PEGMATITES OF THE MIDDLETOWN DISTRICT, CONNECTICUT

by

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GEOLOGY

Granitic pegmatites are widely distributed throughout the metamorphic rocks of Connecticut, but they are especially abundant in the vicinity of Middletown. The pegmatite fields of the Middletown district extend from Glastonbury south to Middletown and southeast to Haddam (Fig. 1). In general, the pegmatites have concordant north-south axial trends in the northern portion of the district but become increasingly discordant to the southeast with east-west axial trends in the vicinity of Haddam. The majority of pegmatites exposed in the Middletown district are hosted by metapelites (Collins Hill Formation of Rodgers, 1986), but many pegmatite bodies also are emplaced in gneisses (e.g., the Maromas gneiss)(Cameron et al., 1954; Stugard, 1958). Although the physical properties of host rocks may have influenced pegmatite shape and size, there is no indication at present that host rock lithology had a significant effect on pegmatite distribution or composition. Methot and Brookins (1973) have demonstrated that Rb/Sr systematics of several pegmatites in the district are distinctly different from those of their enclosing rocks, and thus that the pegmatites originated from some other protoliths (that are not exposed) and were emplaced into their hosts with very little chemical interaction. Most studies of oxygen and hydrogen isotopes in similar pegmatite districts also point to limited but intense pegmatite-wall rock interaction, the result of low water/rock volumetric ratios (e.g., Taylor et al., 1979; Taylor and Friedrichsen. 1983; Walker, 1985). The major and minor element compositions of the Middletown pegmatites vary widely throughout the district, but these chemical differences stem from fractionation processes that operated in pegmatite fields elsewhere (e.g., Cerny, 1982). The principal chemical variations are in modal plagioclase/microcline and in the proportions of minor or accessory minerals that contain high concentrations of the incompatible lithophile elements Li, Cs, Rb, Be, Nb, Ta, P, and B. Internal textures also are varied, but these too are controlled by pegmatitic processes that are typical of pegmatite fields elsewhere. In general, graphic quartz-feldspar intergrowths and aplites are associated with unzoned or weakly zoned pegmatites. With increasing chemical fractionation as

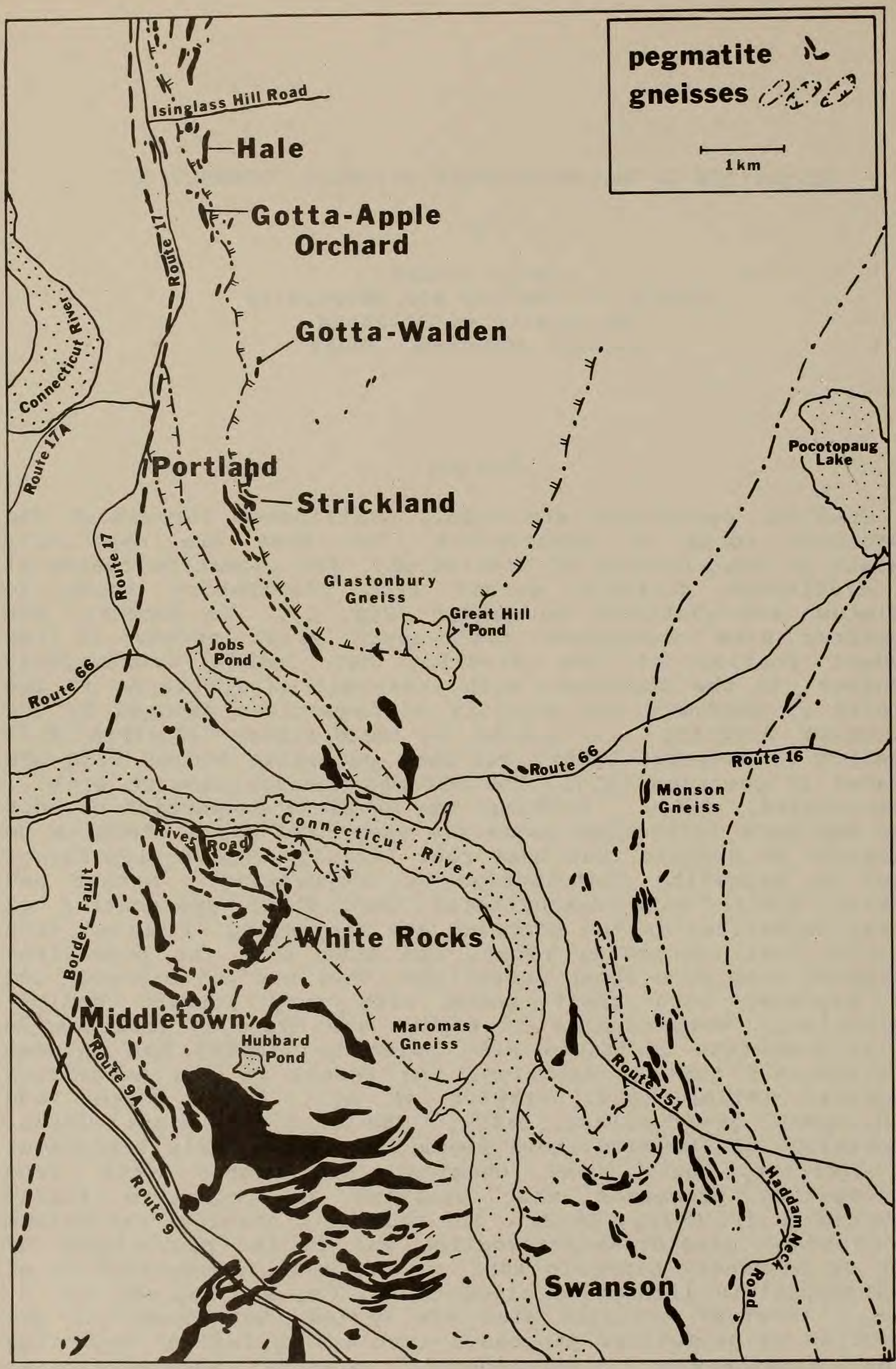


Figure 1. Distribution of pegmatite bodies in the Middletown area. Hachured lines delimit the boundaries of the major gniess formations. Data are from Herz (1955), Stugard (1958), and Eaton and Rosenfeld (1972).

reflected by abundances of rare-element-rich minerals, the pegmatites display increasing mineralogical diversity and zonation. By comparison to other pegmatite districts, the regional chemical and textural zonation of pegmatites in the Middletown district roughly define the directions of pressure-temperature gradients that may have existed at the time of emplacement, or may reflect the folding or doming of isothermal surfaces to yield concentric zonation patterns in present exposures (Figure 2). In this model, compositionally simple pegmatites with graphic and aplitic textures are developed nearest to the parental granite or anatectic source; discretely zoned pegmatites that contain very-coarse-grained microcline, abundant beryl, and quartz-rich cores are further from the magma or thermal center; and complexly zoned, cleavelandite-bearing pegmatites with high concentrations of lithium and other incompatible elements are furthest from source (e.g., see Cerny, 1982). The P-T gradients that are proposed in Figure 2 reflect the fact that with increasing fractionation, pegmatitic magmas contain higher concentrations of more incompatible elements, especially fluxing components such as Li, B, and F. As a result, the most fractionated pegmatites have lower liquidi and solidi, and thus these magmas can migrate down gradients to lower P-T conditions.

Although a variety of pegmatitic rocks are exposed in the vicinity of Middletown (e.g., Erslev, 1976), the characterstic pegmatites of the Middletown district are generally non-foliated, slightly to strongly discordant, and hence were emplaced in a largely atectonic or extensional structural environment after development of the pervasive regional foliation and attainment of prograde metamorphic assemblages. Radiometric isotope systematics yield ages of 260 $\pm$ 3 m.y. (U-Pb, Th-Pb), 258 $\pm$ 1 m.y. (Rb-Sr), and 249 $\pm$ 8 m.y. (K-Ar)(see Brookins et al., 1969; Brookins, 1970). The dates derived from U-Pb, U-Th, and Rb-Sr systematics may be regarded as absolute ages of crystallization. The K-Ar date is interesting because is signifies that the pegmatites cooled from magmatic liquidus temperatures of 600°-700°C to the K-Ar closure temperature of muscovite (approximately 250°C) in roughly 10 m.y. (the relatively large uncertainty in the K-Ar age stems from degrees of retention or loss of radiogenic argon by different host phases, and probably from real variations in cooling ages that are controlled by pegmatite size and the heat contents of pegmatites and their host rocks). Between Middle Haddam and East Haddam, pegmatites that are typical of those of the Middletown group strike east-west and are sharply discordant to the north-south fabric of their metamorphic hosts. In the Moodus area, a north-northwest secondary schistosity developed as feldspathic blastomylonite at medium to high (amphibolite) metamorphic grade cuts the pegmatites, and the pegmatite field is truncated against this zone of blastomylonite, which defines the trace of a ductile shear zone termed the Cremation Hill fault (London, 1984d, 1985c). If the pegmatites involved in this deformation were comagmatic with other pegmatites that have been dated, then two important implications

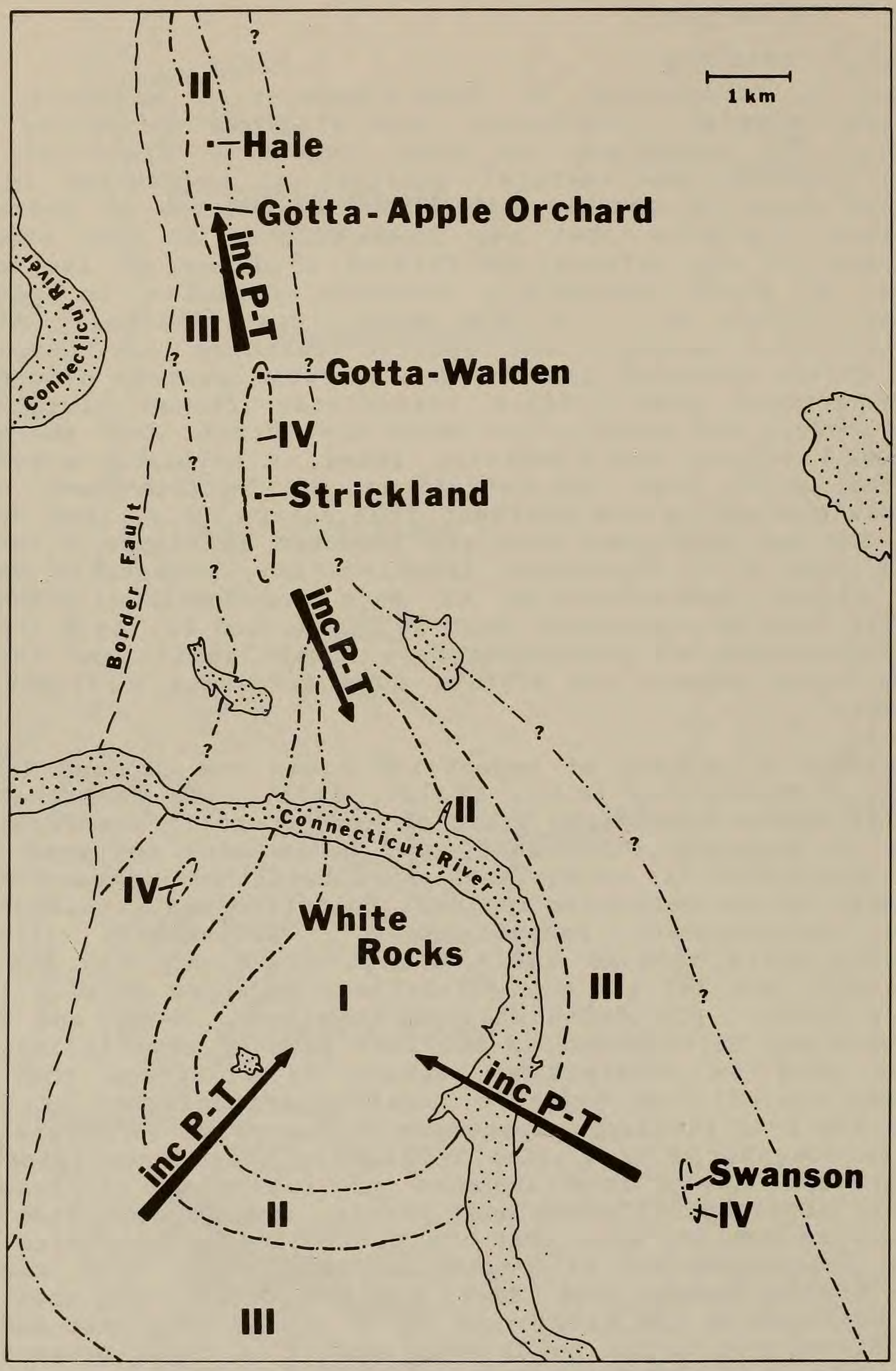


Figure 2. Geochemical zonation of pegmatites in the Middletown district. Pegmatite zonal designations are: I: unzoned microcline-plagioclase-quartz pegmatitic granite; II: graphic microcline-quartz pegmatite; III: zoned microcline-quartz-beryl pegmatite; IV: complexly zoned lithium-rich, rare-element pegmatite. Fractionation increases from I to IV. Note that each successively more fractionated pegmatite type usually contains some or all of the previous, less-fractionated types as outer zones (i.e., lithium-rich pegmatites usually have borders of pegmatitic granite and inner zones of quartz-microcline-beryl pegmatite).

are (1) that regional tectonism (other than Jurassic-Triassic rifting) continued after 260 m.y., and (2) that at the time of pegmatite emplacement, temperatures of hosts at the eastern boundary of the pegmatite field were significantly higher than in rocks to the west. If this last statement is true, then deformed and undeformed pegmatites near and west of the Cremation Hill fault can be expected to give K-Ar ages that are significantly younger than 249 m.y. Future comparisons of absolute and cooling ages within pegmatites may serve to define the thermal regimes at the time of pegmatite emplacement, and differential cooling rates as a function of variable rates of uplift.

There are few means by which the P-T conditions of crystallization can be ascertained in granites or pegmatites. Fluid inclusion analyses and stable isotope systematics usually give unreliable results because of pervasive postentrapment modification of inclusions and extensive retrograde reequilibration of isotopic distributions. Stability relations among the lithium aluminosilicates, however, provide a means by which approximate, sometimes precise P-T conditions can be unequivocally ascertained (London, 1984a, 1986). In the Middletown district, spodumene is the only lithium aluminosilicate mineral (found at the Gotta-Walden prospect and the Strickland pegmatite). If pegmatite liquidus crystallization spanned the approximate range of 600°-700°C, then minimum pressures for spodumene-bearing pegmatites would have been in the vicinity of 3000-4000 bars, with host rock assemblages above the aluminosilicate invariant point and in the sillimanite field (Holdaway, 1971). With respect to regional P-T gradients in the metamorphic hosts as discussed above, it should be noted that rocks on the eastern boundary of the Middletown district record assemblages in the second sillimanite zone, decreasing to first sillimanite zone in the vicinity of Haddam Neck and Higganum, and kyanite zone along the western boundary of the district in Portland.

CHEMISTRY

All of the Middetown pegmatites, even the most fractionated ones, consist principally of quartz, plagioclase, and microcline. Exotic Li-minerals such as spodumene, lepidolite, and amblygonite-montebrasite, Cs-rich beryl and pollucite, and Nb-Ta-Sn oxides are common accessories in some pegmatites but are volumetrically insignificant. The most fractionated pegmatites show only minor amounts of fluorine (mostly in micas and amblygonite-montebrasite) and phosphorus (as apatite, lithiophilite-triphyllite, and amblygonite-montebrasite) but significant enrichment in boron (as reflected by an abundance of tourmaline).

Most studies of pegmatite petrogenesis ultimately focus on the properties or components that serve to distinguish the unusual textures and mineralogies of pegmatites from ordinary granites. The components H_2O, the halides Cl and F, and

incompatible cations such as Li are believed to play major roles in controlling crystallization trends, element partitioning, and fluid properties (e.g., Jahns 1982). The components boron, cesium, rubidium beryllium, and phosphorus may also be important, although their behavior in hydrous granitic melts is not well known.

Most petrologists agree that H_2O plays a major role in the generation of pegmatites and their associated ore deposits. By analogy to experimental results, Jahns and his colleagues have attributed the development of coarse-grained textures, idiomorphic crystal forms, and much of the mineralogical zonation in pegmatites to the separation of an aqueous fluid phase from H_2O-saturated granitic magma early in the crystallization of pegmatite (Jahns and Burnham, 1969; Jahns, 1982). An evaluation of this hypothesis is beyond the scope and intent of this paper; however, there is now evidence that saturation in H_2O is not requisite for the generation of rapidly grown, coarse-grained, idiomorphic crystals in synthetic systems that are analogous to those of natural, highly fractionated pegmatite fluids (London, 1983, 1984b, 1986). Intuitive reasoning suggests that water should be a more effective flux if it is retained in the silicate melt than if it is exsolved, and especially if it dissolves in the silicate liquid in proportions greater than that of albite-H_2O (London, 1986; cf. Burnham, 1979). Thus, large quantities of H_2O should not be necessary to generate pegmatites, and an increasing body of data from pegmatite textures (e.g., Norton, 1983), wall-rock alteration (e.g., Shearer et al., 1984) and stable isotope systematics (e.g., Walker, 1985) are consistent with very low water/rock volumetric ratios in the formation of all types of pegmatites. The development of miarolitic pockets is not contingent on large amounts of exsolved aqueous fluid or on shallow pegmatite emplacement (London, 1983, 1984b, 1985, 1986). Indeed, spodumene, the high-pressure lithium clinopyroxene, is present in miarolitic gem pegmatites in Connecticut, as well as other districts in North America (Maine, California) and around the world (e.g., Afghanistan). In summary, the commonly held notion that much of pegmatite formation results from "crystallization from an aqueous fluid" is probably one of the most important misunderstandings in igneous petrology (Jahns and Burnham, 1969). Indeed, Dick Jahns recognized the confusion that arose from this concept and attempted to clarify matters in his last major paper on pegmatite geology (Jahns, 1982). Pegmatites crystallize from dense silicate melts that contain relatively little water in comparison to the rock volumes that are produced (and in comparison to other types of felsic magmatic-hydrothermal deposits, such as base metal porphyries). At best, pegmatites may crystallize from silicate melt in the presence of an aqueous fluid, whose effects on promoting element partitioning and crystallization rates are still largely unknown.

In the Jahns-Burnham pegmatite model (Jahns and Burnham, 1969), the halogens, principally chlorine and fluorine, have been

regarded as crucial to the dissolution and transfer of mineral components and to extreme element partitioning that leads to pegmatite zonation. Experimental studies of metal solubilities and complexation in aqueous chloride vs. pure H_2O systems generally indicate that Cl does enhance mineral solubilities, especially of alkali components and silica (e.g., Anderson and Burnham, 1967; Flynn and Burnham, 1978; Carron and Lagache, 1980; Webster, 1981; Fournier, 1983). Some recent studies of fluid inclusion compositions in lithium rich pegmatites, however, reveal that primary pegmatitic aqueous fluids have low salinities, generally < 4 wt. % equivalent NaCl (e.g., Foord, 1976; Taylor et al., 1979; London, 1982a, 1983, 1984b, 1985a, 1985b, 1986; cf. Cameron et al., 1953). In spodumene, beryl, quartz, and tourmaline, from miarolitic pockets of the Kulam deposit, Mawi district, Afghanistan, salinities of included aqueous fluids are as low as 0.5 equivalent wt % NaCl, and most are less than 2 eq. wt. % NaCl (London, 1985b, and unpublished data). If Cl contents are low, especially during the primary (vs. subsolidus) stages of crystallization, then the solubilities of most mineral components would be diminished, and fluid/melt partition coefficients would be decreased.

Fluorine has been shown to be effective at enhancing silicate melt-H_2O miscibility and lowering liquidus and especially solidus temperatures of hydrous feldspar and granite melts (e.g., Wyllie and Tuttle, 1961; Koster van Groos and Wyllie, 1968; Manning, 1981); its relevance to pegmatite geology has been recognized in recent years (Jahns, 1982; Cerny et al., 1985). Local concentrations of pink micas (usually called lepidolite) have often been taken as an indication of relatively high fluorine activities in pegmatites; in most cases, however, the bulk of these pink micas are rose-colored muscovites (with Mn chromophore), and are not as F-rich as true lepidolites (e.g., see Rimal, 1962; Munoz, 1971; Rinaldi et al., 1972). The fact that lithian micas of the Connecticut pegmatites do predominate over spodumene is an indication of how low fluorine activities must be in spodumene-bearing pegmatites (London, 1982b). The compositions of minerals in the amblygonite-montebrasite series also can be used to monitor activities of F as HF. Although these are typically referred to as amblygonite (the F-rich member of the solid solution), they usually turn out to be montebrasites with intermediate to low fluorine contents (e.g., Cerna et al., 1972; London and Burt, 1982). Using the d_{131} vs. F x-ray determinative method of Cerna et al. (1973), primary amblygonite-montebrasite from the Strickland and Gotta-Walden pegmatites in Connecticut contain 40 and 45 mole % amblygonite, respectively, and thus the phases should be called montebrasite. Primary montebrasite from Strickland is altered along fractures to a low-fluorine montebrasite (20 mole % amblygonite), as at other localities that have been well studied (e.g., Cerna et al., 1973; Loh and Wise, 1976; London and Burt, 1982). From the equilibrium constant for F=OH exchange (Loh and Wise, 1976) and an assumption of ideal mixing of F=OH (albeit a poor one, because of proton-

proton avoidance), the fluorine activity (as HF) of a fluid phase in equilibrium with a phase of 50 mole % amblygonite at 600°C and 2000 bars is three orders of magnitude below the activity of HF at the minimum field boundary (600°C, 2000 bars) of lepidolite (Munoz, 1971). The magmas from which the Middletown pegmatites crystallized, therefore, contained relatively low fluorine concentrations.

The Middletown pegmatites are not notably phosphate-rich, although manganapatite is abundant in cleavelandite units of zoned pegmatites. Montebrasite and lithiophilite have been found in small quantities at Gotta-Walden and Strickland. In experimental melts, phosphorus behaves in part as a network former, in that it robs the melt of cations and silica tetrahedra of non-bridging oxygens, and as a network modifier, in that its monomers and polymers cut silicate melt structures (e.g., Ryerson and Hess, 1980; Mysen et al., 1981). At the Gotta-Apple Orchard, Gotta-Walden, Strickland, and Swanson mines, apatite-garnet and apatite-tourmaline intergrowths occur in cleavelandite units. The concentration of phosphorus and boron (discussed below) with comparatively alkali-rich rocks (albitites) may be a direct result of complexing between P, B, and alkalis and alkaline earths, and may possibly reflect liquid immiscibility between alkali-phosphosilicate or alkali-borosilicate fluids and silica-rich fluid.

Boron incorporated as tourmaline is abundant in the pegmatites and country rock contacts in the Middletown district, and this is typical of virtually all pegmatite districts around the world (e.g., Page et al., 1953; Cameron et al., 1954; Beus, 1968; Ovchinnikov, 1976). Other than quartz and feldspars, tourmaline is one of few minerals that is present at compositionally simple to complex pegmatites (i.e., it is ubiquitous). Tourmaline is assuming major significance in pegmatite petrogenesis as the role of boron becomes increasingly well understood, and as a growing number of studies demonstrate that the concentrations of the halogens Cl and F may be negligible in typical pegmatite systems (e.g., Chorlton and Martin, 1978; Pichavant, 1981, 1983; London, 1983, 1984a, 1984b, 1985a, 1985b, 1986). In the Middletown pegmatites, tourmaline is locally abundant in altered wall rocks at pegmatite contacts, it is a common constituent of pegmatite border and wall zones, but it is particularly abundant in albitites: both fine-grain aplites and coarse-grained cleavelandite units. In hydrous granitic liquids, boron probably behaves much like phosphorus, but with a distinct tendency to act as a melt network modifier. Experiments with alkali borosilicate systems demonstrate that melts are significantly depolymerized with exceedingly low viscosities (approximately 10^2 poise); crystallization rates are rapid, leading to very-coarse-grained, idiomorphic phenocrysts; silicate liquid-H_2O solubilities are enhanced to the point that complete miscibility may be attained at geologically feasible P and T; and the solubilities of incompatible lithophile cations are greatly increased, probably because of the synergistic

effects of boron and H_2O on melt depolymerization (most of these observations are from London, 1984b, 1986, and also Chorlton and Martin, 1978; Bonniaud et al., 1978; and Pichavant, 1981, 1983). It is important to note that experiments of London (1984b, 1986) produced euhedral albite, quartz, and petalite phenocrysts up to Ø.5 mm in 48-72 hour runs at vapor-undersaturated conditions (i.e., of complete silicate-H_2O miscibility). This can be interpreted to signify that coarse-grained, euhedral textures are not unequivocal evidence of the presence of an exsolved aqueous fluid phase. Although complete silicate fluid-H_2O miscibility may exist in borosilicate fluids at moderate pressures, alkali borate-silica immiscibility is well documented in anhydrous experiments (e.g., Pichavant, 1983; Hervig and Navrotsky, 1985); this is because of the strong tendency for boron, like phosphorus, to form polymers that may coalesce to a separate fluid, and to form strong B-O-M^+ bonds. This leads not only to liquid immiscibility but also expands the quartz saturation field by increasing the silica content and silica tetrahedral polymerization in the fluid that coexists with the alkali borate-rich fluid. In pegmatites, the evidence of such liquid immiscibility may be quartz-rich cores with razor-sharp and smooth contacts with tourmaline- and phosphate-rich albitites.

ECONOMIC GEOLOGY

Much of the pegmatite mining in the Middletown district early in this century was for mica, feldspar, beryl, and especially gemstones (e.g., at the Strickland, Gillette, and Swanson mines); many of the pegmatites produced beryl and mica during the 1940's (Cameron et al., 1954); at present, the only commercial mining of pegmatites in the district is for ceramic-grade microcline, and this is the only economic commodity of the Middletown pegmatites in the forseeable future. Bulk mining of mica from weathered schists and granites and beryllium minerals from zeolitized tuffaceous rhyolites has largely replaced pegmatitic sources for these commodities. Pegmatites continue to be important sources of Nb-Ta-Sn oxides, but these phases occur only in trace amounts in the Middletown pegmatites. If such rare-element enriched pegmatites ever existed in the Middletown district, they would have been structurally highest and farthest from source; thus, they have been eroded, or buried by sediment in the graben of the Connecticut Valley to the west. Some of the Middletown pegmatites (e.g., Gotta-Walden, Strickland, Gillette, and Swanson) still have potential to produce gemstones and mineral specimens for collectors, but these operations are labor-intensive and generally cannot sustain gem mining as a sole economic activity.

DESCRIPTIONS OF STOPS

The Hale, Gotta-Apple Orchard, and White Rocks pegmatites are actively quarried, so it is not possible to describe precisely what the exposures will look like at the time of the trip. The Gotta-Walden and Swanson mines are inactive; the

Strickland pegmatite is shown on Figure 1 because it is one of the larger and better-known exotic pegmatites of the district, but we will not visit it on this trip.

All of the localities are on private land, and permission to enter the properties must be obtained from the owners or operators. In addition, all participants will be required to sign waivers that release property owners from all liability for personal injury and loss or damage to personal property. In addition, MSHA regulations require that all participants wear hardhats, safety glasses or goggles, and reinforced boots into active quarries. Participants must provide their own safety equipment.

ROAD LOG

From New Haven, proceed north on I-91 to the interchange for Rt. 9 southbound (approximately 25 miles from downtown New Haven), and take Rt. 9 south for 3.5 miles to exit 3 at West Street in Cromwell. Take exit 3 south, and we will convene the trip at the north end of the nearby K-Mart parking lot. Allow about 45 minutes for the drive from New Haven, and be prepared to leave the K-Mart lot by 9:ØØ AM. If you have not brought a lunch, we will have several opportunities to stop for food.

Ø.Ø	The trip log begins at the K-Mart parking lot. Return to Rt. 9 south to Middletown.
2.9	First traffic signal on Rt. 9, turn right under the railroad overpass and proceed uphill to the rotary in front of St. John's church.
3.1	Turn left at the rotary onto Main Street in Middletown. Proceed through Middletown on Main Street, past the Middletown Green and straight on the Main Street Extension.
4.1	Turn left off of Main Street Extension onto Cooley Avenue; follow the signs to the Middletown Post Office.
4.2	Turn right off of Cooley Avenue onto East Main Street, still following signs for the Middletown Post Office.
4.3	At the traffic signal, turn left onto Silver Street.
4.7	Cross over Rt. 9 on Silver Street, continue straight on Silver Street uphill and past the Connecticut Valley Hospital.
5.4	Bear right off of Silver Street onto River Road.
5.6	Pass WCNX radio station.

6.6 Turn right off of River Road uphill into the White Rocks quarries of the Feldspar Corporation.

The White Rocks quarries (Figure 1) are located near the apparent center of the pegmatite district. As a whole, they are primitive pegmatites in that they possess simple compositions and generally poorly developed zonation. Contacts with wall rocks are generally sharp without conspicuous metasomatic alteration. Negligible tourmalinization and coarsening of quartz-feldspar-biotite schists are developed locally. There are many pegmatite bodies in the vicinity of White Rocks. As in other districts, these pegmatites probably formed a stockwork through their host rocks. At early stages of crystallization, the fluid communication through the system was good, and compositional gradients established by liquid-state diffusion or zone refining were transmitted through the entire system. As the degree of crystallization increased, the pegmatites may became sealed off from each other and evolved along separate crystallization trends. The pegmatites at White Rocks were almost certainly interconnected, as evidenced by uniform zonation and fractionation trends through many individual bodies. The present quarry exposures are in homogeneous and poorly zoned pegmatite. Toward the west in exposures that are not inaccessible because of mining and backfill, the homogenous and graphic pegmatites evolved to well zoned bodies with almost monominerallic microcline "blocks" sharply bounded against essentially pure quartz pods or "cores"; beryl was abundant but only occurred at the microcline-quartz contacts. One small pegmatite in the westernmost cuts contained a small pod of cleavelandite albitite with lithian mica, polychrome tourmaline, cesian beryl, and accessory microlite. These observations, collected over the past ten years through numerous visits (London, unpublished data), reflect a sharp zonation pattern with increasing fractionation from the center of the White Rocks hill to the west (Figure 2).

In the active quarries, the pegmatites consist predominantly of two zonal assemblages: (1) homogeneous, medium-grained (2-5 cm), microcline-plagioclase phenocrysts with interstitial quartz and accessory garnet, biotite, muscovite, and tourmaline, and (2) graphic quartz-microcline intergrowths. In the first assemblage, scaly muscovite is pseudomorphous after coarse biotite sheets. The contacts between these two zones appear to be gradational through an intermediate texture in which microcline becomes coarsely porphyritic and graphic. Single microcline crystals with graphic quartz intergrowths attain dimensions of approximately 1 meter. Not all coarse-

grained microcline is graphic; some large, quartz-free crystals mark the incipient development of what are termed block microcline zones, which denote the abrupt transition to pegmatitic zoning as reflected by almost quantitative separation of quartz and feldspars. Columbite is a common accessory of the incipient block microcline zones at White Rocks.

Some exposures display intersecting tabular pegmatite dikes that cut the graphic pegmatite. On close inspection, however, the cross-cutting pegmatite dikes are not separate intrusives that are discordant to and significantly later than the graphic pegmatite. The graphic pegmatite grades continuously into the pegmatite dikes; in fact, the pegmatite dikes are developed within single graphic microcline crystals, such that microcline and quartz within the dikes and in the graphic pegmatite on either side are crystallographically continuous. The pegmatite body as a whole apparently was able to sustain shear during crystallization; one possible interpretation is that rapid deformation of partially crystallized pegmatite produced shears in the viscous aluminosilicate liquid, with resultant diffusion of H_2O down pressure gradients toward the shear zones leading to enhanced crystal growth rates and thus coarser grain size in the residual liquid of the pegmatite "dikes".

The origin of graphic microcline-quartz textures was much debated in the early part of this century but now is generally acknowledged to represent simultaneous crystallization of quartz and feldspar. The explanation advanced by Fenn (1979) is that feldspar growth rate exceeds component diffusion rates through the crystal boundary liquid. Crystallization of feldspar on topographic "highs" (e.g., by step growth along edge dislocations) produces liquid that is depleted in feldspar components but enriched in silica in the "valleys" between highs; this leads to saturation in quartz in the valleys. In addition, for graphic textures to be produced instead of granitic textures, crystal nucleation rate and nucleation density must remain low.

6.6 Leave the White Rocks quarries, return to River Road, turn left, proceed back to Silver Street, turn left onto Silver Street, retrace the route back to the Post Office.

8.9 At the traffic signal at the intersection of Silver Street and East Main, continue straight on Silver Street.

9.Ø Turn right onto Main Street Extension. Continue straight on Main Street Extension to downtown Middletown.

9.5 Turn right off of Main Street onto Monitor, proceed Ø.1 miles to a parking lot behind Burger King, which is where we will buy lunch. Rather than eat at the Burger King, we will take our food to the Hale quarry.

9.7 At Monitor and Main, turn right onto Main Street and continue through Middletown.

9.7 Bear left at the rotary in front of St. John's church, follow the signs for Portland and Rts. 66E and 17N.

Cross the Connecticut River into Portland.

11.3 The first traffic signal upon entering Portland is at the junctions of Rt. 17A and Rt. 17N/66E. Proceed straight through the traffic signal on Rt. 17A through Portland.

13.1 Pass the Portland Fire Department.

14.1 Stop sign at the intersection of Rts. 17A and 17. Turn left (north) onto Rt. 17 towards Glastonbury.

15.1 Pass Gottas Farm Store.

16.2 Turn right onto Isinglass Hill Road.

16.4 Turn right into the Hale quarry off of Isinglass Hill Road.

The Hale, Gotta-Apple Orchard, and Gotta-Walden bodies appear to be portions of one large pegmatite system that strikes north-south with a moderate westerly dip. The principal features to see at the Hale and its extension to the Gotta-Apple Orchard quarry are: (1) banded albite-quartz-(garnet)-(tourmaline)-(muscovite)-(apatite) aplites, (2) graphic quartz textures in individual very-coarse-grained microcline crystals, (3) block microcline-beryl-quartz pods, and (4) the spatial distributions of aplite-pegmatite zonation and the location of abundant tourmaline. The Gotta-Walden prospect exposes (1) a cleavelandite unit with abundant garnet and accessory tourmaline and apatite, and (2) a very-coarse-grained, non-graphic zone of block microcline with abundant muscovite at the apex or "hood" of the pegmatite. Although the textures are quite different, the strike and dip of the dike and the distributions of internal zones (by composition) are identical to those at Hale and Gotta-Apple Orchard.

If conditions are dry, we can drive from the Hale quarry past the powder magazines east of the cut to the Gotta-Apple Orchard extension. Alternatively, we will double back on Isinglass Hill road to Rt. 17S to the entrance to the Apple Orchard quarry, as follows:

16.6 To get to the Gotta-Apple Orchard quarry, leave the Hale quarry, return to Isinglass Hill Road, left on Isinglass Hill Road to Rt. 17, left (south) on Rt. 17.

17.2 Turn left off of Rt. 17S onto the asphalt road that leads uphill through the apple orchard to the quarries. The entrance to the apple orchard is marked by a silver metal gate. The quarries are about 1 mile up the road.

The Hale and Gotta-Apple Orchard quarries are discussed together, because they represent portions of the same pegmatite dike. In both quarries, aplites consist principally of albite and quartz with minor garnet and tourmaline and accessory muscovite and apatite. Fine banding defined by alternating concentrations of quartz, albite, and garnet form smooth layers and crenulated masses. In general, the layers are flat and parallel, except in the vicinity of large crystals of microcline or massive quartz; at these intersections, the banding in the aplites commonly deflects around the large crystal. Thus, the crenulations appear to result in part from unidirectional growth and deflection around small perturbations on the inwardly directed solidification surface. The growth of large microcline crystals may also have depleted the boundary fluid in feldspar components and thus led to slowed aplite formation in their vicinity. In most igneous rocks, unidirectional solidification produces comb layering, in which non-equidimensional crystals have their fast growth directions oriented perpendicular to the solidification front. The crystals of microcline within the aplites are oriented perpendicular to the aplite bands and flare inward toward the center of the pegmatite; beryl and tourmaline in most pegmatites near Middletown have a similar comb-textured orientation with their long axes perpendicular to pegmatite borders and flaring into the pegmatite. The tourmaline in aplites at Hale and Gotta-Apple Orchard, however, is generally foliated parallel to layering, or perpendicular to the presumed growth front. This observation suggests that at least some of the layering in the aplites could have resulted from flow segregation of phenocrysts. At the Gotta-Apple Orchard quarry, there is no simple relation between the orientation of aplite bands and the pegmatite contacts (i.e., the aplite banding is not parallel to pegmatite contacts). Aplite layers cut pegmatite, but more commonly pegmatite dikes appear to cut aplite.

Lineated and foliated quartz-muscovite intergrowths that are "axial planar" to the aplite crenulations project into coarse-grained quartz-microcline pegmatite. The microcline crystals, especially in the Hale quarry, usually but not always contain graphic quartz. Single microcline crystals contain graphic and non-graphic portions, suggestive of continuously or episodically changing conditions (perhaps changes in activity of H_2O) during crystallization. As at White Rocks, beryl at the Hale quarry is found only where coarse microcline crystals project into small pods of massive quartz.

Coarse tourmaline is abundant only on the western margin of the pegmatite in coarse-grained microcline-quartz pegmatite (in both quarries). This tourmaline displays the inwardly expanding or flaring habit that is typical of border zone tourmalines at pegmatites throughout the world. The only conspicous wall-rock alteration at either the Hale or Gotta-Apple Orchard quarries is along these tourmaline-rich borders, where foliated hornblende gneisses are altered pseudomorphously to tourmaline + quartz, with detailed preservation of layering and foliation. Coarse tourmalines of the wall and border zones and within the microcline-quartz pegmatite possess different pleochroic zones that correspond to different tourmaline compositions. The nature of the compositional variations are not known at this time. It is interesting to note, however, that tourmalines in the aplites are generally unzoned, and their pleochroic schemes correspond to those of the outer overgrowths of tourmaline in the coarse pegmatite. This zonation could signify that tourmalines in the pegmatitic zones started to crystallize before those of the aplite, and hence that aplite crystallization followed that of pegmatite.

The border-to-border sequence of aplite -> graphic microcline -> microcline + quartz pegmatite -> tourmalinized wall rock is a classical zonation in shallowly dipping pegmatites. The sequence of layered albitic aplites on the lower or footwall, grading upward into coarse-grained microcline pegmatite, and wall-rock alteration along the upper or hanging wall only, defines the zoning sequence in layered aplite-pegmatite intrusives of San Diego county, California; these pegmatites served as the basis for an important model for pegmatite crystallization that was proposed by Dick Jahns (Jahns and Tuttle, 1963). Jahns' explanation for such non-concentric layered sequences involved the upward migration under gravitational gradients of exsolving aqueous fluid; partitioning of components between H_2O-saturated melt and aqueous fluid

provided the means of producing compositional gradients in fluids that resulted in heterogenous, zoned rocks. This model is receiving considerable scrutiny in current pegmatite research. At the Hale and Gotta-Apple Orchard pegmatites, however, the albitic aplites are on the hanging wall, and the coarse microcline pegmatite plus tourmalinized wall rock are on the foot wall; thus, the pegmatite zonation is upside down and could not have been produced by graviationally induced melt-vapor separation, unless the pegmatites have been overturned more than 90° by rotational deformation since their crystallization. There is no evidence of internal deformation in the pegmatites, nor any specific model for such regional deformation in the metamorphic rocks.

19.1 Return to Rt. 17, turn left (south).

19.4 Turn left at the fork off of Rt. 17 onto Cotton Hill Road.

19.6 Continue straight on Cotton Hill Road to the parking lot for Walden's Rock Shop; park next to the shop.

The Gotta-Walden prospect is reknown for gem beryl and rarer phases such as spodumene and pollucite. The pegmatite, however, is compositionally and zonally very similar to the Hale and Gotta-Apple Orchard: cleavelandite albitites with garnet, tourmaline, and apatite on the western hanging wall grade eastward into coarse microcline pegmatite on the foot wall. The exotic Li minerals and beryl, however, are concentrated in the albitite. Of special interest here are nodular garnets in the albitite that are rimmed by manganapatite and tourmaline. Garnet-tourmaline-plagioclase and garnet-manganapatite-plagioclase equilibria are capable of buffering activities of boron and phosphorus, respectively. The relative modal proportions of these phases at Hale, Gotta-Apple Orchard, and Gotta-Walden imply that the albititic liquid components of these pegmatites were not rich in B and P, either because these components were not enriched in the bulk pegmatite fluid, or because they diffused or were partitioned into some other liquid component of the pegmatite system, or were lost to the wall rocks (e.g., London, 1984c).

Exposures at the Hale, Gotta-Apple Orchard, and Gotta-Walden pegmatites display several important characteristics of pegmatitic mineralogical zonation: contacts between feldspar-rich zones are abrupt but gradational, whereas feldspar-quartz zonal contacts are razor sharp. Pegmatite masses can be divided into two fundamental components: one that is feldspar-rich, and

the other quartz-rich; the feldspar component is either sodic or potassic; the two feldspars rarely occur together in nearly equal proportions. Aplite-pegmatite contacts at these Connecticut pegmatites are typical of feldspar (albite)-feldspar (microcline) zonal contacts in that they are abrupt but not as sharp as feldspar-quartz contacts. Boron- and phosphorus-rich minerals are concentrated in feldspathic zones, especially in the albitites (aplites and cleavelandite units), and beryl is concentrated at feldspar (albite or microcline)-quartz zonal contacts. As noted above, the chemical segregation of components in pegmatite systems has been previously ascribed to the effects of element partitioning during exsolution and gravitational ascent of a comparatively saline aqueous fluid from silicate melt (Jahns and Burnham, 1969). The Cl and F contents of pegmatitic fluids, however, are usually quite low, so that aqueous fluids should not be capable of dissolving and transporting large quantities of material. There are a number of other arguments against the involvement of large quantities of saline aqueous fluid in the chemical segregation of pegmatitic magmas (e.g., London, 1985a, 1985b, 1986). One explanation that does not require silicate-H_2O immiscibility is that of liquid-state segregation, termed thermogravitational diffusion, of components under thermal and gravitational gradients. Thermal gradients in pegmatites probably are small but may be of the order of 50°-$100^{\circ}C$; over several million years, such gradients would certainly cause major redistribution of components (e.g., see Orville, 1963). Gravitational gradients may be especially effective in pegmatitic magmas if they are highly depolymerized. Thermally and gravitationally induced chemical segregation is a precursor to liquid immiscibility, and silicate-silicate liquid immiscibility is a real possibility for pegmatitic systems. Such immiscibility would be promoted by the relatively high concentrations of boron and phosphorus in pegmatites, which form such stable complexes with alkalis that these components are significantly removed from the residual silicate liquid. In simple synthetic systems, immiscibility is prevalent, and the immiscible fluids are alkali borate or phosphate liquid that coexists with essentially pure silica. Evidence of such immiscibility in pegmatites might be manifest as the tourmaline- and phosphate-rich albitites that have sharp, smooth, sometimes convoluted contacts with essentially pure massive quartz. Silicate liquid-H_2O immiscibility probably does occur at early stages in most pegmatites, but if the exsolved aqueous fluid is relatively pure H_2O, then it may have a comparatively minor effect on bulk redistribution of elements (n.b. that an assumption of Burnham's (1979) albite-H_2O model is that the activity of albite

component in aqueous fluid that coexists with H_2O-saturated albite melt is essentially zero). In hydrous silicate liquids that are fluxed by boron, phosphorus, and fluorine, H_2O will tend to redissolve or homogenize back into the melt as the contents of hyperfusible components are increased by fractional crystallization of quartz and feldspars, and as the compositional differences between melt-aqueous fluid solvus pairs are minimized. Significant amounts of H_2O may be released only during the late-stage crystallization of these fluids, so that most exsolved aqueous fluid probably exists late in the history of pegmatite consolidation during subsolidus rather than primary magmatic conditions.

19.8 Leave Walden's Rock Shop, proceed south on Cotton Hill Road back to Rt. 17, turn left (south) onto Rt. 17.

20.9 Stop sign at the intersections of Rts. 17 and 17A. Continue straight through the intersection on Rt. 17S.

22.8 Stop sign at the junction of Rts. 17 and 66. Turn left onto Rt. 66E. There is a Dairy Queen at this intersection for those who need refreshment.

25.0 Pass by roadcuts of massive, unzoned pegmatitic granite.

25.8 Traffic signal at the intersection of Rts. 66 and 151 in Cobalt. Turn right onto Rt. 151. Proceed through Middle Haddam.

28.2 Bear left at the traffic signal at the entrance to Hurd State Park. Continue on Rt. 151, which is now called Moodus Road.

29.0 Turn right off of Rt. 151 onto Haddam Neck Road. The turn is marked by a sign for the Connecticut Yankee Information Center.

29.7 Continue on Haddam Neck Road past a series of red barns.

29.8 Cross under powerlines.

29.9 Turn left at the Haddam Neck Fire Department and park in the southwest corner of the lot.

Cross the road and hike approximately 0.3 miles along a path that leads to the Swanson mine under the powerlines on the north side of an electrified livestock fence. As you near the Swanson mine, the path forks in front of a large hill of outcrop; bear right to the Swanson mine dumps.

The Swanson mine was prospected and successfully operated for gem beryl during the 1940's (Cameron et al., 1954). Although very little of the pegmatite is now exposed, the dumps still provide samples of the exotic mineralogy of this highly fractionated pegmatite. The prospect is developed in a small portion of a much larger and compositionally ordinary microcline-rich pegmatite; however, microcline is scarce at the Swanson. The two zonal constituents of of the Swanson pegmatite are massive quartz (core), and cleavelandite albitite that contains abundant beryl, polychrome tourmaline, manganapatite, lepidolite, garnet, cassiterite, microlite, and triplite (a Mn-fluorophosphate); the presence of triplite at the Swanson may signify that the chemical activity of fluorine species was higher here than at other pegmatites of the district; however, the fluorine species would have been largely halide salts (leading to the production of micas), rather than HF (there is no topaz) (London, 1982b). The relative abundance of Nb-Ta-Sn oxide minerals here probably is a direct consequence of the depolymerizing effect of the boron and phosphorus that were obviously important constituents of the albitic liquid. With increasing depolymerization, the melt structure is sufficiently "open" and disordered that comparatively high quantities of incompatible elements may be retained in solution. When the fluxes are removed from such fluids, as by the crystallization of tourmaline and phosphates, the albititic and exotic ore components of the fluid are also dumped from solution.

End of trip. Return to Rt. 66 via Haddam Neck Road and Rt. 151.

Mineralogical and textural variations such as those of the Middletown pegmatites are what have made pegmatite geology so alluring to so many petrologists. Complex as they are, these exposures present only a few of the many pegmatitic features that hold a wealth of untapped data on basic inorganic periodic chemistry, partition coefficients, fluid properties, crystallization processes, and cooling histories. The P-T conditions of many pegmatites can now be evaluated by combinations of lithium aluminosilicate stability relations (London, 1984a), fluid inclusions (e.g., London, 1986), and stable isotope geothermometry (e.g., Taylor and Friedrichsen, 1983). In the future, further insight into pegmatite petrogenesis will require an improved understanding of the properties of the pegmatitic fluid phases from emplacement through subsolidus conditions, and of the causes of chemical and hence mineralogical zonation.

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