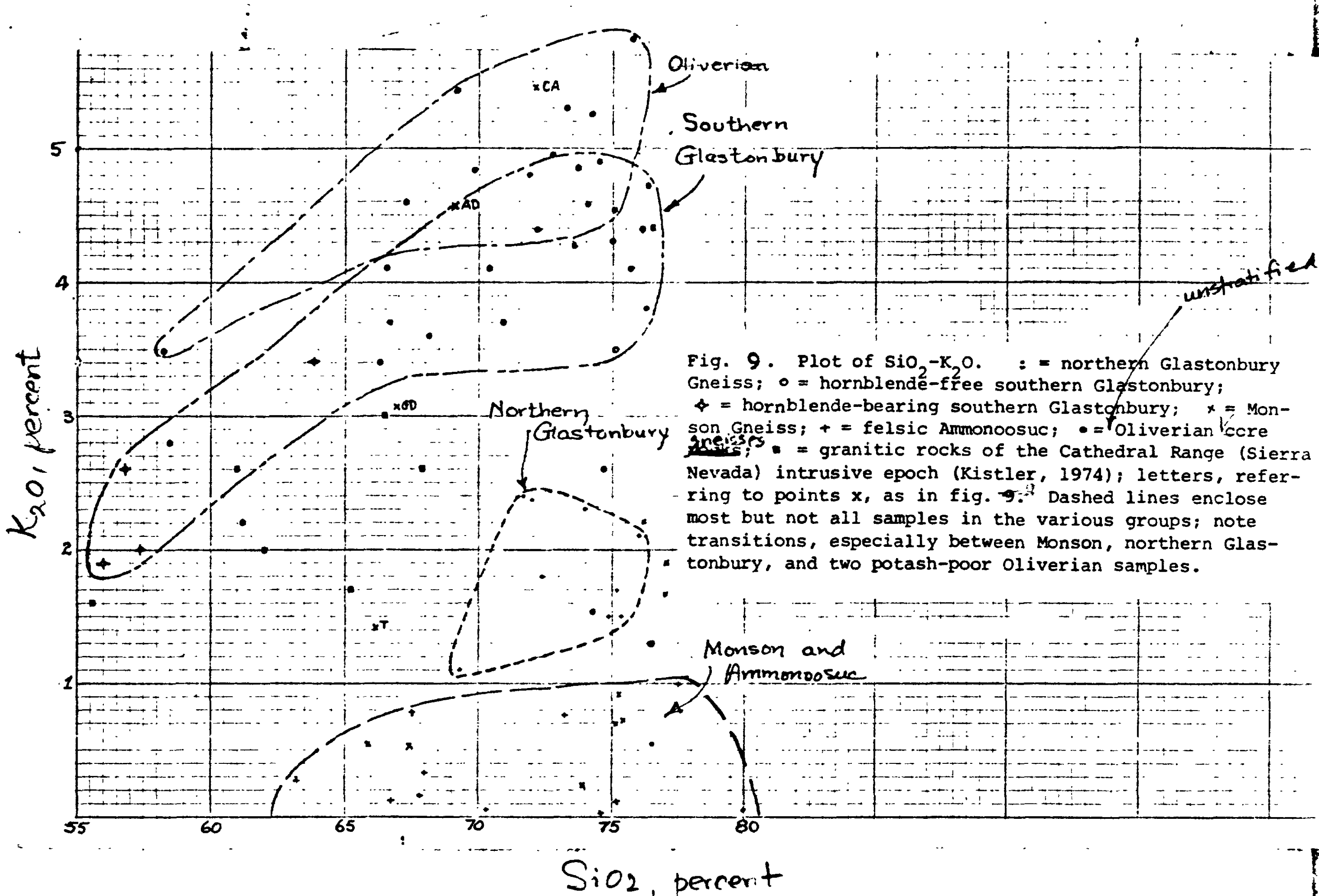


Fig. 9. Plot of SiO_2-K_2O. : = northern Glastonbury Gneiss; o = hornblende-free southern Glastonbury; ✧ = hornblende-bearing southern Glastonbury; × = Monson Gneiss; + = felsic Ammonoosuc; • = Oliverian core rocks; ▪ = granitic rocks of the Cathedral Range (Sierra Nevada) intrusive epoch (Kistler, 1974); letters, referring to points x, as in fig. 9. Dashed lines enclose most but not all samples in the various groups; note transitions, especially between Monson, northern Glastonbury, and two potash-poor Oliverian samples.

Figure 9.--Plot of SiO_2-K_2O for Monson Gneiss and felsic Ammonoosuc volcanics, Glastonbury Gneiss, and unstratified Oliverian core gneisses.

Minor and Trace Elements

Minor and trace elements for about half of the samples in table 1 are listed in table 3. The elements reported, other than Rb and Sr,

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Table 3 near here

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represent a suite routinely determined by instrumental neutron-activation analysis (INAA) in the U. S. Geological Survey laboratories. The main purpose of these determinations was to obtain data on rare-earth elements. Rubidium and strontium were mostly determined by isotope-dilution mass spectrometry in connection with whole-rock Rb-Sr age determinations (Brookins, this volume). Some supplementary Rb-Sr isotopic data are given in Table 8.

Trace elements other than rare earths. These elements show rather wide ranges of variation, reflecting the inhomogeneity of these rocks already indicated by variations in major elements. Nevertheless, by averaging the concentrations of these elements for the three major rock groups one sees a consistent and predictable relationship to the corresponding variations in Ca, K and Na (table 4). A K/Rb plot is shown

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Table 4 near here

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in fig. 10.

Rare-earth elements (REE). Fig. 11A-C shows chondrite-normalized

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Figs. 10 and 11 near here

REE patterns for the northern and southern Glastonbury Gneiss and Monson Gneiss. The patterns reflect considerable scatter which may be due either to real variations in REE concentrations, or to the relatively large margin of error in the INAA determinations, as compared to isotope-dilution analysis (table 3), or both. (However, a group of patterns that define a consistent and narrow range, e.g., most of the southern Glastonbury samples, suggest that the larger variations seen in some of the other patterns are probably real). Furthermore, the inability of the instrumental neutron-activation procedure to determine several REE's (Gd, Dy, Er) creates a certain lack of definition in the patterns, especially of the Eu anomaly. Within these limitations the

Table 4.--Ranges of concentration and average values of trace elements other than REE in the Glastonbury and Monson Gneiss

[Summarized from table 3. Averages in parentheses.]

Element	Northern Glastonbury	Southern Glastonbury	Monson
		Percent	
Ca	1.2-3.6 (2.3)	1.2-5.9 (3.5)	0.5-4.1 (2.2)
Na	2.3-3.2 (2.7)	1.9-2.4 (2.1)	2.5-3.1 (2.8)
K	0.5-2.0 (1.4)	1.7-4.0 (2.9)	0.1-1.8 (0.8)
		Parts per million	
Sc	4.5-16.1 (10.4)	4.5-34 (17.9)	0.7-11.3 (6.4)
Cr	3.8-6 (4.7)	2.7-32 (16.8)	2.7-14.5 (7.5)
Co	2.2-4.0 (3.3)	1.6-9.7 (7.8)	0.5-13.5 (4.5)
Zr	21-290 (207)	160-260 (219)	70-230 (152)
Rb	20-84 (62)	60-~~144~~ 168 (11~~0~~5)	4.4-84 (34)
Sr	80-281 (144)	110-360 (246)	28-440 (218)
Cs	1.0-2.9 (1.9)	1.8-13.7 (6.0)	0.2-0.8 (0.7)
Ba	150-1010 (573)	1080-1340 (1294)	210-450 (343)
Hf	1.7-9.5 (4.2)	2.5-7.4 (5.3)	1.2-6.5 (3.8)
Ta	0.3-0.4 (0.3)	0.4-1.8 (0.9)	0.06-0.4 (0.2)
Th	1.9-15.5 (9.6)	11.2-42.4 (29.0)	0.3-8.1 (4.4)

Fig. 10

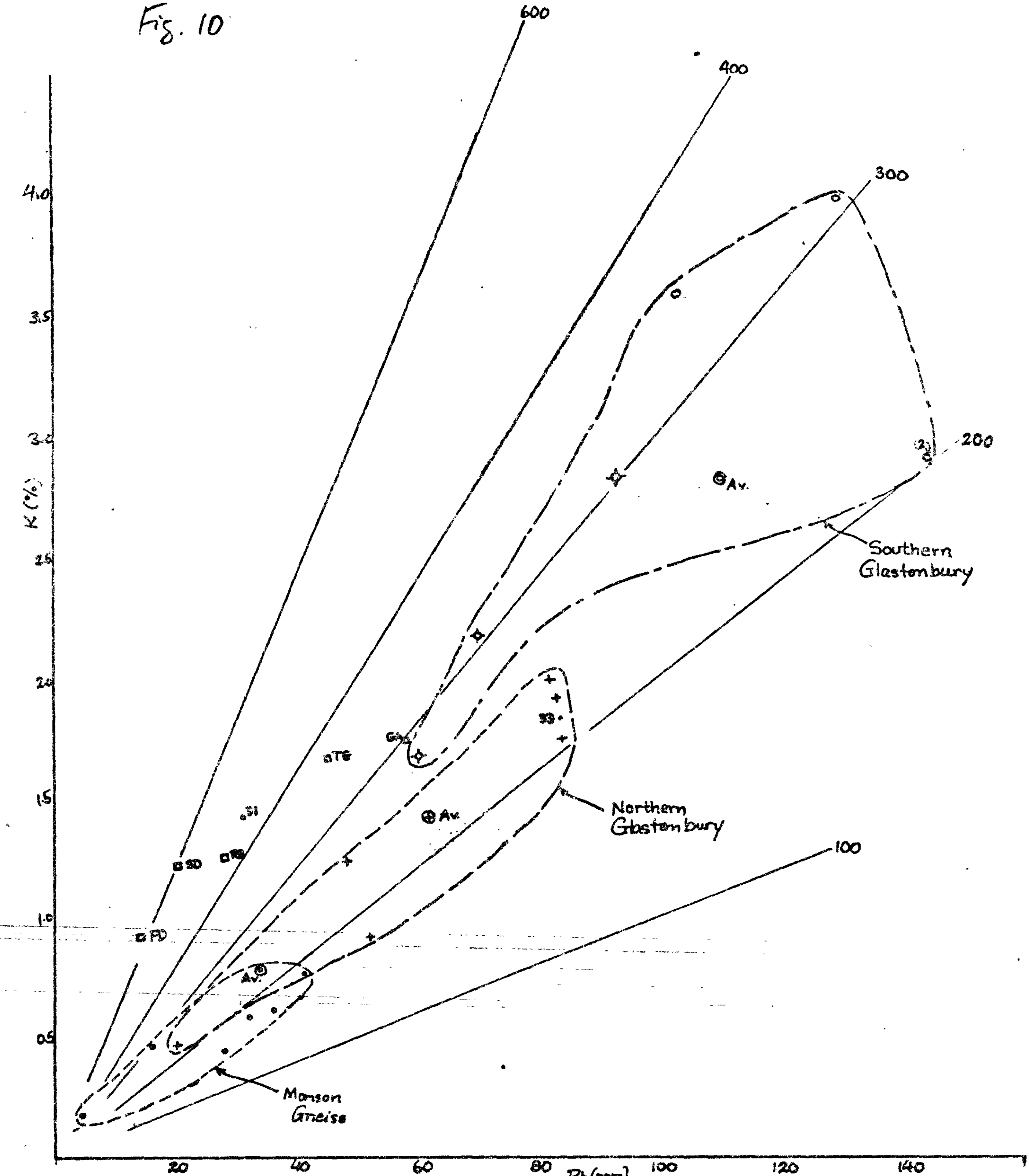
600
400
300
200
100
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
K (%)
20
40
60
80
Rb (ppm)
100
120
140
Av.
Southern Glastonbury
Northern Glastonbury
Monson Gneiss
TG
SI
SD
FD
SG

Fig. 10. K-Rb plot of Glastonbury Gneiss and Monson Gneiss. Notation as follows: • = Monson Gneiss, ⦿ = average; + = northern Glastonbury, ⊕ = average; ○ = hornblende-free southern Glastonbury, ⌖ = hornblende-bearing southern Glastonbury, ◎ = average southern Glastonbury; SD = Saipan dacite, FD = dacite of Fonualei (Bryan and Ewart, 1971, tables 24-25, anal.4), RB = Rio Brazos trondhjemite, TG = Twilight Gneiss (Barker and others, 1976); GA = Graywacke-argillite (Arth and Hanson, 1976, tables 2 and 8). Sloping lines represent K/Rb ratios indicated at ends of lines.

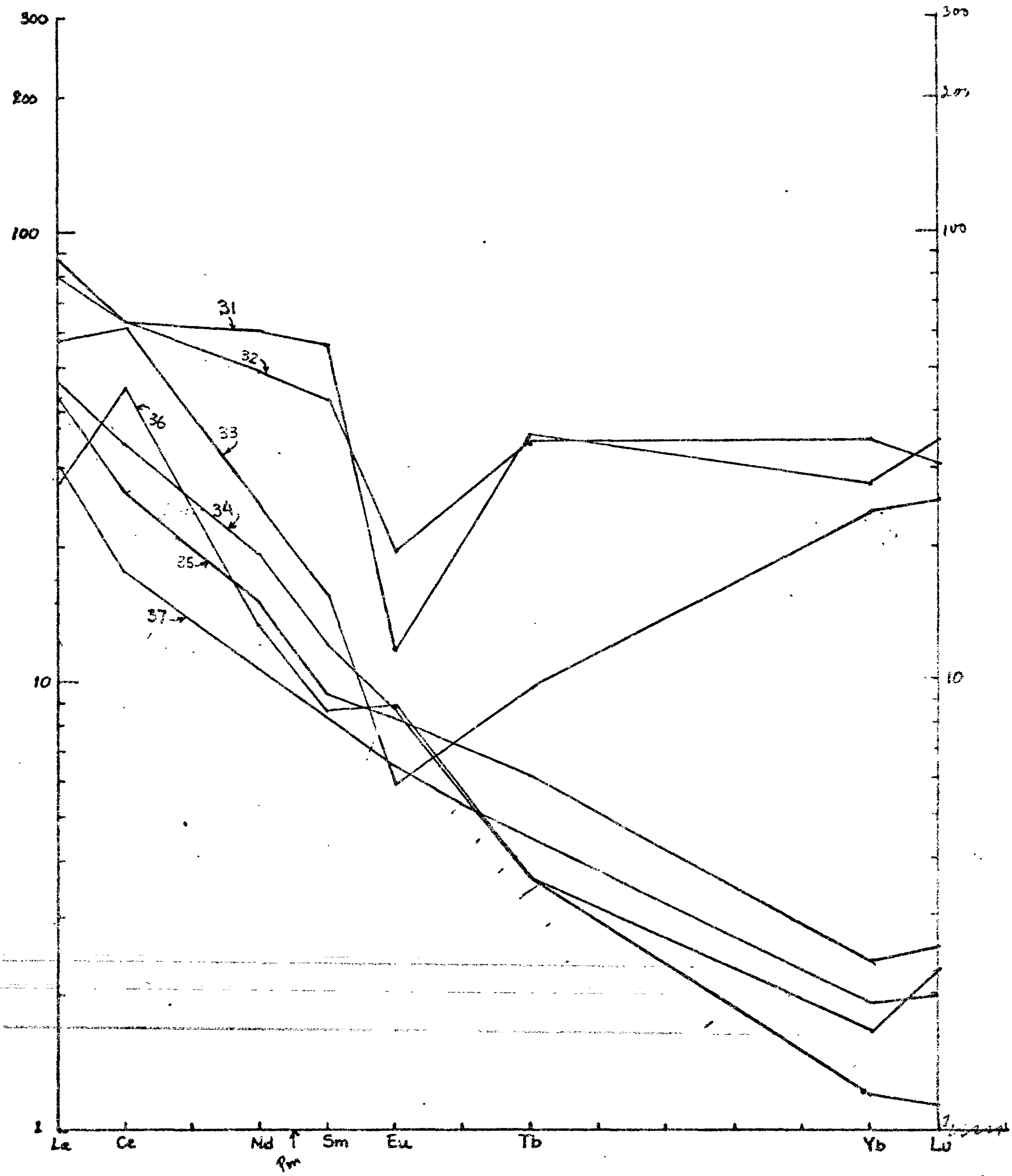

Fig. 11 A. REE patterns of Monson Gneiss. Numbers refer to analyses in table 1.

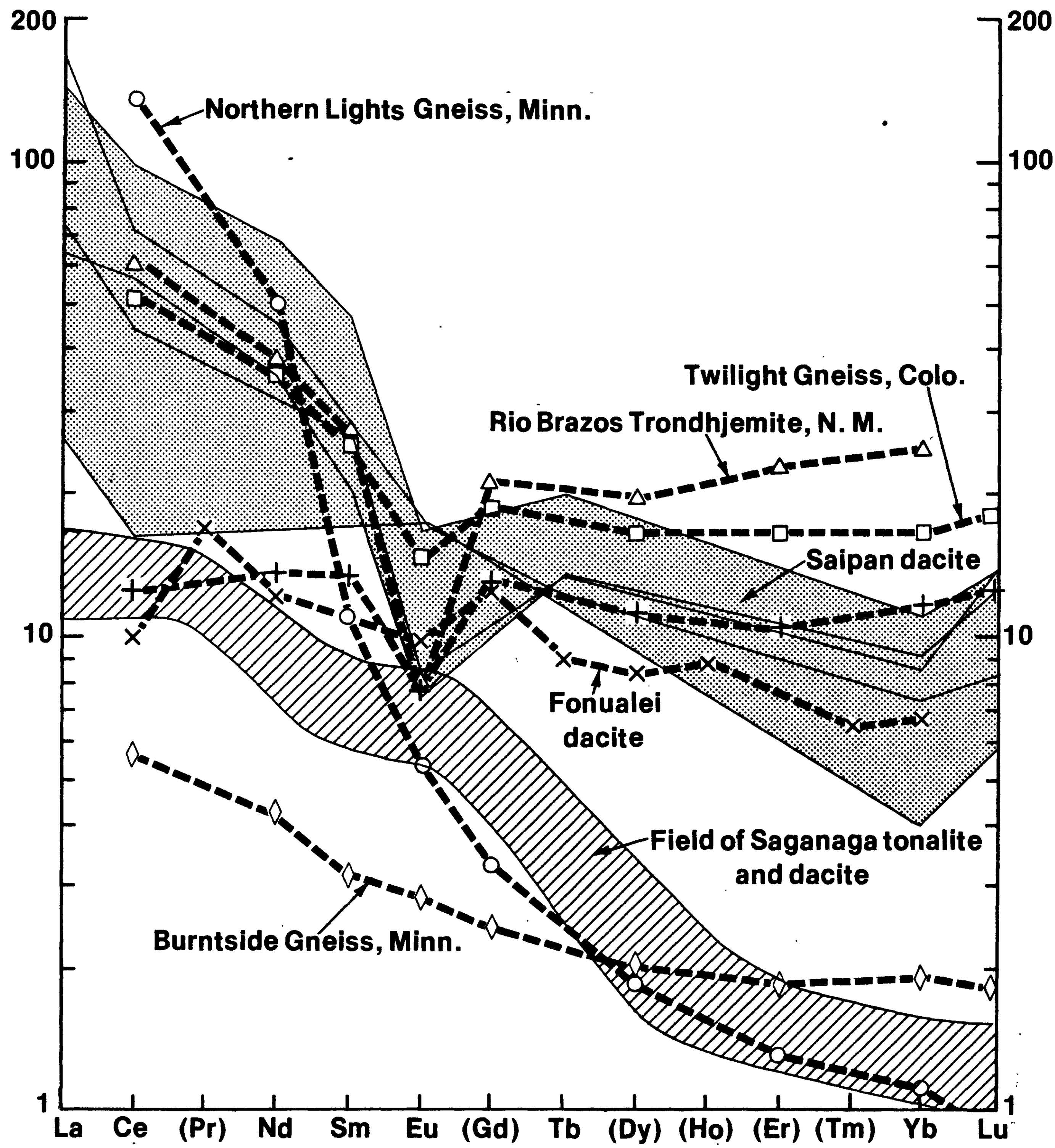
200
100
10
1
200
100
10
1
Northern Lights Gneiss, Minn.
Twilight Gneiss, Colo.
Rio Brazos Trondhjemite, N. M.
Saipan dacite
Fonualei dacite
Field of Saganaga tonalite and dacite
Burntside Gneiss, Minn.
La Ce (Pr) Nd Sm Eu (Gd) Tb (Dy) (Ho) (Er) (Tm) Yb Lu

Fig. 11 B

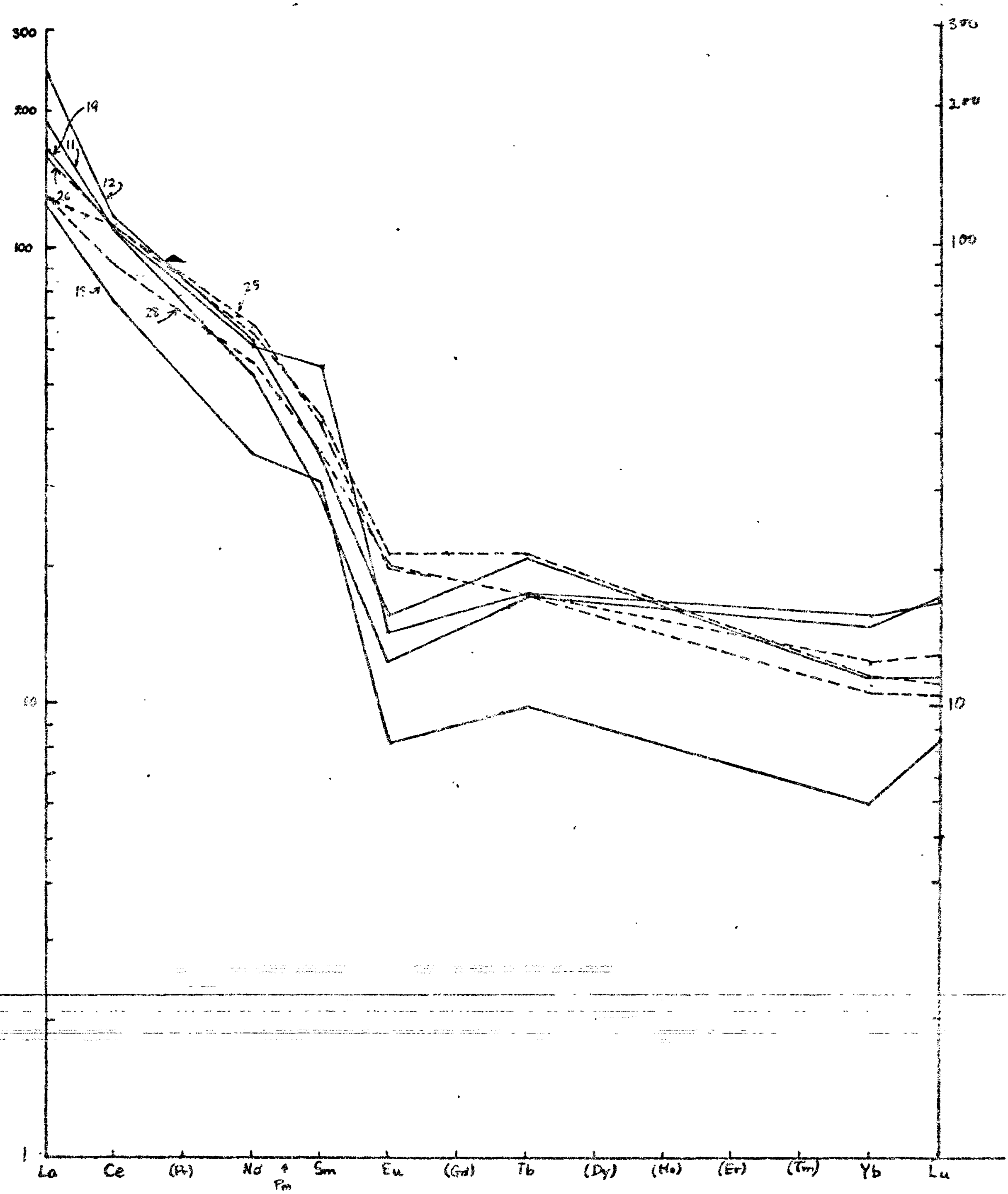

Fig. 11C. REE patterns of southern Glastonbury Gneiss

Fig. 11. Chondrite - normalized rare earth patterns for Glastonbury Gneiss, Monson Gneiss and some trondhjemites and dacites. 11A: Monson Gneiss. Numbers refer to analyses in table 1. 11B: Northern Glastonbury Gneiss (solid lines; numbers refer to analyses in table 1); Δ, Rio Brazos trandhemite, N.M.; □, Twilight Gneiss, Colo; +, Saipan dacite (Barker and others, 1976); x, Fonualei dacite, Tonga (Bryan and Ewart, 1971); O, Northern Lights Gneiss, Minnesota; ◊, Burntside Gneiss, Minnesota; shaded field, Saganaga tonalite and dacite, Minnesota (Arth and Hanson, 1972). 11C: Southern Glastonbury Gneiss; solid lines, hornblende-free gneiss; dashed lines, hornblende-bearing gneiss, Middle Haddam quadrangle (see text). Numbers refer to analyses in table 1.

patterns in fig. 11 are generally comparable with published patterns of similar rocks, and permit some genetic interpretations.

1) Each group shows a moderately to strongly fractionated pattern, with relative enrichment of light REE's and depletion in heavy REE's fairly typical of silicic igneous rocks of crustal origin, although some oceanic rocks, notably alkalic basalts, yield comparable patterns. The overall REE concentration increases in approximate proportion to the K_2O content in the three groups. (A crustal origin for the three gneisses is confirmed by the high $^{87}Sr/^{86}Sr$ ratios).

2) The Monson patterns (fig. 11A) define two distinct trends. One group of analyses (nos. 34-37) has relatively low REE contents and negligible or small positive Eu anomalies. These patterns resemble those of high-Al trondhjemites, tonalites and dacites [1/] (Arth and Barker, 1976); the Al_2O_3 contents of these rocks, in fact, range from 13.7 to 18.4 percent (table 1). The remaining Monson samples (nos. 31-33) have significantly different patterns, with high heavy REE concentrations and negative Eu anomalies; these patterns resemble those of low-Al trondhjemites (Barker and others, 1976) and of graywackes (Arth and Hanson, 1975, fig. 15). The Al_2O_3 contents of the latter 3 samples are between 12.0 and 12.9 percent (table 1). Thus these patterns confirm the distinction between high- and low-alumina types; they seem, further, to reflect a varied provenance for these metamorphosed volcaniclastic rocks.

[1/] Defined as containing more than 15% Al_2O_3 (Barker and others, 1976).

3) The northern Glastonbury patterns (fig. 11B) show considerable scatter but generally have somewhat higher REE contents than Monson Gneiss as well as a negative Eu anomaly. The rare-earth contents generally resemble those of intermediate granitic rocks (Arth and Hanson, 1975, fig. 8), while the form of the curves is comparable to hypothetical partial melts derived from graywacke (Arth and Hanson, 1975, fig. 15). The patterns also resemble those of some low-Al Archean trondhjemites (Barker and others, 1976; see p. 62, this paper). The negative Eu anomaly suggests a plagioclase-rich residue which is to be expected in the course of partial anatexis of graywacke (Winkler, 1974, p. 289-292). In the present case such a residue has, however, not been identified.

The relationship between the REE patterns of the Monson and northern Glastonbury thus do not contradict a partial-melting origin of the latter as proposed on other grounds. However, in view of the scatter of the REE data for these rocks, no attempt was made to test this hypothesis by computer modeling.

4) The southern Glastonbury patterns (fig. 11C) show the highest REE contents, in conformity with the higher potash content of these rocks. The patterns are, moreover, distinctive in defining a relatively narrow field that includes the hornblende-bearing rocks along the southwestern margin of the gneiss body. The relative homogeneity of these rocks revealed by their REE pattenrs, as compared with the Monson and northern Glastonbury, supports the idea that the southern Glastonbury is a differentiated calc-alkaline pluton distinct from the northern gneiss.

Origin of the Glastonbury Gneiss

A petrogenetic interpretation of the Glastonbury gneiss body must be guided by two basic and somewhat conflicting considerations; (1) the assumption, based on stratigraphic and structural relations, that the Glastonbury body is an Oliverian dome, and hence should more or less resemble other Oliverian domes; and (2) the petrology and contact relations of the Glastonbury gneiss, which show some significant differences from typical Oliverian domes (as exemplified by the Mascoma dome).

Contrasts and similarities between the Glastonbury and other Oliverian domes (exemplified by the Mascoma dome, Naylor, 1969) are summarized in table 5. One of the principal differences between the

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Table 5 near here.

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two gneiss bodies is in the contact relationships. In the Mascoma dome, a discrete granitic pluton (unstratified core gneiss) intrudes layered rocks of the dome (stratified core gneiss), which in turn have a gradational contact with overlying Ammonoosuc Volcanics (Naylor, 1969, p. 410). In the Glastonbury body, by contrast, the potash-poor northern gneiss which is compositionally similar to the stratified core gneiss of the Mascoma (fig. 8A) but is unstratified, extensively intrudes the Ammonoosuc; and the more potassic gneiss (analogous to the unstratified core gneiss of the Mascoma) in the southern part of the body may intrude the somewhat younger Collins Hill Formation. A contact between northern and southern gneiss has not been detected. Radiometric ages on the Glastonbury body (fig. 14) likewise fail to establish a clearcut temporal distinction between the northern and southern gneiss. The assumption, made throughout this paper, that the northern and southern gneiss masses represent distinct intrusions is based dominantly on their compositional differences including trace elements.

Table 5. Comparison between the Glastonbury gneiss body and Mascoma dome, N. H.

	Glastonbury Body	Mascoma dome (after Naylor, 1969)
Rock Type I	Northern Glastonbury Gneiss of this paper	Stratified core gneiss
Composition	Inhomogeneous but unstratified felsic gneiss, typically rich in quartz and low in K-feldspar, ubiquitous biotite, muscovite and epidote. Composition variable, mostly ranging from silicic trondhjemite to granodiorite.	Mostly quartz-plagioclase-biotite-epidote gneiss, rare concordant amphibolite layers; K-feldspar scarce or absent. Compositional range from tonalite (incl. trondhjemite) to granodiorite.
Structure and texture	Fine- to medium-grained, inequigranular. Blotchy aggregates of biotite and epidote define weak to strong foliation and (commonly) strong lineation. Flaser structure is typical, compositional layering absent. Locally abundant disk-	Massive layering defined by slight variations in composition and texture, local faint lamination. Weak foliation defined by blotchy biotite aggregates. Upper part of section includes hornblende- and biotite-bearing gneiss and felsite

Table 5. Comparison between the Glastonbury gneiss body and Mascoma dome, N. H.

	Glastonbury Body	Mascoma dome (after Naylor, 1969)
	shaped mafic inclusions, also irregular angular mafic inclusions. Local indications of plastic flow.	layers.
Contact relations	Discordantly intrusive into Ammonoosuc Volcanics along west side of the body; intertonguing intrusive contact with Monson Gneiss SW of Stafford Springs.	Concordant, gradational contact with Ammonoosuc Volcanics over 30 m. interval.
Rock Type II	Southern Glastonbury Gneiss of this paper	Unstratified core gneiss
Composition	Quartz-plagioclase-microcline gneiss with biotite, epidote and traces of muscovite; composition inhomogeneous but generally is granite grading to granodiorite. Hornblende-biotite ~~quartz~~ granodiorite gneiss	Mainly porphyritic quartz monzonite and granite; smaller bodies of fine-grained granite, quartz diorite, and pegmatite.

Table 5. Comparison between the Glastonbury gneiss body and Mascoma dome, N. H.

	Glastonbury Body	Mascoma dome (after Naylor, 1969)
	~~mostly~~ along SW margin, in Middle Haddam quadrangle.	
Structure and texture	Fine-to medium-grained, partly porphyritic; ellipsoidal and/or angular mafic inclusions locally abundant; locally abrupt textural transitions related to shearing or possibly to primary layering, rare elongated mafic septa. Textural variations especially marked along NW side of gneiss body in Glastonbury quadrangle; comparatively homogeneous and equigranular in center and on SE side.	Massive and homogeneous except for some foliation and granulation near margins; generally appears as magmatic pluton.
Contact relations	Contact with northern gneiss probably ~~may be~~ intrusive ~~or gradational or both~~. ~~Concordant and locally abrupt, possibly~~	Quartz diorite cuts stratified core gneiss. Porphyritic granite phase has sharp contact against stratified gneiss,

Table 5. Comparison between the Glastonbury gneiss body and Mascoma dome, N. H.

	Glastonbury Body	Mascoma dome (after Naylor, 1969)
	~~intrusive contact with mafic border gneiss~~, ~~on SW side. Possibly~~ Probably intrudes Collins Hill Formation, in Middle Haddam quadrangle.	but cross-cutting relationship not observed.
Regional metamorphic grade	Kyanite-staurolite zone, evidence of retrogression from sillimanite-muscovite zone.	Andalusite zone (Morgan, 1972).
Radiometric age	Composite whole-rock Rb-Sr isochron age of northern and southern gneiss, 383 ± 41 m.y.; dikes and pegmatites in southern gneiss, 36~~0~~2 ± 10 m.y.	Whole-rock Rb-Sr isochron age of granitic, unstratified core gneiss, 440 ± 40 m.y.; lead-lead zircon age of stratified and unstratified core gneiss, 450 ± 25 m.y.

Another major difference between the two domes is the condition of the core rocks themselves. In the Mascoma dome, intrusive granite and stratified metavolcanic gneiss are unambiguous and clearly separable. Despite the overprint of the Acadian metamorphism, there is no evidence of anatexis, migmatitization, or general "juicing up" (Naylor, 1969, p. 411). By contrast, the compositionally and texturally heterogeneous Glastonbury Gneiss which changes subtly from outcrop to outcrop, yet lacks compositional layering and has an overall massive aspect so distinct from enclosing wall rocks, must have been emplaced in a mushy if not liquid condition, implying a much greater depth of formation and higher pressures and temperatures than those prevailing during formation of the Mascoma and similar Oliverian domes.

Finally, radiometric age determinations (summarized in table 5; see Brookins, this volume) show the Mascoma dome to be Ordovician whereas the Glastonbury Gneiss appears to be Early or early Middle Devonian. This indicates that the Glastonbury was subjected to intense heating with associated Rb-Sr rehomogenization in the Acadian which evidently did not affect the Mascoma Dome. Whether the apparent age of the Glastonbury represents its time of original emplacement or, alternately, the time of heating and partial melting of an original Mascoma-like dome cannot be determined on the basis of available evidence; indeed, perhaps the point is moot.

Concerning these differences and similarities between the Glastonbury and the classical Oliverian domes, several questions thus arise: (1) what were the conditions of formation~~s~~ of the Glastonbury gneiss? (2) can the Monson Gneiss and related rock units be plausibly regarded as the protolith for the Glastonbury? (3) what is the relation between the northern potassium-poor gneiss and the southern granite-granodiorite? ~~(5) is the Glastonbury gneiss body properly regarded as an Oliverian dome?~~ These questions are considered below.

Northern Glastonbury Gneiss

A scheme for the origin of the northern, generally potassium-poor part of the Glastonbury Gneiss must take the following observations into account: (1) the gneiss is intrusive on a large scale, (2) although texturally and compositionally heterogeneous, the gneiss is homogeneous relative to the adjacent Monson Gneiss and Ammonoosuc Volcanics, especially in its lack of consistent compositional layering; and (3) major- and minor-element chemistry of much of the gneiss is comparable with that of low- alumina trandhjemites; (4) its composition shows considerable overlap with Monson Gneiss and the felsic phase of Ammonoosuc Volcanics; it is also comparable to some dacites, marine volcanic sediments and their metamorphic equivalents, and certain volcanogenic graywackes; (5) it has a rather high $^{87}Sr/^{86}Sr$ initial ratio (Brookins, this volume), indicative of crustal origin.

The composition and textures of the gneiss are difficult to reconcile with intrusion of calc-alkaline granitic magma. In contrast the many post-Ordovician granitic plutons throughout New England studied by Chayes (1952) are both exceptionally homogeneous and compositionally close to the granite minimum melt. The Oliverian plutons (figs. 8, 9) show the same tendency.

A metasomatic origin, involving large-scale conversion of Ammonoosuc Volcanics and overlying Siluro-Devonian metasediments in the Ellington quadrangle by "fluids" bearing silica and alkalies was proposed by Collins (1954). However, the writers' observations, supported by recent work in the Ellington quadrangle (M. H. Pease, personal commun., 1973-4) and in the Hampden quadrangle to the north (Peper, in press) tend to invalidate this idea. In particular, large-scale metasomatism of the kind evisaged by Collins is incompatible with the intrusive character of the gneiss, its lack of gradation to adjacent rocks, and the total absence of relict compositional layering.

A more plausible origin for the northern Glastonbury Gneiss is partial anatexis of Monson Gneiss and possibly of underlying units.[1/]

1/ Footnote near here.

Progressive melting of natural rock materials over a range of temperatures, pressures, and water content has been the subject of much recent experimentation, e.g., the work of Winkler and von Platen on graywackes (summarized in Winkler, 1967, p. 208-216) and by Piwinskii and Wyllie (1968, 1970) on granitic rock suites. Winkler and von Platen showed that melts corresponding to granodiorite, tonalite, and trondhjemite may be produced by melting graywacke in the presence of excess water. At P_{H_2O} = 2kb, melting begins in the range 670-705°C depending upon bulk composition, producing a liquid enriched in Q and Or; at 780°C, melting is largely complete, and the liquid composition is near that of the starting materials. Generally similar results were obtained (Winkler, 1974, p. 295-301) using quartz-plagioclase-biotite-(muscovite) gneisses containing no K-feldspar. Fig. 8B shows compositions of two anatectic melts (Winkler, 1974, p. 301) that are not far from northern Glastonbury compositions. Piwinskii and Wyllie (1968) found that, at 2 kb H_2O, melting of granodiorite began at 705°C and was nearly half completed by 730°C, while tonalite began to melt at 725°C and was less than one-third complete at 800°C. Again, the liquid had a bulk composition of granite and crystalline residues were mostly plagioclase and mafic minerals.

1/ In Massachusetts and northern Connecticut, the base of the Monson has not been recognized, and is largely truncated by faults. In the New London area of southern Connecticut the Monson is underlain by the New London Gneiss, the Mamacoke Formation, and the Plainfield Formation (Goldsmith, 1966). The two first-named units are largely of similar composition as the Monson, whereas the Plainfield Formation is metasedimentary, consisting dominantly of quartzite. In the Middle Haddam area, Connecticut, the Monson is underlain by the compositionally similar Haddam Gneiss (Eaton and Rosenfeld, 1972).

Water-saturated systems like the above may have only limited application to anatexis in an open system with an unknown water content. A key question in this regard is the condition of the sedimentary-volcanic sequence (Monson Gneiss and underlying units) at the time of the metamorphism culminating in anatexis. If this event was the first metamorphic episode to affect these rocks, the latter may have contained several percent water (as a basis of comparison, 36 analyses of Ohanapecosh Formation show a range of 0.6 to 5.0 percent H_2O, with a median value of 2.7 percent; R. S. Fiske, unpubl. data). If, on the other hand, the Monson and underlying units were already metamorphosed and largely dehydrated at the time of anatexis, their water content would be substantially less, i.e., it would approximate the present water content. Both possibilities will be considered below.

Assuming an average initial water content of 2.5 percent for the Glastonbury protolith, of which perhaps 0.5 percent represents water bound in hydrous minerals (see Table ~~4~~ 6), 2 percent water remains as

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Table ~~4~~ 6 near here.

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a vapor phase. Such rocks constitute the type III system as defined by Robertson and Wyllie (1971, p. 253), i.e., water-deficient and vapor-present. As in the case of the water-saturated system, melting of a water-saturated liquid begins at the solidus (about 705°C for granodiorite and 725°C for tonalite). In the presence of 2 percent pore water, some 25 percent liquid is produced until, with increasing temperature, the saturation boundary is reached at which point the liquid becomes water-undersaturated; for the natural granodiorite used, this temperature would be approximately 720°C, and for a tonalite, approximately 900°C (Robertson and Wyllie, 1971, fig. 7 and 8). The resulting crystal mush, consisting chiefly of plagioclase, mafic minerals, and any excess quartz in a water-undersaturated granitic liquid could migrate upwards for a considerable distance through the crust "without excessive crystallization until the load pressure is decreased to a level approaching the water pressure in the undersaturated liquid: (Robertson and Wyllie, 1971, p. 271). Assuming incomplete homogenization in such a mush, the resulting intrusive rock ~~could~~ might well be texturally ~~as well as a~~ and compositionally similar to the Glastonbury Gneiss prior to its subsequent (late Acadian) recrystallization.

Table 6. Estimated content of pore water, Monson Gneiss

Col. No. (from table 1)	29	30	32	33	34	35	36	37
Sample No.	212	768	807	M-CC	A-14	MQ-2	P8-270	P8-272
Mica content	7.4	10.0	19.0	6.4	1.9	7.0	7.8	8.5
Water in micas	0.33	0.45	0.85	0.29	0.01	0.31	0.35	0.38
Hornblende content	--	--	--	--	--	6.3	--	3.9
Water in hornblende	--	--	--	--	--	0.12	--	0.08
Total bound water	0.33	0.45	0.85	0.29	0.01	0.43	0.35	0.47
Water in analysis	0.54	0.65	1.0	0.54	0.43	0.71	0.84	0.81
Estimated pore water	0.2	0.2	0.2	0.3	0.4	0.3	0.5	0.3

Water content of minerals determined on basis of 4.5% H_2O in muscovite and biotite, 2.0% in hornblende. Estimated pore water = difference between water in analysis and water in hydrous minerals.

Sample 74 GWL 358-1 (col. 31, table 1) not included because water not determined. Mineral contents in volume percent, water contents in weight percent; difference between weight and volume percent for minerals neglected.

The limiting case of a fully dehydrated gneiss protolith for the Glastonbury is most readily considered by using the actual Monson compositions (table 1, cols. 29-37; table 6). Table 6 indicates an excess of water over that estimated to be bound in micas and hornblende ranging between 0.2 and 0.5 percent; this excess is regarded as pore water. This amount of pore water, in turn, would suffice for some 3 to 7 percent granitic melt--possibly too little to lubricate a crystal mush for any significant upward migration. The mechanism obviously is more plausible with a larger amount of water. Breakdown of hydrous mineral phases, mostly biotite and muscovite, could contribute to a vapor phase (cf. Lundgren, 1966, esp. p. 446-450; Winkler, 1974, p. 295-301), which would increase the proportion of melt. ~~However, the resulting rocks should be granulite-facies, which is not the case, hence it is unlikely that micas were a significant source of water.~~ The implications of micas as a source of water are discussed in the following section.

The discussion thus far has been based mostly upon phase relations at 2 kb, but the ambient pressure during anatexis certainly would have been higher than this. Indeed, consideration of pressures compatible with melting temperatures--approximately 700° to 850°C in a water-undersaturated system-- of the proposed model indicates that, assuming a thermal gradient of 20° to 30°C/Km and straddling the sillimanite-kyanite equilibrium boundary (Brown and Fyfe, 1970, p. 314, fig. 2) the corresponding pressure range is approximately 7-10 kb, equivalent to a depth of 26 to 38 km. These estimates of temperature and pressure exceed estimates based on aluminosilicate polymorph relations (Robinson, 1966) and on garnet zoning (Tracy and others, 1976).

The latter technique indicates a northwest to southeast temperature gradient between Orange and Ware, Mass. (fig. 1; Tracy and others, 1976, fig. 1) of approx. 580°-700°C and pressures in the range of 5-7 Kb.--conditions insufficient to account for anatexis of the northern Glastonbury Gneiss. However, eastward of the axis of the Glastonbury body the metamorphic grade rises to sillimanite-orthoclase within a few kilometers (Morgan, 1972), and the Monson Gneiss itself is largely sillimanite-orthoclase grade (P. Robinson and J. D. Peper, oral commun., 1977). Thus the present axis of the Monson Gneiss provides a plausible locus of the anatexis as envisioned; this implies some westward flow of the postulated crystal mush prior to its emplacement as northern Glastonbury.

It is also possible, although unprovable, that a higher heat flow prevailed during the early Acadian than the 20-30°C/Km assumed above. Some modern heat-flow determinations support this idea. Birch, Roy and Decker (1968) reported heat flow as high as 2.2 cal/cm^2 from the white Mountains (Conway Granite) of New Hampshire, which corresponds to a thermal gradient of approximately 60°C/Km, and gradients in excess of 80°C/Km have been reported from the Carpathians in Hungary (Boldizsar, 1965). A gradient of 60°C/Km in the case under discussion would produce the required temperatures at a depth of some 15 Km. Also, the possibility cannot be ruled out that Precambrian rocks at greater depth were involved in the postulated anatexis.

The possibility may be considered that, instead of being of anatectic origin, the northern Glastonbury may simply represent the product of a primary magma in a volcanic pile which has risen to intrude its extrusive cover (Ammonoosuc Volcanics).

If the field evidence (flowage structures in Monson Gneiss) and unusual composition (high silica content and irregular variations over short distances) which has been cited in support of anatexis are not considered compelling, a magmatic origin certainly cannot be ruled out; indeed, this hypothesis, with less constraints on depth of formation circumvents the problem of explaining the high P-T conditions at relatively shallow depths required by the anatectic model. However, the problem may be merely turned around, since a hypothetical northern Glastonbury magma would have had to be very hot, perhaps 1000°C (e.g., Piwinskii and Wyllie, 1968, fig. 11), which in turn would require improbably great depths (possibly 100 Km in a continental environment). Moreover, it appears fortuitous that two such disparate and seemingly unrelated magmas as the southern and hypothetical northern Glastonbury should develop at about the same time and, of necessity, in distinct chambers.

Whichever of the above models for the northern Glastonbury is closer to the truth, its composition, trace element assemblage and Rb-Sr isotopic data (Brookins, this volume; fig. 12, 14) place definite constraints on its genetic environment.

The chemical resemblance of the Ammonoosuc, Monson, and northern Glastonbury to eugeosynclinal volcanics has already been discussed (p. 33-34 and Fig. 8A). The low potassium content, moreover, resembles that of trondhjemites; this association will be further explored in the following section. As pointed out earlier, composition and structures of the layered rocks of the mid-Ordovician sequence--Monson Gneiss, Ammonoosuc Volcanics, and Partridge Formation-- are indicative of a largely detrital origin, with subordinate flows and intrusive components (?). Such an assemblage ~~appears~~ may be compatible with an ensialic island arc (exogeosyncline as used by Bird and Dewey, 1970, p. 1048).

The development of Cambro-Ordovician island area along broad belts in New England including the present axis of the Bronson Hill anticlinorium was recognized 30 years ago (Kay, 1948) and has been elaborated by Bird and Dewey (1970) in the context of plate tectonic theory. According to ~~the latter~~ Bird and Dewey's formulation, the Oliverian ~~dawes~~ domes with their volcanic cover constitute an ancient island arc along the southeast piedmont margin of their mobile zone A with a subduction zone to the southeast related to the Ordovician closing of the proto-Atlantic ocean (Bird and Dewey, 1970, p. 1047-48, fig. 9).

The data here presented on the Glastonbury Gneiss and mantling rocks is partly but not wholly compatible with such a lithologic-tectonic environment. Potassium-poor dacites with compositions comparable to the Monson and northern Glastonbury are fairly common in island-arc environments, although such rocks may show genetically important distinctions based on trace-element contents (and/or Rb-Sr isotope data). By way of example, two unmetamorphosed dacites from modern island arcs, the Saipan dacite (Schmidt, 1957; Barker and others, 1976) and dacite from Fonualei Island, Tonga (Bryon and Ewart, 1971) have superficially similar compositions to the Monson-northern Glastonbury (fig. 8B), but they have lower Rb contents (fig. 10) and flatter, less fractionated REE patterns (fig. 11B). Both of these features suggest that these dacites originated from mafic rocks of the lower crust or upper mantle, either by fractional crystallization or by partial melting. The northern Glastonbury, by contrast, with its strongly fractionated REE patterns, is much more likely to have originated in the upper crust. This is further borne out by the high $^{87}Sr/^{86}Sr$ initial ratios; fig. 12 indicates that Glastonbury and Monson fall into the field of felsic volcanic rocks. In the context of the proposed island arc

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Fig. 12 near here

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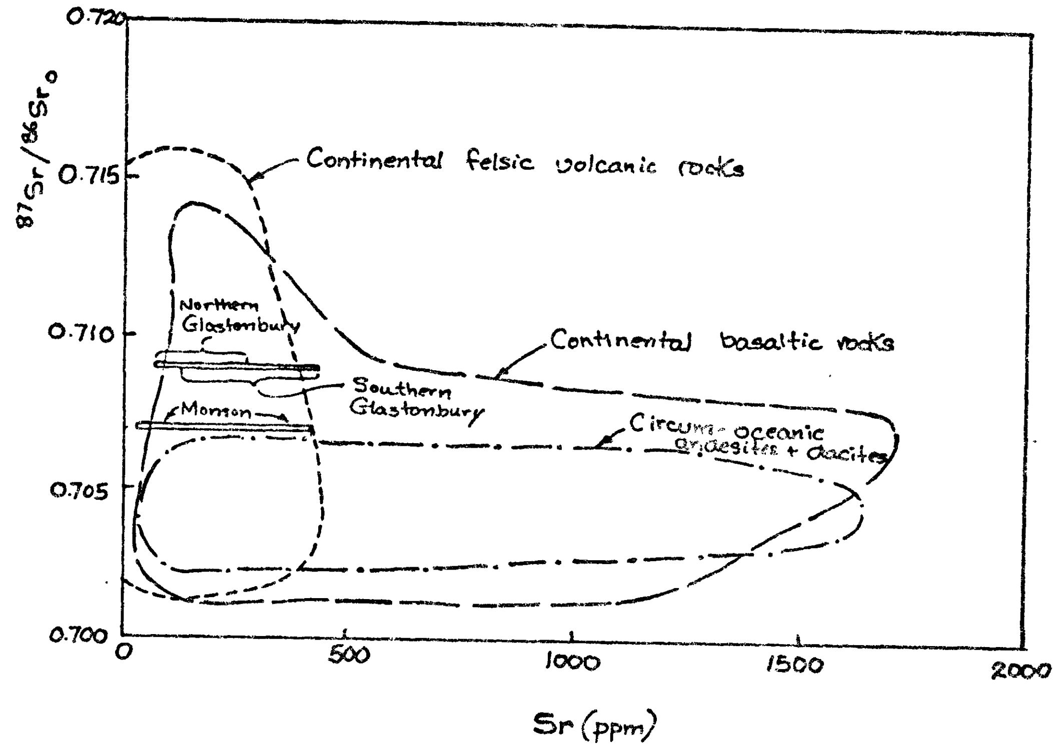
origin of the Ordovician volcanic sequence, this probably reflects the contribution of the piedmont crust overlying the subduction zone to the volcanic rocks, either by contamination or by admixture of detritus from an erosion surface or both.

Fig 12.A



0.720
0.715
0.710
0.705
0.700
$^{87}Sr/^{86}Sr_o$
0
500
1000
1500
2000
Sr (ppm)
Continental felsic volcanic rocks
Continental basaltic rocks
Northern Glastonbury
Southern Glastonbury
Monson
Circum-oceanic andesites + dacites

(table 4)

Fig. 12A/ Plot of $^{87}Sr/^{86}Sr_o$ against Sr, showing Monson and Gastonbury Gueisses in relation to continental and circum-oceanic volcanic rocks (adapted from Faure and Powell, 1972, fig. IV. 1.)

The Bronson Hill volcanic rocks, however, differ in the fundamental respect from most island arcs, i.e., the apparent scarcity of andesitic rocks which commonly far outweigh dacites, rhyolites, or basalts (Carmichael and others, 1974, p. 528-530). Some of the amphibolite of the Ammonoosuc volcanics (and to a lesser extent of the Monson Gneiss) may be andesitic, but it is more likely to be basaltic, and in any case mafic rocks are quite subordinate in the overall sequence. A more comprehensive study of compositions of the ~~composition of the~~ metavolcanic rocks related to their relative volumes would be required to properly assess the analogy between this mid-Ordovician volcanigenic assemblage and present-day island arcs.

Effect of mid-Acadian metamorphism
~~Metamorphism of the Glastonbury Gneiss~~

Textures, fabric and mineral assemblages of the Glastonbury Gneiss indicate thorough recrystallization at intermediate metamorphic grade that reflect the regional Acadian metamorphism. Although critical assemblages are lacking in the Glastonbury itself, the ubiquitous plagioclase (oligoclase-andesine)-epidote pair is compatible with lower to middle amphibolite facies; in flanking pelitic rocks of the Lower Devonian Erving Formation the assemblage staurolite-kyanite-garnet, with relict sillimanite armored by garnet, was observed (Leo and others, 1977). According to the scheme of Tracy and others (1976) this assemblage suggests a temperature range of approx. 580°-630°C at 5-6 Kbars.

The contrast between this metamorphic environment and the much higher P-T conditions portulated as necessary for anatexis of the northern Glastonbury Gneiss raises questions which can be answered only speculatively. The question of a plausible locus of anatexis has already been discussed. At the temperatures, earlier estimated as 700°-850°C, required to produce a partial melt, both muscovite and biotite (by far the more abundant phase in Monson Gneiss-see table 1) would begin to break down (Evans, 1965; Winkler, 1974, p. 300 ~~Wones and Eugster, 1965)~~. The resulting residual rocks would be granulite-facies; such rocks have not been specifically identified in the present context, but the sillimanite-orthoclase isograd east of the Monson anticline has been reasonably well established (Morgan, 1972; Lundgren, 1966, fig. 1). The palingenetic crystal mush, meanwhile, may be assumed to have remained a closed system and to have retained most of its water during its migration upwards and westwards (?) through the crust. The water content of Monson Gneiss and northern Glastonbury is, in any case, quite similar (table 1). The micas in the present Glastonbury are part of the metamorphic mineral assemblage produced by pervasive recrystallization following its intrusion.

Given the radiometric age data on the Glastonbury, it is necessary to assume that metamorphism followed rather quickly upon intrusion; indeed, the two processes quite likely were continuous, recrystallization taking place in response to regional stresses at the lower temperatures discussed above. Nevertheless, the large margin of error on the radiometric age permits the supposition that the "true" age of intrusion of the northern Glastonbury is somewhat greater than 383--perhaps about 400 m.y. Such an intrusive age, corresponding to early Acadian, is in accord with regional geologic relationships, in particular the seemingly accurate m.y. age determination on the Belchertown pluton (380 ± 5 m.y.) combined with the structural-metamorphic relationship of the Belchertown to the northern Glastonbury.

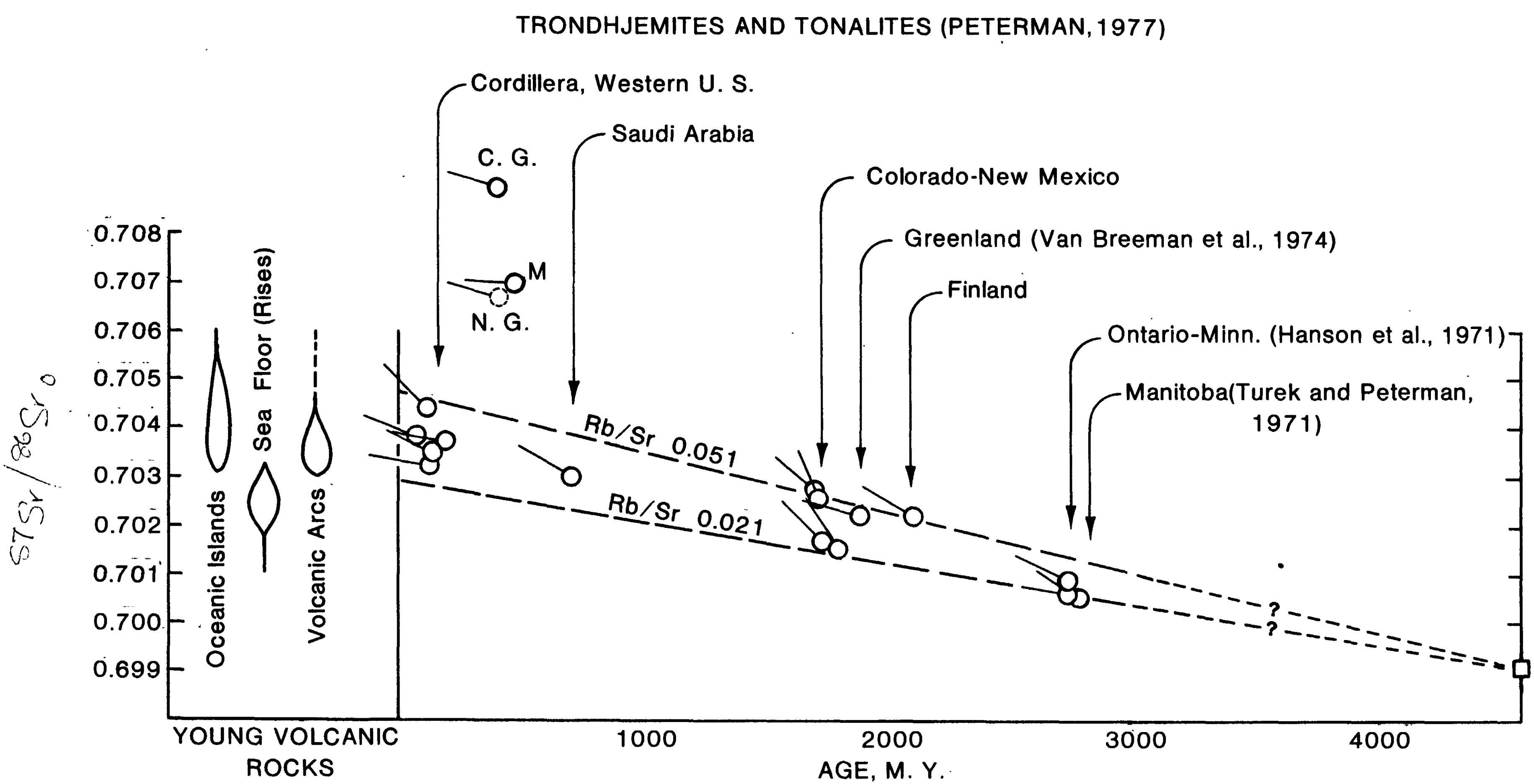
The postulated anatectic origin for the northern Glastonbury Gneiss represents a different mechanism for producing trondhjemite-like rocks. The derivation of the Glanstonbury trondhjemite from granitic melt as a minor component of a crystal mush rich in plagioclase and quartz differs fundamentally from processes leading to production of trondhjemite magma from mafic and ultramafic rocks. The two types of trondhjemite are similar in their mineralogy and major elements but may differ significantly in trace elements and consistently differ in Sr isotopic ratios. Figure 11B shows that the low- Al Twilight Gneiss and Rio Brazos Trondhjemite (Barker and others, 1976) have REE patterns generally similar to the northern Glastonbury; trondhjemites from northeastern Minnesota, by contrast (Arth and Hanson, 1972, 1975) have variable patterns, generally highly depleted in heavy REE and with a negligible Eu anomaly as is typical of high-Al trondhjemites (Barker and Arth, 1976). Clearly, therefore, the northern Glastonbury REE patterns primarily reflect overall composition, not origin, as do the Monson patterns (fig. 11A). The $^{87}Sr/^{86}Sr$ initial ratios, however, provide a more consistent picture. $^{87}Sr/^{86}Sr$ initial ratios in Archaean trondhjemites are invariably under 0.703 and commonly under 01701 (Barker and others, 1976; Arth, 1976), whereas initial $^{87}Sr/^{86}Sr$ ratios for the Monson and Glastonbury are 0.707 ± 0.002 and 0.7093 ± 0.0010 , respectively (Brookins, this volume, table 7 and fig. 14); as mentioned earlier, such high initial ratios suggest a reworked source of crustal origin.

Fig 12B near here

This point is emphasized by Fig. 12B, which indicates that initial $^{87}Sr/^{86}Sr$ ratios for Monson and Glastonbury Gneiss fall well above the rather narrow band of $^{87}Sr/^{86}Sr$ initial ratio vs. age which defines trondhjemites of presumed mantle origin. This is true even for the hypothetical northern Glastonbury initial ratio of 0.7066 from fig. 14 (NG on fig. 12B) as well as for the composite Glastonbury initial ratio (CG on fig. 12B). In other words, the lowest initial ratio for northern Glastonbury based on present data is distinctly higher than that of other trondhjemites and falls within the crustal range. Two points should be made in this connection: 1) the NG point on Fig. 12B is in a much more reasonable position than CG in terms of possible ~~evaluation~~ evolution from Monson Gneiss (M), even though the initial ratio for the northern Glastonbury should be slightly higher, not lower, than that of the Monson. The relative positions of the NG and M points thus seem to support the validity of a distinct northern Glastonbury isochron with a lower initial ratio than the composite ratio of 0.7093. Greater refinement of the Monson and northern Glastonbury isochrons and initial ratios, however, would be required to confirm an ~~evaluationary~~ evolutionary relationship between them; and 2) the high degree of scatter in the Rb-Sr data (fig. 14), referred to earlier in connection with the uncertainty in the apparent Glastonbury age, similarly affects the uncertainty in initial ratios, so that at the 95 percent (2σ) confidence level the possible downward variation for the NG point (fig. 21B) would actually extend into the band defining the other trondhjemites (about 0.703). For the present it is fair to state that the Glastonbury initial ratios appear to be significantly higher than trondhjemite ratios, and that a crustal origin for both the northern and southern Glastonbury is suggested by the data.

66E (66C follows)

Fig. 12 B



TRONDHJEMITES AND TONALITES (PETERMAN, 1977)
Cordillera, Western U. S.
Saudi Arabia
C. G.
M
N. G.
Colorado-New Mexico
Greenland (Van Breeman et al., 1974)
Finland
Ontario-Minn. (Hanson et al., 1971)
Manitoba(Turek and Peterman, 1971)
Rb/Sr 0.051
Rb/Sr 0.021
?
?
0.708
0.707
0.706
0.705
0.704
0.703
0.702
0.701
0.700
0.699
Oceanic Islands
Sea Floor (Rises)
Volcanic Arcs
YOUNG VOLCANIC ROCKS
1000
2000
3000
4000
AGE, M. Y.

66C

Fig. 12 B. Initial $^{87}Sr/^{86}Sr$ ratios of trondhjemites and tonalites related to whole-rock Rb-Sr isochron ages (data of Zell Peterman, 1977, written commun.). Data not referenced are unpublished. CG = composite Glanstonbury, NG = northern Glastonbury, M = Monson Gneiss (see text for discussion). The tails on the points indicate growth rates of $^{87}Sr/^{86}Sr$ as a function of the average Rb/Sr ratios of the particular unit.

The Glastonbury type of trondhjemite, which should perhaps be referred to as pseudotrondhjemite, may be fairly common in crystalline basement terrains. Such trondhjemites have probably not always been recognized because of the frequent failure, especially in older literature, to distinguish between igneous or metaigneous rocks and paragneisses. A case in point is the Relay quartz diorite of Hopson (Hopson (1964, p. 155-160)) which plots within or close to the trondhjemite field (fig. 8). Hopson (1964) regarded this rock as a locally albitized and silicified differentiate of the Baltimore Gabbro. This interpretation was disputed by Higgins (1972), who considered the Relay rocks to be of volcanic-sedimentary origin, and correlates them with the widespread Cambro-Ordovician James Run Formation in the southeast Maryland Piedmont.

"Oligoclase granite", compositionally trondhjemite, is reported from North Stonington, Conn. (Loughlin, 1912), this rock is now regarded as a late differentiate of Preston gabbro (Walker & Sclar, 1976). A single analysis of Williamsburg Granodiorite (Emerson, 1917, p. 253-254), an extensive pluton of Carboniferous (?) age (Willard, 1956) in central Massachusetts is trondhjemite.

The two analyses of trondhjemite reported by Hadley (1942) have been referred to. The sample from the margin of the Mascoma dome is likely to be a gneiss of sedimentary-volcanic origin, equivalent to felsic Ammonoosuc or Monson. The sample from Smarts Mountain, on the other hand, may be representative of the inner, unstratified(?) core of the Smarts Mountain dome, but this is uncertain because of the limited exposure in the area.

Southern Glastonbury Gneiss

The differences between the northern and southern Glastonbury Gneiss (primarily the higher potassium content, more "granitic" character, and internal differentiation of the southern gneiss relative to the northern) point to differences in origin of the two phases of the Glastonbury body. At least two possibilities must be considered: 1) the southern gneiss essentially is a continuation of the northern gneiss, but was produced by anatexis of a more calc-alkaline protolith (this implies that the Monson Gneiss and (or) some of the underlying units become more potassic southwards from central Connecticut); 2) the southern Glastonbury is analogous to the unstratified core gneiss of the Mascoma dome, i.e., it is a separate intrusion which rose from a magma chamber spatially separated from the low-potassium rocks to the north. A third alternative, that the southern Glastonbury rocks were formed by alkali metasomatism of flanking schists and metavolcanics has been proposed by several earlier workers, notably Herz (1955).

Regarding the first alternative, there is no record of significant portions of the Monson Geniss or underlying startified rocks having the composition of granite. These rocks adjacent to the southern part of the Glastonbury body are described mostly as volcanogenic, micaceous quartz-plagioclase gneisses much like the Monson north along strike (Herz, 1955; Goldsmith, 1966; Snyder, 1970; Lundgren and others, 1971; Eaton and Rosenfeld, 1972). On the basis of the proposed anatectic model for the northern Glastonbury gneiss it appears unlikely that partial melting of Monson composition could produce a granitic mass the size of the southern Glastonbury Gneiss.

However, the possibility of a deep-seated, unrecognized granitic protolith which could have produced the southern Glastonbury magma must certainly be considered. The data in Table 3 and figs. 10-12 indicate that the trace-element suites of the northern and southern Glastonbury Gneiss are generally similar; the differences which do exist between the two are consistent with the higher potassium content of the southern gneiss. The $^{87}Sr/^{86}Sr$ initial ratio, moreover, is now regarded as being the same for both parts of the gneiss (fig. 14). These similarities indicate that, although the southern gneiss is unlikely to have been produced by differentiation of the northern gneiss, nevertheless the two parts of the gneiss body evolved from a geochemically similar crust. Given the granitic composition of the southern gneiss, a magma of this composition would have been largely liquid under the P-T conditions required to produce the postulated crystal mush which became the northern gneiss.

A possible protolith for the souther gneiss is suggested by the Sterling plutonic group in the core of the Willimantic Dome (fig. 1) and farther east. These rocks are compositionally granite to granodiorite; moreover, they appear to be older than the overlying stratified volcanic-metasedimentary sequence (R. Goldsmith, oral commun., 1977). Although Sterling-type rocks have not been recognized along the Bronson Hill anticlinorium, it is reasonable to postulate that such granites could be present there at depth.

~~The second interpretation, that~~ A magmatic origin of the southern gneiss ~~represents a distinct calc-alkaline intrusion,~~ is consistent with the comparatively homogeneous granitic composition of much of this gneiss, but is somewhat difficult to reconcile with the marked and locally abrupt variations in texture and grain size, and local hints of compositional banding, mostly on the ~~north~~ southwest side of the gneiss body. Some of these features might have been produced by intense shearing or other deformation during and after emplacement; but possibly could be primary sedimentary structures in granitized metasediments. Throughout much of its extent, however, the southern Glastonbury is so massive and homogeneous, save for the pervasive Acadian foliation and/or lineation, that an origin by crystallization of a largely liquid magma appears reasonable.

The well-foliated hornblende-bearing gneiss along the ~~north~~ southwest side of the Glastonbury body differs from any of the northern Glastonbury gneiss in that it has a more normal calc-alkaline composition compared to the trondhjemite which is the most mafic type in the north (table 1, no. 10). Its position on a calc-alkaline differentiation trend with felsic southern gneiss (fig. 9, 10) and similar REE abundances (fig. 10) strongly suggests that the hornblende-bearing gneiss is an early differentiate of the southern Glastonbury.

Herz (1955) envisioned a complex origin for the Glastonbury gneiss in the Glastonbury quadrangle involving metasomatic replacement of pre-existing metasediments of the Bolton schist along an axis parallel to the length of the dome, and cataclasis by Triassic faulting to produce the finer-grained rocks ("schistose facies" of Herz, 1955) along the northwest side. Herz's interpretation rests on the assumption that "Bolton schist" and related rocks equivalent to Littleton, Fitch, and Clough Formations of New Hampshire (Rodgers, Gates, and Rosenfeld, 1959) formed an anticline over the Glastonbury, and that relict sedimentary features of these rocks can be discerned throughout the Glastonbury Gneiss. As discussed earlier, such structures are relatively uncommon, and are not necessarily primary. Recent regional structural interpretations, moreover, show that the arenaceous to pelitic Bolton-type rocks are not antiformal over the Glastonbury; instead, rocks intruded by the Glastonbury more likely were Ammonoosuc or Collins Hill, which because of their more mafic composition might be less readily and pervasively granititized than the Bolton-Littleton lithology. As there is no evidence of such large-scale replacement of Ammonoosuc or Collins Hill elsewhere, it appears unlikely in the Glastonbury area.

Herz (1955) cited the abundant pegmatites along a west-central axis of the Glastonbury body as further evidence for metasomatism. An Rb-Sr isochron age on some of these pegmatites (Brookins, this volume) ~~is~~ 362 $\pm$.10 m.y. In view of the 383 $\pm$ 41 m.y. age determined for the Glastonbury body, the pegmatites could represent late Acadian mobilization of the southern Glastonbury itself.

Summary and conclusions

The sum of observations on the Glastonbury gneiss body leads to the following conclusions regarding its origin:

1) The northern part of the body, a potash-poor, silica-rich gneiss partly of trondhjemitic composition, may have originated by anatexis of Monson Gneiss and underlying lower Paleozoic rocks; conceivably the Precambrian crust also was involved. Anatexis produced a water-unsaturated crystal mush which rose (or migrated laterally) to intrude Ammonoosuc Volcanics and overlying Partridge Schist. An anatectic origin from reworked crustal rocks is supported by trace-element (especially REE) data and (and, to some extent, by) $^{87}Sr/^{86}Sr$ initial ratios. Crystallization of the northern Glastonbury from a largely liquid magma is considered unlikely because of the excessively high temperature required for a melt of that composition.

2) Field and chemical evidence suggest that the southern part of the gneiss body is a moderately differentiated calc-alkaline pluton, which evidently originated from a portion of the crust that was more potassic than the northern Glastonbury (and Monson Geniss) but otherwise was geochemically similar. A possible protolith for the southern Glastonbury is deep-seated granitic rocks equivalent to the Sterling plutonic group to the east. Though more homogeneous and less intensely foliated than the northern gneiss, the southern rocks nevertheless show distinct signs of pervasive recrystallization. The southern gneiss appears to intrude the Collins Hill Formation (middle Ordovician); its relationship to the Silurian Clough Formation has not been observed but the new radiometric age data suggest that the age is post-Clough.

3) The locus of the Glastonbury body in an Ordovician island arc flanked by a northwest-dipping subduction zone (Bird and Dewey, 1970) is compatible with the ensialic nature and high $^{87}Sr/^{86}Sr$ initial ratio of the entire Glastonbury and the silicic, potassium-poor composition of the northern Glastonbury on the assumption that a thick wedge of crustal rocks contributed to the Ordovician volcanic sequence, by voluminous detritus or by contamination of magma rising above the subduction zone, probably by both.

4) Rb-Sr whole-rock age determinations show much scatter, reflecting disturbance of Rb-Sr systematics (Brookins, this volume). Data points for the northern and southern parts of the gneiss are not distinctly separated, and a composite isochron yields an apparent date of 383$\pm$ 41 m.y. From this one can conclude that intrusion of all of the Glastonbury was during the early (?) Acadian; in view of the large uncertainty in the age the possibility is not ruled out that the age of intrusion of the southern gneiss is somewhat younger than that of the northern as suggested by field relations. (p.69 continues w/o paragraph)

An effective minimum age, moreover, is imposed on the northern Glastonbury Gneiss by a 380± 5 m.y. zircon age on the Belchertown pluton (Leo and others, in press) which both deforms the north end of the Glastonbury body and has been much less intensely metamorphosed than the latter.

Given these time relationships one must conclude that most if not all of the thermal and tectonic events producing the Glastonbury Gneiss--anatexis and intrusion of the northern gneiss, intrusion of the southern gneiss, deformation, and thorough recrystallization at kyanite grade--took place in the approximate interval 400-350 m.y. B.P., i.e., ~~in~~ the Acadian. This conclusion appears equally valid regardless of whether the Glastonbury already was a dome-like structure mantled by Ammonoosuc Volcanics, analogous to the Mascoma and other Oliverian domes, in pre-Acadian time or whether it was not. The record of Ordovician (Taconic) events within the Glastonbury Gneiss has been effectively obliterated, although detailed structural studies might provide some clues to pre-Acadian conditions. In the present context the significant point is the contrast between the intense, early-Acadian thermotectonic disturbance of the Glastonbury and the virtual absence of ~~such effects~~ of Mascoma rocks during the same period, ~~and all that this~~ implies regarding deeper burial, greater heat flow, and more intense tectonism some 200 km south along the Bronson Hill anticlinorium.

The rapid evolution of the Bronson Hill anticlinorium southwards from central Massachusetts in Early to Early Middle Devonian time, marked by deposition and burial of thousands meters of sediments, the onset of metamorphism, and the piling up of nappes is well established (Thompson and others, 1968; Naylor, 1971). This is certainly the most plausible period during the entire Paleozoic for the elevated P-T conditions implied especially by the genesis of the northern Glastonbury magma. Moreover, abundant evidence of intrusive activity around 380 m.y. B.P. has by now accumulated (Naylor, 1970, 1971; Moench and Zartman, 1976; Leo and others, in press). Thus the Glastonbury Gneiss is but one of a series of intrusive complexes emplaced near the climax of the Acadian orogeny. Somewhat younger ages, in the 365-350 m.y. range, determined for a large number of volcanic rocks, granitic plutons and minor intrusions (Lyons and Faul, 1968) including possible dikes cutting the southern Glastonbury (Brookins, this volume) are traditionally regarded as Acadian. A recent K-Ar age on hornblende from the gneissic outer margin of the Belchertown pluton (by R. E. Zartman; Leo and others, in press) tends to confirm long-enduring Acadian metamorphic recrystallization, although this latter age value may have been influenced by the ca. 250 m.y. Alleghanian thermotectonic event and therefore must be regarded as a minimum age.

Rb-Sr Geochronologic Study of the Glastonbury Gneiss

by Douglas G. Brookins

1. The Problem.

The Glastonbury Gneiss (described in detail elsewhere in this paper) has posed many problems in terms of its absolute age of formation: possible different ages of intrusion into some of the flanking rocks, and with the Pelham Dome to the north, the effects of metamorphism on Rb-Sr systematics, igneous versus metamorphic events, and the relationship of the gneiss to the 250- to 300-m.y. old granitic rocks and pegmatites in the southern area.

Elsewhere in this paper (p. 19-22) it has been documented that the Glastonbury Gneiss intrudes the Ammonoosuc Volcanics which have been dated at 460 ± 10 m.y. by Brookins (1968) based on samples from New Hampshire. Brookins and Hurley (1965) reported a 440 ± 15 m.y. date for samples of the Middletown Formation (Ammonoosuc Formation equivalent) from the Middle Haddam and Glastonbury quadrangles in Connecticut. This was later questioned by Brookins and Methot (1971) who pointed out that this date was based on only four samples and that the 460 ± 10 m.y. Ammonoosuc Volcanics date should be used for the Middletown Formation. Similarly G.P. Eaton (written communication, 1964) mentioned intrusive contacts between the southern Glastonbury Gneiss and the Collins Hill Formation in the Middle Haddam quadrangle, Connecticut. Brookins and Hurley (1965) reported a preliminary date of 390 ± 40 m.y. for the Collins Hill Formation which was revised based on later work to 424 ± 41 m.y. by Brookins and Methot (1971).[1] Table 7 summarizes the preferred Rb-Sr age dates, except for the Glastonbury Gneiss, as reported

77A (77B and C follow)

Footnote p. 77

The unit for which the 424 ± 41 m.y. age reported actually is referred to by Brookins and Methot (1971) as Brimfield Schist (?); however the dated rocks are Collins Hill Formation from Collins Hill, Connecticut, as used by Eaton and Rosenfeld (1972). The reason for this apparent discrepancy is that, at the time the sample was collected for dating, the Collins Hill was regarded as Brimfield wrapping around the south end of the Glastonbury Gneiss (cf. Snyder, 1970).

TABLE 7

Summary of Rb-Sr Age Determinations from the Middle Haddam and Glastonbury Quadrangles, Connecticut.

Rock Unit	Rb-Sr Age (m.y.)	Initial $^{87}Sr/^{86}Sr$	Ref.
Large, granitic pegmatites	258 ± 5	0.734 ± 0.009	1
Maromas Gneiss and related dikes	287 ± 15	0.712 ± 0.001	2
Folded pegmatite dikes	355 ± 15	0.715 ± 0.005	2
Granite dikes (in Monson gneiss)	420 ± 15	0.71 (assumed)	3
Collins Hill Formation	424 ± 41	0.717 ± 0.002	1
Middletown Formation (based on Ammonoosuc formation age)	460 ± 10	0,705 ± 0.001	4
Monson Gneiss	480 ± 15	0.707 ± 0.002	2

Notes: (1) Data based on 50 b.y. half life for ^{87}Rb.

(2) References:

1. Brookins and others (1969); Methot and Brookins (1971).
2. Brookins and Methot (1971).
3. Brookins and Hurley (1965); Brookins (1963).
4. Brookins (1968).

by Brookins and Methot (1971).

It is known that the Glastonbury Gneiss intrudes the Ammonoosuc Volcanics (i.e. Middletown Formation equivalent), and that it is pre-pegmatites (i.e. both the 350 m.y. old folded pegmatite dikes and 258 ± 5 m.y. massive pegmatites; see Table 7). Accordingly, because of the relatively large error for the age of the Collins Hill Formation, all one can state within safe limits is that the age of the Glastonbury Gneiss in south-central Connecticut is post-450 m.y. and pre-350 m.y.

The situation is made even more complex by the early published date of 355 ± 10 m.y. for the southern Glastonbury Gneiss in the Middle Haddam and Glastonbury quadrangles, Connecticut by Brookins and Hurley (1965), and a slightly different revised date of 362 ± 10 m.y. date for the same areas by Brookins and Methot (1971) must be discussed in this connection. These dates are suspect primarily because the former includes a probable pegmatite-gneiss mixed sample (R3372; Table 2). At the Spinelli quarry the country rocks of the pegmatite have in part been contaminated by the pegmatite by either infiltration of quartzo-feldspathic material into fissures or else by reaction between the pegmatite and wall rock (i.e. similar to reaction zones noted at the nearby Hale quarry pegmatite by Methot and Brookins, 1971). The typical wall rock to the Spinelli quarry pegmatite is a foliated, partially chloritized biotite-quartz-feldspar (Sample 4998 is typical) which is very different in both $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ than Sample 3372. The isochron age of the latter is weighted heavily by three samples (R4792a-c; Table 2) which are possibly not true southern Glastonbury Gneiss as they contain more Rb, less Sr and possess very high $^{87}Sr/^{86}Sr$ ratios relative to more carefully collected northern and southern Glastonbury Gneiss samples. These last three samples were collected near the Strickland-Cramer pegmatite quarry close to many pegmatite dikes and veinlets and it is possible that the samples are from granite dikes produced by Acadian anatexis.

Billings (1956) classified the Glastonbury Gneiss as an Oliverian Dome whose core rocks are probably intrusive into its flanking rocks, yet Eaton and Rosenfled (1960), following the mantled gneiss dome model of Eskola (1949), preferred to describe the doming as due to tectonism and accordingly the cores of domes are older then the flanking rocks. By contrast, the work of Naylor (1968) on the Mascoma Dome of New Hampshire, a typical Oliverian dome, indicated that this is a composite dome and that core rocks have both intrusive and non-intrusive contacts with flanking rocks.

One of the more obvious features of any regional map of the Bronson Hill anticlinorium is the alignment of the Glastonbury Dome with the Pelham Dome to the north, the two being separated by the Belchertown quartz monzodiorite (Leo and others, 1977) which intrudes the Pelham Dome. It is clear that the Ammonoosuc and other rocks which flank the Pelham Dome have not been intruded by the dome rocks. Recently, Naylor (written communication) has confirmed what others have suspected viz. the Pelham Dome is Precambrian in age (1,200 m.y.). South of the Belchertown quartz monzodiorite the northern Glastonbury rocks are intrusive into the Ammonoosuc volcanics. It is thus strange that although the Glastonbury and Pelham domes are aligned in north-south fashion along the Bronson Hill anticlinorium they are sufficiently different in lithologies and absolute age as to preclude any genetic relationship between them.

Turning again to the southern Glastonbury Gneiss area one is confronted with the problem of the nature of the contact of the gneiss with the Clough Formation (Upper Llandoverian, e.g., Silurian) in the Middle Haddam and Marlborough quadrangles, Connecticut (Snyder, 1970). ~~The Clough Formation is Upper Llandoverian (Silurian) in age.~~

Regardless of this particular problem, of more importance is the fact that it is not certain whether or not the Glastonbury is in fault or intrusive contact with the Clough. Snyder (1970) suggests intrusion of the Clough by the Glastonbury followed by faulting which has obscured the intrusive nature of the original contact. Another possibility is that the Glastonbury is intrusive into the Collins Hill but unconformably overlain by the Clough. The absolute age for the Silurian Period is still an unsolved question although recent (1973) charts published by the U.S. Geological Survey suggest limits from about 410 m.y. to 430- to 440-m.y.. Thus a possible age for the Clough Formation might be 420 + 15 m.y. Unfortunately, the previously cited 424 $\pm$ 41 m.y. date for the Collins Hill Formation is of little help in resolving this problem.

Another problem is the age of the Taconic Orogeny and its role in south-central Connecticut. The Taconic Orogeny is Late Ordovician (Rodgers, 1970) which would place it at about 440 $\pm$ 10 (?) m.y. ago. In south-central Connecticut Brookins and Hurley (1965) report granitic dikes emplaced about 420 $\pm$ 15 m.y. ago but no other clear-cut intrusions, small or large, have been documented from the area. It is possible that many effects of the Taconic Orogeny have been obscured by the 360- to 400 m.y. Acadian Orogeny and the later thermal resetting of both mineral and whole rock systems during the '250- to 280' m.y. (?) Alleghanian Orogeny.

Much of the burden of this paper is the geologic and chemical evidence for distinct and fairly consistent differences between the northern and southern parts of the Glastonbury body which imply fundamental differences in modes of origin. With the recognition of these differences, the possibility of distinct ages for the two parts of the Glastonbury also presents itself.

To attempt to examine this possibility and to illuminate the other problems discussed above in which age is a factor, we undertook a further investigation of the Glastonbury Gneiss by the Rb-Sr whole rock method described in the following section.

II. Analytical Methods.

Rb and Sr contents were determined either by x-ray fluorescence (data in table 8) or isotope dilution analysis (data in table 3). For the former, the Rb/Sr weight ratio is precise to ± 3 percent (one sigma) but the absolute abundance of each element is subject to a larger error hence only the atomic $^{87}Rb/^{86}Sr$ ratios calculated from the weight ratios are reported. For samples for which the Rb/Sr ratio was determined by x-ray fluorescence a separate aliquot was used for the determination of the isotopic composition of strontium. For the data from Brookins and Hurley (1965) the $^{87}Sr/^{86}Sr$ ratios are accurate to ± 0.0006 of the reported values; for similar data from Brookins and Methot (1971) the data are accurate to ± 0.0005 of the reported value. For Rb and Sr analyzed by isotope dilution for some of these samples the precision is ± 1.0 percent (one sigma).

The more recently analyzed samples collected by G.W. Leo (table 3) have all been analyzed by isotope dilution both for Rb and Sr contents and for the isotopic composition of Sr. The techniques (described below) have improved over earlier work such that the precision of the Rb and Sr analyses is ± 0.5 percent (one sigma) and the calculated $^{87}Sr/^{86}Sr$ data accurate to ± 0.0003 of the reported value.

For x-ray fluorescence analyses finely powdered samples were analyzed in replicate using a Norelco Instrument; these techniques have been described by Brookins (1963). For samples analyzed for $^{87}Sr/^{86}Sr$ only, the procedures are only slightly modified from those described by Brookins (1963). Approximately one gram of sample is carefully weighed into a deionized water-wetted teflon evaporating dish and the sample dissolved in a 25 ml:3 ml mixture of reagent HF: vycor distilled $HClO_4$ using a hot plate. When near dryness is noted by the evolution of dense white fumes from the $HClO_4$ an additional 10- to 15-ml HF is added and the contents evaporated to dryness. The dish is then cooled and to the contents is added 100 ml of a 50:50 mixture of vycor distilled 2N HCl:deionized water to digest the perchlorate cake. When near dryness is attained by heating on a hot plate this digestion is repeated until only 10 to 20 ml of solution-mush is left. This is cooled overnight and then filtered. The filtrate is then placed on a pre-calibrated cation exchange column filled with Dowex 50 x 8 cross-linked resin and stontium separated by ion exchange chromatography. For samples analyzed by isotope dilution the procedure is essentially the same except that the sample is very carefully weighed and ^{87}Rb-enriched and ^{84}Sr-enriched tracers are added to the wetted powder prior to sample dissolution. Contamination from the reagents used is negligible for the Glastonbury Gneiss samples; typical blanks for Rb and Sr in our laboratory are less than 0.01 microgram/gram.

The isotopic analyses are conducted using a Nuclide 12-90 (Nier design) mass spectrometer with solid source and Faraday Cup collection. Amplification is by a D.C. electrometer and magnetic sweeping is used in conjunction with a strip recorder for readout. Forty-eight to 60 sets of data are routinely taken to assure enough data to be statistically meaningful. All $^{87}Sr/^{86}Sr$ data measured are normalized by adjusting the $^{86}Sr/^{88}Sr$ ratios to 0.1194. Data for fifteen runs on Eimer and Amend Standard $SrCO_3$ (Lot No. 496327) yielded $^{87}Sr/^{86}Sr = 0.7080 \pm 0.0002$ during the course of this investigation As mentioned above, because most of our samples were only analyzed once an absolute error of $\pm$ 0.0003 is used in the data reduction. A decay constant for ^{87}Rb of 1.39×10^{-11}/y was used in the age calculations. The isochrons were constructed using the method described by York (1969) and are shown in Figures 13 and 14. The data from this and previous studies are presented in Table 2.

III. Discussion of Results.

Table 8 appear here

Figs. 13 and 14 appear here

The Rb-Sr data are presented in Tables 3 and 8 and various calculated and/or reference isochrons are presented in Figures 13 and 14. As samples from the area near the Strickland-Cramer pegmatite quarry (Analyses no. 4792a, 4792b, 4792c, Table 8) and one possible pegmatite-country rock mixture (Analysis no. 3372) have been mentioned earlier they will be given only brief treatment here. The samples define an approximate 360 m.y. isochron (Figure 13). I interpret this isochron as indicating an Acadian event which could have involved either anatectic or truly magmatic processes. I do not believe sample 3372 to be representative of either the Glastonbury Gneiss or the Spinelli quarry pegmatite. This particular sample, studied by Brookins (1963), was obtained from the MIT collection where it is simply described as "wall rock to the Spinelli quarry pegmatite" and only powdered sample was available. Brookins (1963) confirmed that the Rb and Sr contents were accurate but questioned its being representative of the wall rock to the Spinelli quarry pegmatite based on field observations,

Table 8 -- Supplementary Rb-Sr on Glastonbury Gneiss (southern) including pegmatitic material

[Analyses by D. G. Brookins. $^{87}Rb/^{86}Sr$ calculated from XRF analyses]

	Glastonbury Gneiss (southern)								Pegmatitic material			
Map loc. (fig. 2) 1/	I		II	III			IV	V	VI			VII
Analysis no.	1132 b	1132 d	1136 a	1066 a	1066 b	1066 c	4998	4999	4792 a	4792 b	4792 c	3372 2/
$^{87}Sr/^{86}Sr$	0.7164	0.7178	0.7230	0.7170	0.7159	0.7167	0.7169	0.7095	0.7743	0.7975	0.7440	(0.8458)
$^{87}Rb/^{86}Sr$	1.41	1.55	2.90	1.84	1.47	1.77	1.30	0.56	13.26	17.43	6.80	(27.90)

1/ I Tower Hill granite quarry, approximately 1 km WNW of intersection of New London Tpk. and Chestnut Hill Road, Glastonbury quadrangle

II Roadcut on New London Turnpike 3.2 km southeast of Spinelli quarry, Glastonbury quadrangle

III Outcrop approximately 800 m south of Isinglass Hill Road 1.6 km east of intersection of Isinglass Hill Road with Route 17

IV Gneiss near contact with Hale quarry pegmatite, approximately 650 m SE of intersection of Isinglass Hill Road with Route 17, Glastonbury quadrangle

V Gneiss wall rock at Spinelli quarry pegmatite; not in contact with nor cut by pegmatite

VI From just east of Strickland-Cramer pegmatite quarry, Collins Hill, approximately 350 m NE of Rose Hill Road-Bartlett St. intersection, Middle Haddam quadrangle

VII From Spinelli quarry, approximately 150 m south of New London Turnpike (old Rte. 2) along power line, Glastonbury quadrangle

2/ Probably Spinelli pegmatitic

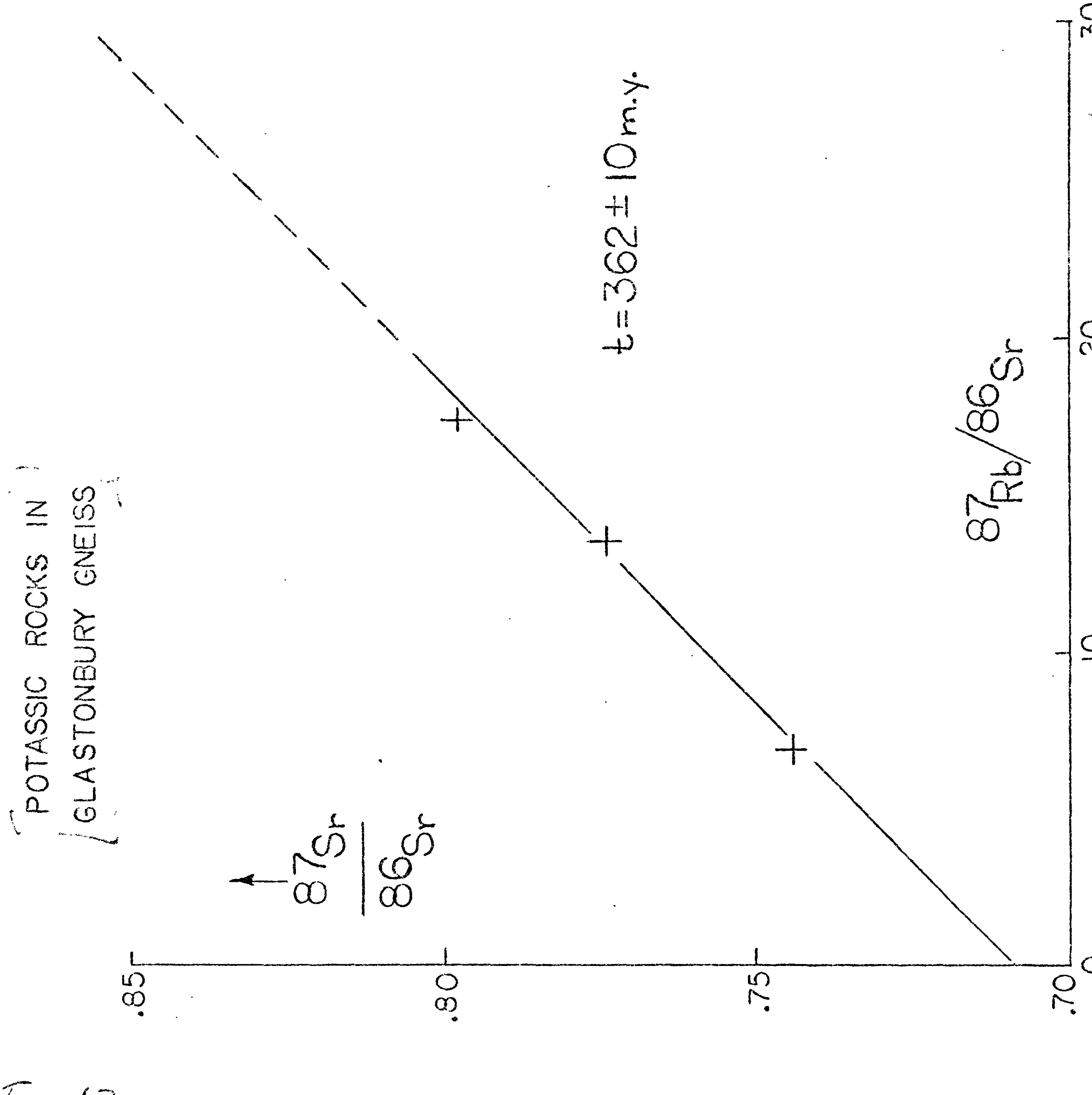
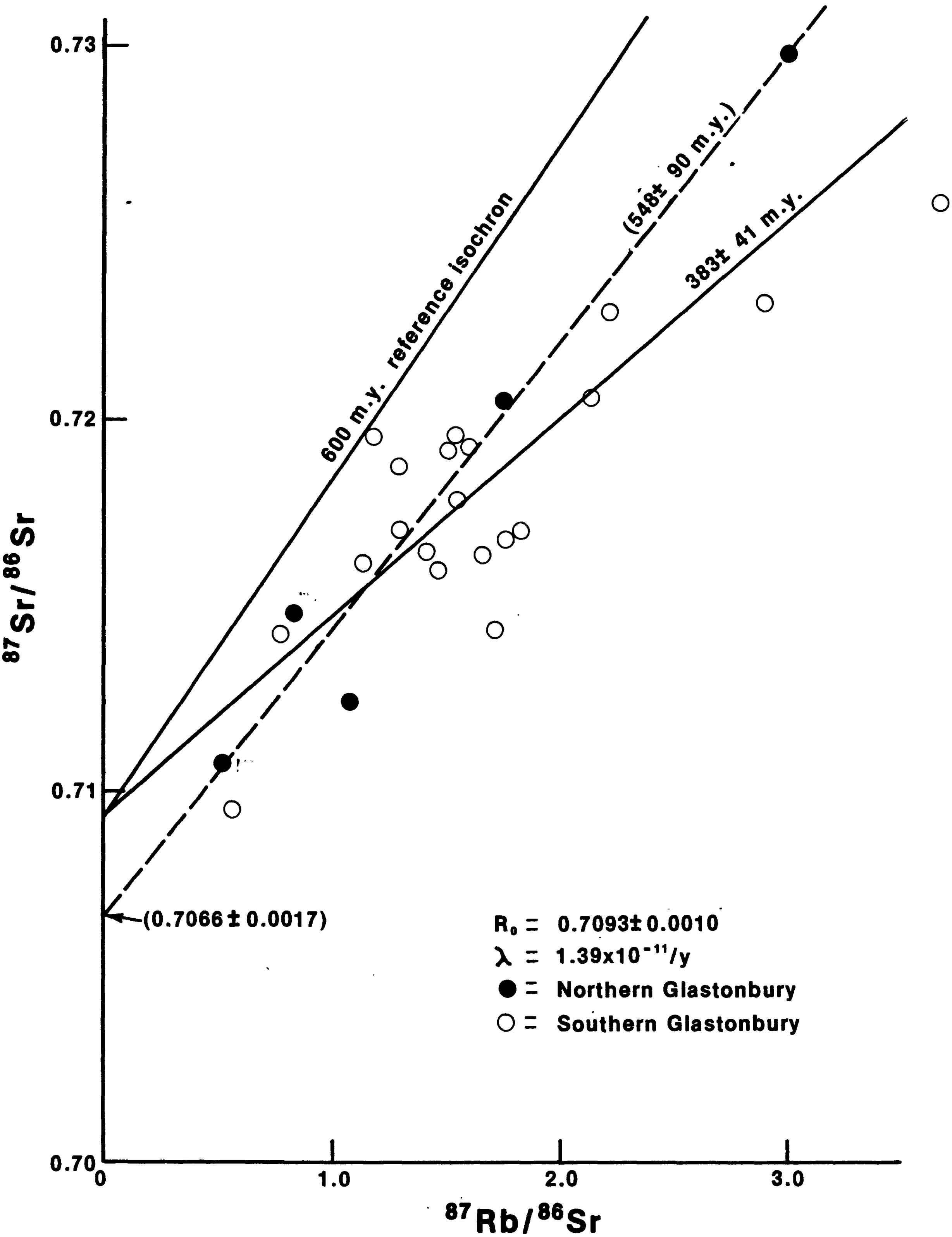

POTASSIC ROCKS IN
GLASTONBURY GNEISS
$^{87}Sr/^{86}Sr$
$t = 362 \pm 10$ m.y.
$^{87}Rb/^{86}Sr$
.85
.80
.75
.70
0
10
20
30

Fig. 13

Fig. 13. Rb-Sr whole-rock isochron plot of potassic rocks associated with southern Glastonbury Gneiss.



0.73
0.72
0.71
0.70
0
1.0
2.0
3.0
$^{87}Sr/^{86}Sr$
$^{87}Rb/^{86}Sr$
600 m.y. reference isochron
(548± 90 m.y.)
383± 41 m.y.
(0.7066 ± 0.0017)
R_0 = 0.7093± 0.0010
λ = $1.39x10^{-11}$/y
● = Northern Glastonbury
○ = Southern Glastonbury

Fig. 15

Fig. 14. Composite Rb-Sr isochron plot of Glastonbury Gneiss, and hypothetical plot of the northern gneiss.

etrography, and additional Rb-Sr study of samples not contaminated by pegmatic material. Samples of the Glastonbury Gneiss similar to 4998 (nos. 1066a, 1066b, 1066c, 4999) are strikingly different from 3372 (Table 8.) hence, I have excluded use of 3372 in construction of Fig. 13.

It is also possible, for example, that samples 4792a, 4792b, 4792c represent a dike formed by anatexis close to the time when pegmatitic material is known to have been injected at about 350 m.y. (Methot and Brookins, 1971). But until further work is carried out, this remains just one of many possibilities. What is clear, though, is that samples 4792a, 4792b, 4792c yield a well-defined 362 $\pm$ 10 m.y. isochron which substantiates igneous activity at about that time (Methot and Brookins, 1971).

In Figure 14 are shown the data for samples from both the northern and southern Glastonbury Gneiss. By inspection it is obvious that there is too much scatter to attempt other than reference isochrons. If samples from the northern Glastonbury analyses (2, 5, 7, 7A, and 10, fig. 2 and table 3) only are used, a York (1969) regression of the data yields an apparent date of 548 $\pm$ 90 m.y. with an initial ratio (i.e., $^{87}Sr/^{86}Sr_o$) = 0.7066 $\pm$ 0.0017. This apparent age is clearly too old as the northern Glastonbury rocks intrude the 460 $\pm$ 10 m.y. old Ammonoosuc Volcanics. Further, if the northern Glastonbury Gneiss has indeed been formed by anatectic processes then one would usually expect not only a younger age (i.e., relative to the Monson Gneiss as well as the Ammonoosuc Volcanics) plus a higher initial ratio (greater, say, than 0.708). The small number of samples from the northern Glastonbury makes it difficult to compare them with samples from the more extensively studied southern Glastonbury Gneiss.

The southern Glastonbury Gneiss is represented by 20 samples (tables 3 and 8); a York regression through these data yields an apparent age of 316 ± 43 m.y. with an initial ratio of 0.7108 ± 0.0011 (not shown in fig. 14). This apparent age is too low as 350-360 m.y. old pegmatites (and possibly granitic dikes) intrude the Glastonbury (see fig. 13). The problem is due to the relatively narrow range of $^{87}Sr/^{86}Sr$. Further, if the southern Glastonbury rocks are truly coeval, which we do not dispute, then the initial ratio must fall below 0.710 based on data for sample 4999 which must be a mineral-dominated system relative to a whole rock-dominated system for the initial ratio to fall above 0.710 if the system has remained closed.

Regression of the 25 data from both the northern and southern parts of the Glastonbury body yields an apparent age of 383 ± 41 m.y. with an initial ratio of 0.7093 ± 0.0010. The large error for this date is a reflection of the scatter about the 20 southern samples and the data for the northern samples. However, collectively, the Rb-Sr age data argue for possible formation (regardless of anatectic versus magmatic origin) near 380 m.y. which is consistent with the post-Ammonoosuc and post-Collins Hill ages commented on earlier. As pointed out previously, however (Leo, this paper p. 8A-8C), the well-established age of the Belchertown pluton of 380 ± 5 m.y. requires that the Glastonbury be somewhat older, while the optimum time for the requisite P-T conditions to be attained is early in the Acadian, about 400-380 m.y. B.P. Subsequent disturbance of the rock systems due to later Acadian as well as Appalachian events may well have influenced the Rb-Sr systematics.

Of interest is the fact that the Rb and Sr contents for the northern and southern samples are quite different; the average Rb contents are; norther: 62 ppm (n=8), southern: 115 (n=16). For Sr the averages

(200)
R290
no 77-554

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.]

Glastonbury Gneiss (northern)

Analysis No.	1	2	3	4	5	6	7	8	9	10
Field Sample No.	73 GWL 34-1	74 GWL 357-1 1/	71 GWL 35-1/2	367	620	H7-A	74 GWL 361 1/	P9-32	P9-26	73 GWL 329-2
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	ND	1.4	1.2	0.92	1.3	ND	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	ND	0.43	0.64	0.69	0.61	ND	0.97	0.68	0.73
H_2O-	.02	ND	0.01	0.02	0.01	0.01	ND	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	ND	0.02	0.02	0.04	0.06	ND	0.04	0.06	0.02
F	0.03	ND	0.01	ND	ND	ND	ND	ND	ND	ND
Cl	0.062	<0.10	0.039	ND	ND	ND	<0.10	ND	ND	ND
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	4.5	2.8	1.6	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}	An	An_{10-17}	An_{25-37}	An_{23-31}	An_{6-13}	An	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		41.5	42.6	46.6	45.7	41.5	39.1	44.3	56.1
K-Feldspar	5.5		4.5	--	3.7	4.7	10.4	--	9.6	.6
Biotite	2.6		4.9	3.1	6.5	8.0	8.5	11.7	8.1	12.6
Muscovite	3.8		.2	.3	.3	6.0	1.7	8.7	--	1.5
Epidote	.3		.2	6.1	2.5	1.2	3.8	--	3.7	5.4
Hornblende	--		--	0.2	--	--	--	--	--	--
Other amph.	--		--	--	--	--	--	--	--	--
Garnet	.2		--	--	--	--	--	.3	--	--
Opaque	--		.1	--	--	--	--	.2	--	--
Remainder 3/	--		--	--	--	--	tr. 4/	--	--	--

Glastonbury Gneiss (southern)

Analysis No.	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Field Sample No.	73 GWL 330	73 GWL 331-1	73 GWL 331-2	2309	2392	2379	2424	74 GWL 359 1/	73 GWL 334	7968	1680	1702	1704	1594	1728	804	809	1716
Major Elements																		
SiO_2	75.1	68.1	66.3	73.56	66.54	74.08	76.30	75	71.9	76.2	66.7	74.7	76.3	75.7	63.8	56.8	56.0	57.4
TiO_2	.12	.37	.40	.17	.39	.15	.09	.05	.24	.11	.29	.14	.10	.07	.42	.47	.55	.55
Al_2O_3	13.1	14.7	15.0	14.00	15.00	13.68	12.90	14	13.8	12.9	16.2	14.1	12.8	13.7	16.2	17.7	17.4	17.3
Fe_2O_3	.50	1.9	2.3	.48	1.80	.61	.26	1.4	.60	.29	2.0	.16	.9	.14	2.3	2.8	3.2	3.3
FeO	.76	1.2	1.4	1.08	2.25	.88	.86	ND	.96	.92	1.5	1.4	1.1	.76	2.2	3.8	4.1	3.4
MnO	.03	.07	.07	.06	.10	.03	.05	.04	.03	.02	.04	.16	.06	.06	.12	.17	.19	.18
MgO	.40	1.0	1.2	.46	1.94	.45	.21	.35	1.1	.23	1.1	.43	.31	.22	1.7	2.8	3.3	2.8
CaO	4.0	4.4	5.0	1.98	4.16	1.76	.92	1.61	1.9	1.1	4.6	2.0	1.5	1.7	5.8	8.3	8.9	8.2
Na_2O	3.1	2.8	2.7	3.24	2.44	2.90	3.15	3.25	2.8	3.0	2.6	3.5	3.1	3.0	2.6	2.6	2.1	2.5
K_2O	3.5	3.6	3.4	4.28	4.10	4.59	4.72	4.30	4.8	4.4	3.7	2.6	3.8	4.1	3.4	2.6	1.9	2.0
H_2O+	.54	.57	.69	.30	.87	.33	.28	ND	.61	.49	.97	.64	.82	.58	.90	1.1	1.2	1.2
H_2O-	.04	.02	.20	.04	.07	.14	.07	ND	.10	.00	.04	.00	.02	.02	.00	.03	.04	.04
P_2O_5	.09	.16	.25	.05	.10	.04	.02	< .10	.12	.02	.17	.06	.03	.06	.22	.31	.27	.38
CO_2	.04	.06	.05	.01	.02	.01	0.3	ND	.02	< .05	< .05	< .05	< .05	< .05	< .05	< .05	< .05	< .05
F	ND	ND	ND	.04	.05	.06	.04	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cl	ND	ND	ND	.00	.00	.00	.00	< .10	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Subtotal	101	99	99	99.75	99.83	99.71	99.88	--	99	100	100	100	100	100	100	99	99	99
Less O	--	--	--	.02	.02	.03	.02	--	--	--	--	--	--	--	--	--	--	--
Total	101	11	99	99.73	99.81	99.68	99.86	100	99	100	100	100	100	100	100	99	99	99
										2.72	2.66	2.64	2.64	ND				
Norms																		
Q	35.64	28.72	27.02	31.83	33.13	24.73	35.21	37.46	36.57	36.80	26.12	38.54	39.26	38.21	21.68	10.99	13.58	15.06
Or	20.41	21.50	20.30	28.66	25.32	24.27	27.21	27.93	25.82	26.08	21.88	15.38	22.45	24.45	24.25	20.16	15.44	11.91
Ab	25.89	23.94	23.10	23.94	27.45	20.68	24.62	26.52	27.95	25.47	22.02	29.65	26.22	25.41	22.08	22.12	17.92	21.31
An	11.34	17.90	18.97	8.60	9.18	17.90	8.02	3.97	6.65	5.34	21.62	9.54	7.24	8.05	22.57	29.10	32.72	30.30
c	--	--	--	.89	.68	--	1.02	1.19	--	1.25	--	2.04	.93	1.18	--	--	--	--
Di	3.68	2.77	3.23	--	--	1.38	--	--	1.13	--	.08	--	--	--	3.91	8.35	8.14	6.56
Wo	1.87	1.47	1.73	--	--	.71	--	--	.60	--	.04	--	--	--	2.03	4.28	4.19	3.42
En	.98	1.22	1.44	--	--	.45	--	--	.52	--	.03	--	--	--	1.35	2.54	2.59	2.94
Fs	.83	.08	.07	--	--	.21	--	--	--	--	.01	--	--	--	.53	1.53	1.36	.94
Hy	--	1.38	1.66	3.70	2.46	6.37	2.06	1.83	.36	1.88	3.40	3.58	2.66	1.83	4.04	7.17	8.71	6.81
En	--	1.30	1.58	2.77	1.15	4.39	1.12	.52	.36	.57	2.71	1.07	.77	.55	2.90	4.74	5.70	4.79
Fs	--	.08	.07	.94	1.31	1.98	.94	1.31	--2/	1.31	.69	2.51	1.89	1.28	1.14	2.70	3.01	2.02
Mt	.72	2.78	3.37	.88	.89	2.61	.86	.38	--2/	.42	2.90	.23	.13	.20	3.35	4.08	4.68	4.82
Il	.23	.71	.77	.46	.32	.74	.29	.17	.09	.21	.55	.27	.19	.13	.80	.90	1.05	1.05
Ap	.21	.33	.60	.29	.12	.24	.10	.05	--	.05	.40	.14	.07	.14				
CC	.09	.14	.12	.05	.02	.05	.02	.07	--	--	--	--	--	--	--	--	--	--
Ab/An	2.3	1.3	1.2	2.8	3.0	1.2	3.1	6.7	4.2	4.8	1.0	3.3	3.7	3.2	.98	.76	.55	.70
Plag.comp.calc.	An_{30}	An_{43}	An_{45}	An_{26}	An_{25}	An_{46}	An_{25}	An_{13}	An_{19}	An_{17}	An_{50}	An_{24}	An_{22}	An_{24}	An_{50}	An_{57}	An_{65}	An_{59}
Plag. comp observed	ND	An_{25}	An_{25-27}	ND	ND	ND	ND	ND	An	An_{13-32}	An	An	An	An	An	An	An	An
Modes 5/																		
Quartz	46.3	32.8	24.1	ND	ND	ND	ND	30.0	30.5	ND	41.1	38.0	29.7	39.6	28.8	ND	24.0	18.5
Plagioclase	29.5	28.2	25.7					35.7	28.4		27.0	40.0	44.8	27.1	30.2		32.2	31.2
K-Feldspar	15.3	22.1	33.0					27.3	26.8		12.4	14.2	17.6	28.9	12.8		1.1	0.5
Biotite	7.0	9.5	10.7					7.1	11.8		12.5	7.5	7.7	4.4	14.6		21.4	22.6
Muscovite	.8	--	--					--	1.7		--	--	--	--	--		--	--
Epidote	.7	7.4	5.9					--	.6		6.7	--	.1	--	10.0		13.3	16.5
Hornblende	.1	--	--					--	--		tr.	--	--	tr.	5.5		7.8	10.1
Other amph.	--	--	--					--	--		--	--	--	--	--		--	--
Garnet	.1	--	--					--	--		--	.3	--	--	--		--	--
Opaque	--	--	--					--	--		--	--	--	--	--		[illegible]	--
Remainder 3/	.2	tr.	.7					tr.	.2		.4	.1	.2	--	.2		.2	.5

Monson Gneiss

Analysis No.	29	30	31	32	33	34	35	36	37
Field Sample No.	212	768	74 GWL 358-1 1/	807	M-CC	A-14	MQ-2	P8-270	P8-272
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.	< .10	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}	An	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		44.4	35.3	57.4	47.5	49.4	48.5
K-Feldspar	11.4	--		--	9.6	--	--	--	--
Biotite	5.3	10.0		19.0	5.6	.9	7.0	7.2	8.5
Muscovite	2.1	--		--	.8	1.0	--	.6	--
Epidote	--	--		--	1.6	.2	.1	.3	1.1
Hornblende	--	--		--	--	--	6.3	--	3.9
Other amph.	--	--		--	--	--	--	--	--
Garnet	--	--		.2	.5	.5	.1	--	--
Opaque	--	--		.4	--	--	.3	.9	.1
Remainder 3/	--	.4		--	--	--	--	.4	--

Ammonoosuc Volcanics

Analysis No.	38.	39	40	41	42	43	44	45	46	47	48
Field Sample No.	71-GWL 17-1	71-GWL 35-4/6	71-GWL 43-1/4	71-GWL 41-4/1	71-GWL 41-4/3	357	71-GWL 45-2/4	71-GWL 46-4/1	71-GWL 43-1/1	71-GWL 66-2/4	H7-B
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	15.5	6.4	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	.55	.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}
Plag. 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.	--	--	--	--	--	--	--	--	7.6 6/	6.9 6/	7.0 6/
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, MuO and P_2O_5 by XRF, J. S. Wahlberg, USGS, analyst; Mgo, CaO, Da_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

14A

(200)
R290
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Table 3.--Minor and trace elements including Rb-Sr isotope data, 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. Values are averages of 2 to 3 replicate runs and may be considered accurate to ± 10%. Sr data without asterisks obtained by atomic absorption spectroscopy (limit of error approx. ± 10%) by Robin Moore and Violet Merritt.

Rb and Sr data with asterisks, and Rb-Sr isotopic data, obtained by D. G. Brookins by isotope dilution analysis (see Brookins, this volume, for details of analytical procedure). N.D., not determined; ---, 1) result inconclusive, 2) calculation not made because data lacking, or 3) not applicable.

Glastonbury Gneiss (northern)

Analysis No.1/	1	2	2a	4	5	7	7a	10	11	11a	12	12a	12b	12c
Field No.	71 GWL 34-1	74 GWL 357-1	357-2	P 367	73 GWL 337-1	74 GWL 361	361-2	73 GWL 329-2	73 GWL 330	330-3	73 GWL 331-1	331-2	331-4	331-5
Sc	7.9	12.1	N.D.	16.1	N.D.	11.2	N.D.	4.5	6.9	N.D.	15.0	N.D.	N.D.	N.D.
Cr	3.8	5	N.D.	6	N.D.	18	N.D.	3.9	4.9	N.D.	21.5	N.D.	N.D.	N.D.
Co	2.2	5.0	N.D.	2.0	N.D.	4.0	N.D.	3.1	2.8	N.D.	5.0	N.D.	N.D.	N.D.
Zr	160	21	N.D.	21	N.D.	170	N.D.	290	215	N.D.	250	N.D.	N.D.	N.D.
Rb	83	76	83.5*	20	48.2*	82.0*	56.0*	52.1*	144	128*	115	43.6*	168*	140*
Sr	95	83	80.0*	150	128*	136*	196*	281*	113*	167*	N.D.	250*	264*	270*
Cs	2.3	2.9	N.D.	1.7	N.D.	1.0	N.D.	1.5	5.3	N.D.	13.7	N.D.	N.D.	N.D.
Ba	525	400	N.D.	150	N.D.	780	N.D.	1010	1060	N.D.	1300	N.D.	N.D.	N.D.
La	21	24	N.D.	8	N.D.	47	N.D.	55	59	N.D.	74	N.D.	N.D.	N.D.
Ce	46	36	N.D.	13	N.D.	79	N.D.	57	91	N.D.	94	N.D.	N.D.	N.D.
Nd	20	26	N.D.	29	N.D.	39	N.D.	26	32	N.D.	34	N.D.	N.D.	N.D.
Sm	3.9	4.9	N.D.	3.2	N.D.	8.9	N.D.	5.2	8.3	N.D.	7.7	N.D.	N.D.	N.D.
Eu	.52	.59	N.D.	1.20	N.D.	1.17	N.D.	1.9	.82	N.D.	1.14	N.D.	N.D.	N.D.
Tb	.63	.64	N.D.	.58	N.D.	.94	N.D.	.58	.83	N.D.	.98	N.D.	N.D.	N.D.
Yb	1.9	1.8	N.D.	1.5	N.D.	2.3	N.D.	.8	3.1	N.D.	2.1	N.D	N.D.	N.D.
Lu	.43	.47	N.D.	.29	N.D.	.48	N.D.	.20	.59	N.D.	.46	N.D.	N.D.	N.D.
Hf	3.8	2.7	N.D.	1.7	N.D.	3.3	N.D.	9.5	5.8	N.D.	7.5	N.D.	N.D.	N.D.
Ta	.3	.4	N.D.	.2	N.D.	.4	N.D.	.3	.4	N.D.	1.4	N.D.	N.D.	N.D.
Th	9.2	8.8	N.D.	1.9	N.D.	15.5	N.D.	12.5	25.6	N.D.	39.8	N.D.	N.D.	N.D.
K/Rb	230	218	---	235	258	247	---	175	202	---	260	197	---	---
Rb/Sr	.87	.92	1.04	.13	.38	.60	.29	.19	1.27	.77	.58	0.57	0.64	0.52
Sr/Ba	.18	.20	---	1.0	---	.17	---	.28	.11	---	.19	---	---	---
$^{87}Sr/^{86}Sr$	---	---	.7297	---	.7124	.7205	.7148	.7107	.7263	.7228	---	.7163	.7195	.7191
$^{87}Rb/^{86}Sr$	---	---	3.02	---	1.09	1.76	1.83	.54	3.68	2.22	---	1.66	1.18	1.50

Glastonbury Gneiss (southern)

Analysis No.1/	12D	18	18A	19	45	50	51	25	26	28
Field No.	331-6	74 GWL 359	359-2	73 GWL 334	74 GWL 367-3	74 GWL 368-2	74 GWL 371-2	1728	804	1716
Sc	N.D.	4.5	N.D.	8.2	N.D.	N.D.	N.D.	23.1	33.8	34.0
Cr	N.D.	2.7	N.D.	13.0	N.D.	N.D.	N.D.	25.3	32.1	18.0
Co	N.D.	1.6	N.D.	3.4	N.D.	N.D.	N.D.	9.7	16.3	16.1
Zr	N.D.	---	N.D.	160	N.D.	N.D.	N.D.	220	210	260
Rb	142*	103*	119*	129	112*	140*	138*	93	70	60
Sr	210*	137*	302*	160	424*	254*	309*	360	360	110
Cs	N.D.	5.1	N.D.	6.0	N.D.	N.D.	N.D.	1.8	7.2	3.2
Ba	N.D.	1870	N.D.	1210	N.D.	N.D.	N.D.	1080	1200	1340
La	N.D.	41	N.D.	54	N.D.	N.D.	N.D.	42	49	42
Ce	N.D.	60	N.D.	88	N.D.	N.D.	N.D.	89	89	74
Nd	N.D.	20	N.D.	35	N.D.	N.D.	N.D.	38	37	32
Sm	N.D.	5.7	N.D.	10.3	N.D.	N.D.	N.D.	7.7	8.0	6.7
Eu	N.D.	.58	N.D.	.99	N.D.	N.D.	N.D.	1.37	1.47	1.41
Tb	N.D.	.46	N.D.	.82	N.D.	N.D.	N.D.	.81	1.00	.81
Yb	N.D.	1.3	N.D.	3.3	N.D.	N.D.	N.D.	2.6	2.4	2.2
Lu	N.D.	.29	N.D.	.59	N.D.	N.D.	N.D.	.45	.39	.37
Hf	N.D.	2.5	N.D.	5.2	N.D.	N.D.	N.D.	3.9	5.1	7.4
Ta	N.D.	.5	N.D.	1.8	N.D.	N.D.	N.D.	.9	.9	.7
Th	N.D.	15.5	N.D.	42.4	N.D.	N.D.	N.D.	39.8	11.2	28.9
K/Rb	---	331	---	308	---	---	---	303	308	277
Rb/Sr	.53	.74	.40	.81	.26	.55	.45	.26	.19	.55
Sr/Ba	---	.07	---	.13	---	---	---	.33	.30	.08
$^{87}Sr/^{86}Sr$	.7185	.7205	.7161	---	.7142	.7193	.7187	---	---	---
$^{87}Rb/^{86}Sr$	1.53	2.14	1.14	---	.77	1.60	1.29	---	---	---

Monson Gneiss

Analysis No.1/	31	32	33	34	35	36	37	Chondrite normalizing values 2/
Field No.	74 GWL 358-1	807	M-CC	A-14	MQ-2	PB-270	PB-272	
Sc	11.3	10.1	10.1	0.7	8.1	2.2	5.6	---
Cr	17.4	14.5	5.2	7.0	9.1	2.7	10.4	---
Co	.5	2.3	1.1	.7	8.5	5.5	13.5	---
Zr	---	230	230	70	---	120	---	---
Rb	33	41	84	4.4	16	32	28	---
Sr	28	75	80	400	400	160	440	---
Cs	.8	.4	1.5	.2	.8	.5	.7	---
Ba	470	260	440	210	340	450	250	---
La	29	26	19	15	13	9	10	.325
Ce	51	51	49	27	21	36	14	.798
Nd	35	38	14	11	9	8	6	.567
Sm	10.0	7.9	2.9	1.9	1.8	1.6	1.6	.186
Eu	.83	1.38	.41	.57	.57	.62	.45	.0692
Tb	1.63	1.63	.46	.22	.29	.17	.25	.047
Yb	5.8	7.2	5.0	.3	.5	.4	.4	.209
Lu	1.21	1.07	.88	.04	.09	.08	.07	.0349
Hf	4.8	6.5	5.6	1.7	1.6	4.7	1.2	---
Ta	.4	.3	.5	.06	.2	.2	.12	---
Th	7.1	6.9	8.0	2.1	1.9	8.1	.9	---
K/Rb	427	188	218	409	294	181	161	---
Rb/Sr	1.18	.55	1.05	.01	.05	.20	.06	---
Sr/Ba	.05	.29	.18	1.90	1.18	.36	1.74	---
$^{87}Sr/^{86}Sr$	---	---	---	---	---	---	---	---
$^{87}Rb/^{86}Sr$	---	---	---	---	---	---	---	---

1/ Analysis numbers correspond to those in table 1. Numbers from table 1 not listed were not analyzed. Samples denoted by A, B, C, and D are additional samples from respective localities (fig. 2) selected to show a range of composition at large outcrops. Samples 49, 50 and 51 are from new localities (not in table 1) as follows:

49. Gray, fine- to medium-grained gneiss from roadcut on south side of Connecticut Rte. 2 at intersection of power line, 2.1 km southeast of Nipsic Road, Glastonbury quadrangle

50. Strongly foliated, medium to coarse-grained, biotite-rich gneiss from roadcut on southwest side of Rte. 2, 1 km southeast of loc. I.

51. Fine-grained laminated pinkish-gray gneiss from Tower Hill quarry, approx. 1 km WNW of intersection of New London Turnpike and Chestnut Hill Road, Blastonbury quadrangle.

2/ Sources: Haskin and others (1968) and Hubbard and Gast, 1971.

are; northern: 144 ppm; southern: 246 ppm (see Table 4). Yet using the average K contents of Table 4 (i.e. 1.4 percent and 2.9 percent for northern and southern respectively) the K/Rb ratios are not very different (226 and 252 respectively; Fig. 10). The southern samples do possess a slightly higher Rb/Sr ratio of 0.47 relative to the northern samples value of 0.43 which reflects the more potassic nature of the southern body (i.e. calcium- and therefore strontium-deficient relative to potassium).

Further examination of Figure 14 suggests that provenance for most of the Glastonbury samples is Phanerozoic as all samples plot to the right of the reference Precambrian isochrons. This further suggests that the Pelham dome and Glastonbury Gneiss are not genetically related.

If one uses the K and Th data in the Table 4 and assumes a Th/U ratio of 4, then the southern Glastonbury rocks could very easily have been subjected to more heating and isotopic disturbances than the northern rocks. The trace element data plus the Rb-Sr data suggest that two distinct bodies of Glastonbury Gneiss exist: a southern plutonic part and a northern, possibly anatectic, part. While the Rb-Sr apparent ages are not convincing, the Rb and Sr contents plus the other trace element data establish a clear distinction between the two.

The scatter in the data in Fig 14 may result from several causes. First, the rocks may have been truly open systems so that whole rocks would act like mineral systems (with or without complete re-homogenization in any or all samples) in which case there would be little chance of obtaining even a crude isochron. This seems unlikely as the K/Rb ratios are very constant for these samples plus the fact that none plot above the 600 m.y. reference isochron. If open system conditions were realized, then a hypothetical isochron would be rotated so that a higher initial ratio would result, and so that samples with lower Rb/Sr ratios, using the initial ratio of the 600 m.y. isochron, would yield model Precambrian dates. Second, local redistribution of $^{*87}Sr$ due to the combination of greater depth of burial and relatively high heat generation for the southern gneiss relative to the northern could cause local open system conditions. This factor can not be ruled out at present but, for such a situation, one would also expect wider fluctuation in the K/Rb ratios and in REE patterns than are noted. Third, addition of varying amounts of $^{*87}Sr$ due to fluids associated with pegmatite genesis (or equivalent events) associated with the Acadian Orogeny may account for some of the scatter. While this cannot be unequivocally ruled out it seems unlikely except where actual infiltration of Glastonbury samples with pegmatitic material (i.e. sample 3372, Table 8) has occurred. Fourth, the possibility exists that the parent magma of the southern gneiss was not homogeneous with respect to $^{*87}Sr$ because it was generated in a relatively rapid fashion, in which case the t = zero isochron at t_f would exhibit scatter. This has been observed in several areas of New England. Brookins (1968; 1976) has pointed out that the Wallamatogus granite of New England, for example, exhibits wide scatter, and discordant mineral dates are obtained for muscovites and biotites from the same, unmetamorphosed whole rock samples (See also Faul and others, 1963). Similar scatter is obtained for other granites from Maine (usually the two-mica varieties). Although the Maine granites formed at relatively shallow depths, it is not difficult to predict that should a rock body system already somewhat disturbed by open-system conditions be buried to the depths at which the Glastonbury

Gneiss probably originated then the isotopic systematics are likely to be even more disturbed and a great deal of scatter of data would result.

Hence, I feel that the scatter in Figure 14 is mostly, if not entirely, due to a cause such as number four outlined above. Certainly, despite scatter, the isochron age is compatible with a post-Ammonoosuc age and probably post-Clough age as well. As discussed by Leo (this volume) geological relationships and P-T requirements especially for genesis of the northern Glastonbury magma argue for an age corresponding to early Acadian, perhaps 400-380 m.y.

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