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Contributions of crystallography, mineralogy, and petrology to the geology of the Lucerne pluton, Hancock County, Maine[1]

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Abstract

Mineralogical studies of the Lucerne pluton, Hancock County, Maine, have established the pre-intrusive geology and the intrusive nature of the pluton, contributed to the interpretation of gravity and magnetic anomalies, explained geomorphic features surrounding the pluton, and identified post-plutonic faulting. The pluton is a biotite granite, rich in alkali feldspar, containing both seriate and porphyritic facies. Post-intrusive faulting, followed by erosion, has exposed two levels of the pluton. The northern, or higher, level has a slightly greater Fe/(Fe + Mg) but is lower in total Fe + Mg. Five percent of the alkali feldspars in both facies are mantled by An_{24} plagioclase. The alkali feldspars are microcline perthites of $Ab_{20-40}Or_{80-60}$ composition.

Biotite, which varies in Ti and Al contents, was the primary major phase to crystallize from the magma, closely followed by the apparently simultaneous crystallization of plagioclase, quartz, and alkali feldspar. Most of the magmatic crystallization took place at 1–2 kilobars total pressure at temperatures between 650° and 700°C. Boron may have been a significant constituent. The source region for the magma may have been a previously metamorphosed graywacke containing quartz, plagioclase, alkali feldspar, and biotite.

Introduction

Minerals make up a large part of the inorganic natural substances found within the earth. If we exclude liquids and natural glasses, then almost all rocks are made up of minerals. The properties of the rocks are dependent upon the configurations of the minerals that they contain. I would like to share with you some of the contributions that mineralogy has made to my understanding of the Lucerne pluton in central Maine.

Mineralogy impinges on geological studies in many ways. The most fundamental is the recognition and classification of rocks. The development of a given stratigraphy, the recognition of separate igneous events, and the description of structural elements within an area are all dependent on the recognition of minerals, their morphology, and their orientation.

Although my title includes crystallography, I will use that discipline within the Mineralogical Society's triad of interests as fundamental to the mineralogical observations that I will be sharing with you. Without crystallography we would not understand the basis of the optical measurements made in thin sections, the morphology and polymorphism of feldspars and alumino-silicates, or thermodynamic models of mineral solid solutions, or recognize the ductile deformation of quartz. Crystallography is fundamental to all the phenomena discussed in this article.

The Lucerne pluton (Fig. 1) is located near (but, unfortunately, not on) the Maine seacoast, just east of the Penobscot River. Six hundred seventy-two km^2 in area, it is one of the ten largest plutons in New England and is located in a region of geological complexity. I chose it for study as a pluton that had not been mapped, had sufficient outcrop to make modal and chemical studies feasible, and was large enough to represent a significant intrusive event in its own right. The project also has uncovered new regional relationships. The chemical and modal data of the

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Fig. 1. Location of the Lucerne pluton.

Lucerne pluton are similar to those of neighboring plutons, but the Lucerne is distinct in its texture and mineralogy.

Geologic setting

The geology of coastal Maine can best be described as a collection of fault-bounded blocks, each of which has a unique stratigraphy. The multiple deformations and high grades of metamorphism that characterize these rocks have obliterated much of the stratigraphic and paleontological evidence for the ages of the rocks of this area. Stewart and Wones (1974) and Wones and Stewart (1976) suggested that there are three or four major crustal blocks in the area; Osberg (1974, 1978) has suggested two or three. The Lucerne pluton intrudes all but the most northwestern of these blocks, from which it is separated by the Norumbega fault zone (Fig. 2).

The stratigraphy of each fault-bounded block is presented in northwest–southeast cross sections (Fig. 2 and 3). The most southeasterly block, the Ellsworth block, contains the Ellsworth Schist, a polydeformed quartzo-feldspathic chlorite-rich schist. Southwest of the area studied, the Ellsworth Schist is unconformably overlain by the Castine Volcanics, a Silurian–Devonian unit containing conglomerate, schists, agglomerates, pyroclastic deposits, and lava flows (Osberg, 1974; Stewart and Wones, 1974). To the

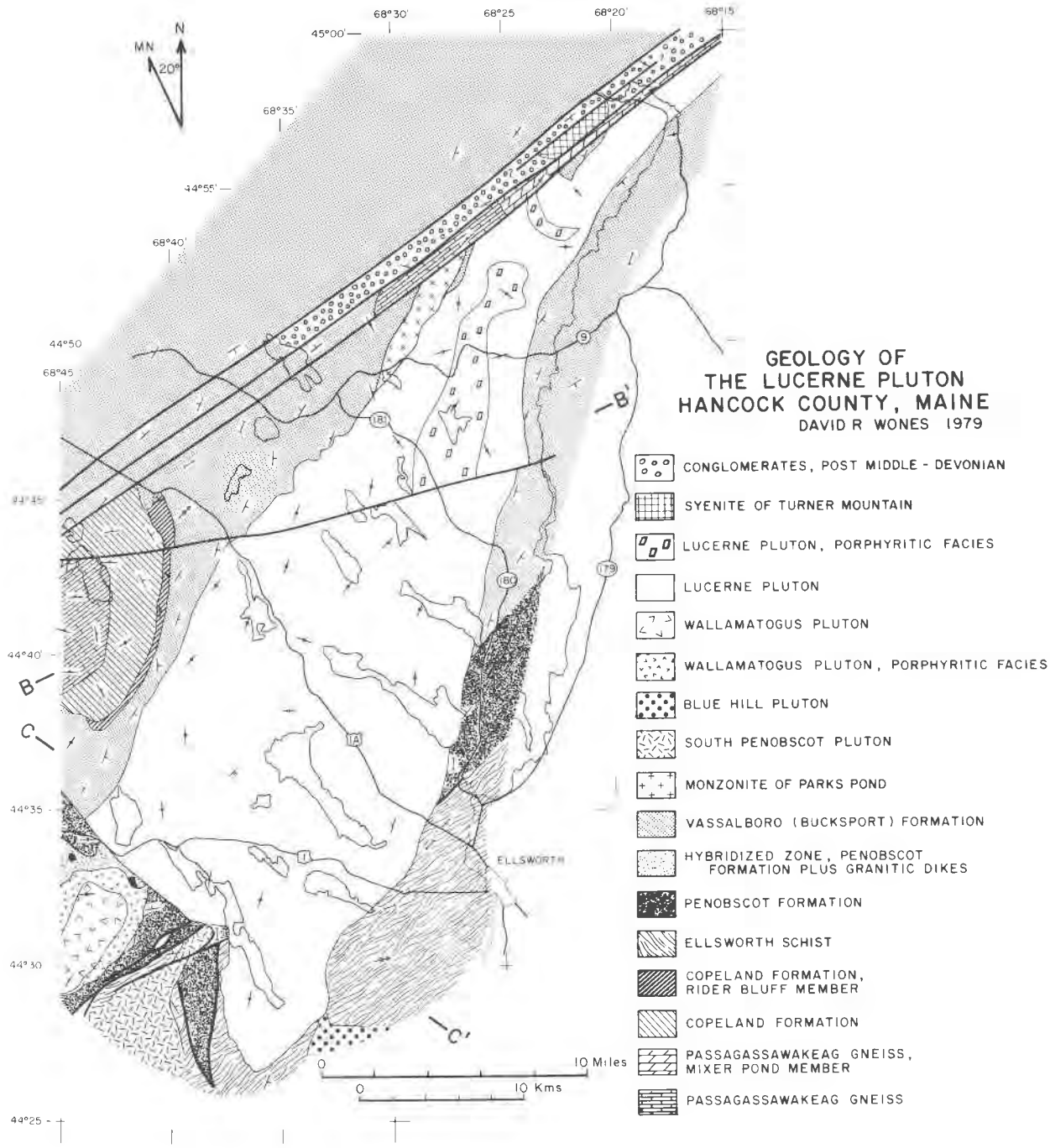

Fig. 2. Generalized geologic map of the Lucerne pluton.

northeast, in New Brunswick, the Ellsworth block projects into a terrane that contains the Green Head Formation of Precambrian age (Stewart, 1974; personal communication).

The Ellsworth block is bounded on the north by the Turtle Head fault zone (Stewart, 1974). Stewart and I interpret this zone as a right-lateral strike–slip fault, although Osberg (1978) has suggested that it is a thrust fault. This fault zone displaces the South Penobscot pluton by 2–4 km. The Turtle Head fault zone is intruded by the Lucerne Pluton, and there is no evidence of displacement along this zone after the intrusion.

Northwest of the Turtle Head fault zone lies the Penobscot block. This block is named for the Penobscot Formation, a graphitic, sulfide schist made

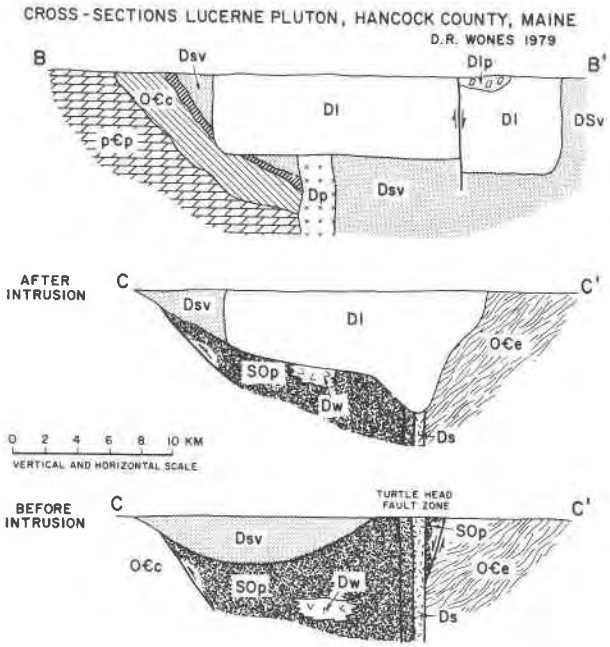

Fig. 3. Cross sections through the Lucerne pluton. Locations of cross sections are indicated in Fig. 2. Symbols for formations as in Fig. 2.

up of thin (0.5–5 cm) beds of siltstone intercalated with pelitic beds of variable (0.5–50 cm) thickness. The Wallamatogus pluton, made up of muscovite–biotite granite, intrudes the Penobscot Formation, and is confined to this block. Similar granitic rocks have been found in the Belfast region (Bickel, 1976; Stewart, 1974) to the southwest, and in the Pleasant Mountain region to the northeast. Dikes of monzonite and gabbro also have been observed in the Penobscot block.

West of Penobscot Bay, Bickel (1976) has mapped the western contact of the Penobscot Formation (and the Penobscot block) as a fault. The rocks west of this boundary are complexly folded and polymetamorphosed. The oldest of these units is the Passagassawakeag Gneiss. Osberg (1978) has suggested that this fault continues to the northeast as the contact between the Penobscot Formation to the southeast and the Vassalboro Formation to the northwest. Wones (1976) has suggested that this contact is an unconformity between the Vassalboro Formation and the Penobscot Formation. Ludman (1978) has demonstrated that the analogous contact near the St. Croix River is a reverse fault, but Ruitenberg and Ludman (1977) have suggested that the Waweig Formation in New Brunswick is coeval with the Vassalboro (Flume Ridge) Formation and unconformably overlies the Cookson (Penobscot?) Formation. Clearly the Penobscot Formation lies in fault contact against the Passagassawakeag block, but whether this faulting precedes or follows the deposition of the Vassalboro Formation is uncertain.

The Passagassawakeag Gneiss is not found northwest of the Norumbega fault zone. This fault zone truncates the Lucerne pluton (Wones and Thompson, 1979; Wones and Stewart, 1976) and displays right lateral offset of unknown total amount.

The Vassalboro Formation, a calcareous pelite containing laminar beds of silty and shaly material, contains beds of sulfide-bearing pelite, 10 to 100 cm thick. The Vassalboro Formation is assumed to be Silurian or Early Devonian (Osberg, 1968) and is probably equivalent to the Kellyland (Larrabee *et al.*, 1965), Bucksport (Trefethen, 1950), and Flume Ridge (Ruitenberg and Ludman, 1977) Formations. The Vassalboro Formation lies on both sides of the Norumbega fault zone. This implies that the Norumbega fault zone may not be a large feature, except that rocks similar to the Vassalboro are known from Long Island Sound in the south to the St. John River in New Brunswick. Unfortunately, at present there is no rigorous estimate of the motion associated with this fault zone.

The number of blocks is dependent on the magnitude of the Norumbega fault zone. Stewart and I split the Passagassawakeag and Vassalboro Blocks at the Norumbega fault zone. Osberg (1978) treats them as a single block.

The Lucerne pluton intrudes a group of fault-bounded blocks of disparate stratigraphies of early to middle Paleozoic age. The faults bounding these blocks were active in Paleozoic time and have been described as strike–slip faults, thrust faults, and reverse faults. The northern portion of the Lucerne pluton has been removed by faulting, and has not been located as of this writing. The rocks of the Bottle Lake Quartz Monzonite (Bottle Lake Complex of Ayuso, 1979) to the NE have been carefully examined by myself, Douglas Tietbohl, and Robert Ayuso, but we have not found granitic rocks petrographically similar to the Lucerne pluton NW of the Norumbega fault zone.

The definition of these formations, their contacts, their deformational histories, and their metamorphism has been accomplished through the use of mineralogy. To be sure, the hand-specimen observations do not require sophisticated equipment for this purpose, but years of mineralogical investigations give us a high degree of confidence in our definitions of formations and interpretations of their history.

Geology of the Lucerne pluton

The intrusive nature of the Lucerne pluton can be observed in a variety of locations (Wones, 1974, 1976) (Fig. 2). In North Penobscot, Maine, an apophysis of the pluton, 100 m wide, exploits a preexisting fault zone between the Penobscot Formation and the South Penobscot pluton. Rotated xenoliths of both the Penobscot Formation and the South Penobscot pluton can be found within the apophysis of the Lucerne pluton. Dikes of the Lucerne can be found within both country rocks within a few meters of the contact. The dikes are coarse-grained; single crystals of alkali feldspar are found across the entire width of the small (2–4 cm) dikes.

Large dikes of the granite of the Lucerne pluton can be found in the hybrid zone of the Penobscot Formation southeast of the town of Orland. These dikes are approximately 2 to 4 m wide and intrude a zone of Penobscot schist previously intruded by diorite, gabbro, monzonite, and muscovite–granite dikes.

The western boundary of the Lucerne against the Vassalboro is relatively straight where the pluton intrudes the Vassalboro Formation. The intrusive nature of the contact can be seen one half mile north of Dedham, on Route 1A NE of Dedham Elementary School, on the summit of a small hill NW of Hatcase Pond, on Blackcap Mountain, and SW of Parks Pond. At Parks Pond the Lucerne pluton intrudes the Parks Pond Monzonite and inclusions of the monzonite can be seen within the granite (Cavalero, 1965). Along the entire western boundary, dikes of the Lucerne are uncommon and only extend a few meters from the contact. Large rotated inclusions of Vassalboro Formation several meters across have been observed within the pluton but only within a few meters of the contact.

The NW boundary of the Lucerne pluton is the Norumbega fault zone. A roof pendant has been identified in the region of Morrison Ponds, and in this region the pluton narrows to 2 km. The coarse texture persists up to all the contacts, including the roof pendant, and the fault zone. Near Great Pond, the Lucerne pluton has undergone extreme cataclasis and is brecciated and mylonitized within a few meters of the fault zone (Fig. 4f).

The eastern contact is not as well exposed as the western contact. However, just west of the Union River and north of Route 9, familiarly known as "the Airline," both intrusive and mylonitic contacts can be seen between the Lucerne pluton and the Vassalboro Formation. The mylonites presumably represent small faults, but they do not appear to persist regionally. They are interpreted as extensions of a trace within the Norumbega fault zone that becomes better developed to the NE in the region of Sabao Mountain in the Nicatous Lake quadrangle.

Contacts of the Lucerne pluton with the Penobscot Formation are well developed on the shores of Beech Hill Pond and Green Lake. Here the contact is abrupt, there are relatively few inclusions, and rare dikes of the Lucerne Pluton are found within the Penobscot Formation.

South of Route 1A the Ellsworth Schist appears to be deformed by the Lucerne pluton. Drag folds in the schist are interpreted to show that the Lucerne Pluton moved north relative to the Ellsworth Schist. At the SE corner of the Lucerne pluton, contacts (of the Lucerne pluton) with both the Blue Hill pluton and the Ellsworth Schist are well exposed at the town line between Surry and Blue Hill. There the contact zone is marked by disseminated arsenopyrite within the older units. The Lucerne pluton is clearly younger than the Blue Hill pluton, and is a distinctly separate pluton.

The southern contacts are not well exposed, although mapping by D. B. Stewart in the Blue Hill quadrangle (Stewart and Wones, 1974) has closely constrained the contact west of Toddy Pond. This is the only region in which the granite of the Lucerne pluton becomes porphyritic near the contact. A significant characteristic of the Lucerne pluton is that it remains coarse-textured and seriate throughout the body, except for a central core facies that is only exposed in the northern third of the pluton.

A small fault extends across the Lucerne pluton from Dedham Elementary School on the west side of the pluton to North Mariaville on the eastern side of the body. Both contacts are offset by right-lateral displacement of about 300 m. A zone of mylonitic rock has been followed more or less continuously (outcrop permitting) between these two offsets. This fault may be equivalent to the Sunnyside fault described by Bickel (1976) in the Belfast Quandrangle.

North of the fault, the core of the pluton is occupied by a porphyritic facies of the granite. Quartz, plagioclase, alkali feldspar, and biotite all occur as medium to coarse (biotite excluded) phenocrysts within a fine- to medium-grained matrix of the same minerals. Miarolitic cavities of about 3 mm diameter occur within the groundmass, and contain terminated feldspar crystals. The contacts of the porphyritic facies with the seriate facies are gradational. Near Springy Pond Mountain the contact is marked

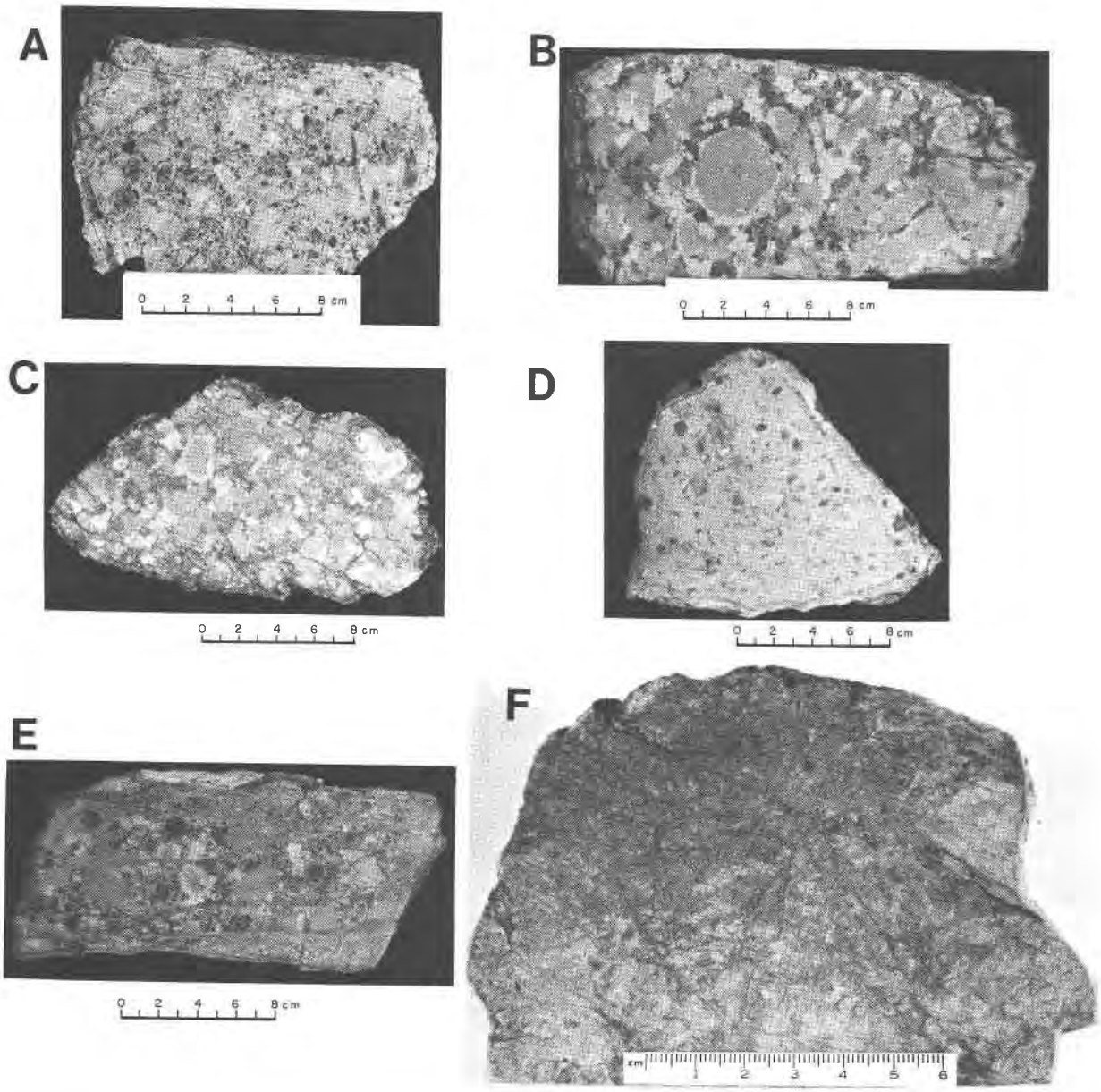

Fig. 4. Representative slabs of the Lucerne pluton: (A) EL 417, seriate facies near eastern margin, south of Sunnyside fault; (B) ORC 65, seriate facies near core of pluton, south of the Sunnyside fault; (C) GPC 604, seriate facies north of the Sunnyside fault; (D) GPC 603, porphyritic facies north of the Sunnyside fault; (E) GPC 607, mylonitized seriate facies north of Sunnyside fault; (F) brecciated seriate facies adjacent to Norumbega fault Zone, north of Great Pond.

by sprays of tourmaline several cm across, but at other localities the boundary is simply marked by a gradual coarsening of the groundmass over tens of meters towards the outer perimeter of the pluton.

The fabric of the pluton is massive. There is no tendency for the minerals to be oriented either as lineations or foliations, except in the west-central portion of the southern part of the body (see foliation symbols in Fig. 2). In this region the pluton has been deformed by subsolidus deformation. Ductile deformation of quartz and biotite and brittle deformation of the feldspars can be observed in thin sections of the rocks of this zone (Fig. 5a–c) which is marked by a pervasive deformation rather than by mylonites. This feature occurs entirely within the interior of the pluton and does not appear to offset any of the contacts, although the contacts near Moose Stream at the south end of the western contact are not well exposed. Ductile deformation of quartz and brittle behavior of the feldspars suggests that this deformation

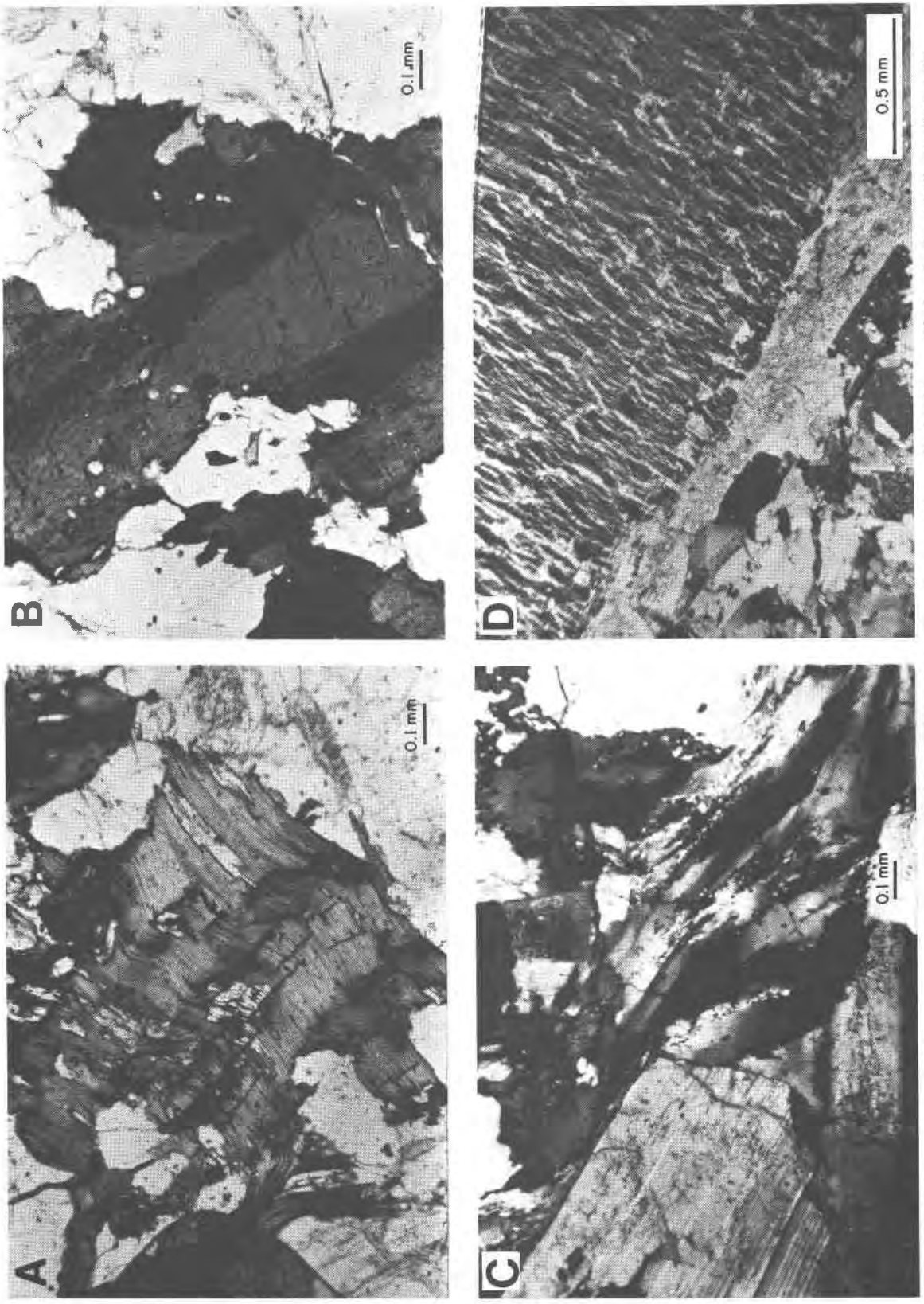

Fig. 5. (A) Photomicrograph (plane polarized light), sample ORB323. Deformed chlorite–sphene pseudomorph after biotite. Displaced sphene indicates deformation after alteration. (B) Photomicrograph (plane polarized light), sample ORB323. Kink-banded biotite. (C) Photomicrograph (crossed nicols), sample ORB323. Ductile deformation of quartz and biotite, with partial recrystallization of strained quartz. (D) Photomicrograph (crossed nicols), sample EL505. Plagioclase mantle on perthitic alkali feldspar.

was subsolidus and took place at about 500°C (Tullis and Yund, 1977). Kink-banding of altered biotites coupled with deformation of secondary sphene suggests that the deformation took place after the subsolidus alteration.

North of the Sunnyside fault numerous mylonites are found with the pluton (Fig. 4e). These usually trend N60E or N20W. They do not seem to line up into continuous zones, nor do they dominate single outcrops. Their overall density has not been determined. I interpret these features as the termination of one of the fault traces of the Norumbega fault zone. There is no major offset of the contacts of the Lucerne pluton in this region, yet the small mylonites strike NE into a fault contact between the granite of Cranberry Lakes and the Vassalboro Formation.

Age of the Lucerne pluton

The Turtle Head fault zone displaces the Castine Volcanics (Stewart, 1974), a sequence of rocks clearly of late Silurian and Early Devonian age. The Lucerne pluton cuts the Turtle Head fault zone, and this must be younger than Early Devonian. The Lucerne pluton is cut by the Norumbega fault zone, which also deforms Pennsylvanian sediments in New Brunswick (Wones and Stewart, 1976).

Brookins (1976; personal communication) has been working on the ages of the plutonic rocks of the Penobscot Bay region. He has determined a preliminary age for the Lucerne pluton of 375±25 million years. This is in agreement with a K–Ar age of 365 m.y. by Faul *et al.* (1963) for the Lucerne pluton. R. E. Zartman (personal communication) has determined a single zircon Pb/Pb age of 380±4 million years. The Lucerne pluton is Middle Devonian in age.

Texture and fabric of the Lucerne pluton

The Lucerne pluton is made up of granite containing quartz, alkali feldspar, plagioclase, and biotite. The texture is seriate. This term is used all too little by petrographers, and I would like to urge petrographers to seriously consider it in future descriptions of their rocks. Equigranular and porphyritic have long been popular terms, but not so seriate. If one examines textures of the Lucerne pluton (Fig. 4a–e), it is clear that quartz, plagioclase, and alkali feldspar all occur in a variety of grain sizes, ranging from a few mm to several cm. Alkali feldspars are always coarsest, in maximum size, followed by quartz, plagioclase, and biotite in that order. The biotite is never coarser than 5 mm and often occurs as grains less than a millimeter in diameter. Table 1 lists average grain sizes for the minerals within the three facies of the pluton.

The porphyritic core in the northern third of the pluton contains phenocrysts as coarse as several cm in length within a fine- to medium-grained groundmass. The mineralogies of the phenocryst and the groundmass are essentially identical. Although the main body of porphyritic material is found in the northern core of the pluton, scattered pods of porphyritic material a meter or less in diameter have been observed throughout the entire pluton. These porphyritic zones are never well developed near the contacts of the body except near the SW contact near the western shore of Toddy Pond. The total number of porphyritic pods observed is about two dozen, and they are concentrated toward the central axis of the pluton.

I have divided the pluton into three facies: seriate facies south of the Sunnyside fault; seriate facies north of the Sunnyside fault; and porphyritic facies north of the fault.

Inclusions are very rare except that rotated blocks of country rocks are common within a meter of the contact.

Table 1. Average range of grain sizes of essential minerals in rocks of the Lucerne pluton

	Maximum Long Dimension (cm)		Minimum Long Dimension (cm)		% K-feldspar mantled by plagioclase
Seriate granitic rocks south of Sunnyside Fault (135 samples)					
Quartz	0.98 ± 0.03 (s.d.)		0.20 ± 0.12		
K-feldspar	2.96	0.90	0.31	0.26	0.05 ± 0.03
Plagioclase	1.39	0.57	0.20	0.30	
Biotite	0.19	0.09	0.10	0.03	
Seriate granitic rocks north of Sunnyside Fault (87 samples)					
Quartz	1.10	0.35	0.24	0.13	
K-feldspar	2.63	1.03	0.32	0.29	0.07 0.08
Plagioclase	1.34	0.59	0.22	0.13	
Biotite	0.19	0.09	0.09	0.05	
Phenocrysts of porphyritic granitic rocks north of Sunnyside Fault (27 samples)					
Quartz	1.07	0.33	0.12	0.06	
K-feldspar	2.76	0.86	0.33	0.25	0.05 0.02
Plagioclase	1.12	0.52	0.14	0.08	
Biotite	0.17	0.10	0.09	0.03	

Well-developed schlieren (Fig. 6) have only been observed near the southeastern contact on the east shore of Lower Patten Pond. Grains of biotite define fabrics analogous to cross-bedding and funnel-shaped bedding common to clastic sediments.

Most outcrops are rough and coated with lichens. This makes routine observations of porphyritic apophyses and schlieren difficult, so these features may be more common than I have indicated.

Aplite dikes are also uncommon and tend to occur in swarms. The most extensive occurrence is along the Nature Trail at the Craig Brook National Fish Hatchery (Wones, 1974) on the northeast shore of Alamoosook Lake in East Orland. Along a 75-m trail, four aplitic dikes were observed. The thickest is about 20 cm thick, and all of them are medium-grained, rather than fine-grained. Scores of bald outcrops, each hundreds of square meters in area, do not contain aplitic dikes.

The only pegmatite observed was along the western margin of the pluton, about 800 m north of Moose Brook. The pegmatite, about a meter in diameter, was enclosed in coarse seriate granite and was made up of quartz, plagioclase, alkali feldspar, and tourmaline. As the bulk of the alkali feldspar in the Lucerne pluton is 2 to 4 cm long and 1 to 2 cm wide, the entire pluton could be construed as a pegmatite. However, the regularity of the seriate texture from place to place makes such a classification highly inappropriate.

Any smooth, weathered outcrop shows that about 5 percent of the alkali feldspar megacrysts in the seriate facies of the Lucerne are ovoidal and are rimmed by plagioclase (Table 1). This viborgite or "rapakivi" texture is common among the granitic plutons of coastal Maine (Terzaghi, 1940; Stewart, 1959; Abbott, 1978). Within the porphyritic facies, this texture is not obvious in outcrop, but measurements of stained slabs indicate that it is as common in that facies as in the seriate facies.

Tabular zones of salmon-colored granite occur adjacent to quartz-filled joints in the southern third of the pluton. Granite within 1 to 2 cm of the quartz veins is salmon-colored; biotites are chloritized, plagioclase is absent, and the turbid feldspar has few perthite lamellae. These regions of alteration are rare, and have only been observed near Craig Brook and along U.S. Route 1 near Upper Patten Pond. They occur in sets that strike N60E and N60W, and are nearly vertical.

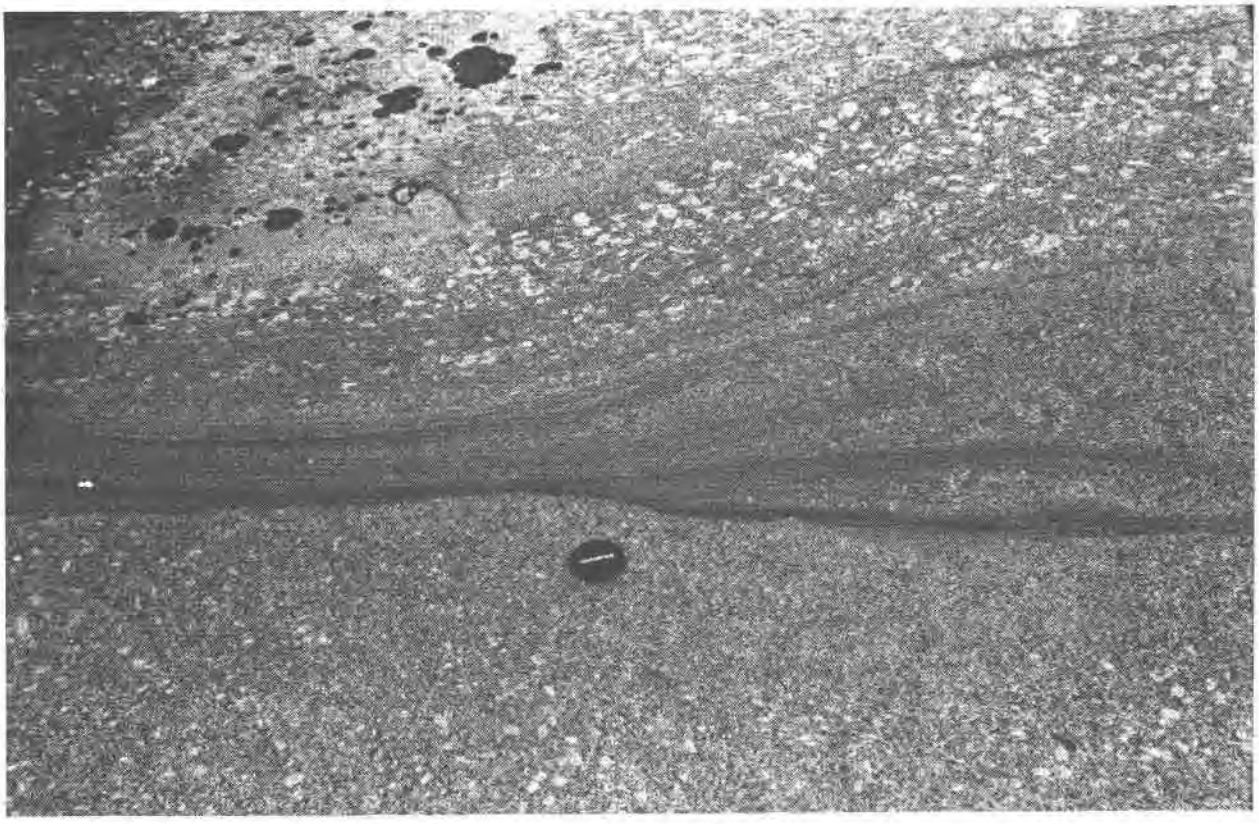

Fig. 6. Schlieren of biotite near the eastern margin of the Lucerne pluton. Lens cap is 55 mm in diameter.

NW-trending, quartz–tourmaline veins about 2 to 4 cm across have been observed at six localities. These veins do not appear to be accompanied by any alteration of adjacent granite, but clearly transect early textures and fabric.

Modal and analytical data

In making a recent comparison (Wones, 1980) between plutonic rocks of the New England region, USA, and those of the Sierra Nevada batholith (Bateman *et al.*, 1963; Bateman and Clark, 1974), I found that very little systematic work has been done on the variations of composition within plutons in New England. Part of the object of this study was to provide modal data for the Lucerne pluton. Sample locations are shown in Figure 7, and the modal data are presented in Figures 8 and 9. The data were acquired by counting 1000–1500 points on stained slabs which varied in size from 100 to 500 cm^2. This size is a compromise between the size required because of the coarse feldspar grains (ideally 1600 cm^2) and my energy in removing such large samples from the Maine woods.

Recent road cuts along Route 1 near Upper Patten Pond, in the southern portion of the pluton, show local segregations of alkali feldspars (Fig. 10) on the scale of meters to tens of meters similar to those seen adjacent to the schlieren (Figure 6). My hand specimens do not appear to be large enough to be representative of a local area, and this leads to the scatter observed in Figure 8. Thus, these 220 modal determinations probably give a satisfactory average composition for the different facies of the Lucerne pluton but are not sufficient to show regional gradients, even though the sample localities are 1 to 2 km apart. The averages are given in Table 2.

In preparing Figures 8 and 9, I have divided the pluton into three facies: seriate facies south of the Sunnyside fault, seriate facies north of the Sunnyside fault, and the porphyritic facies. As can be seen from Table 2, the seriate granite south of the fault and that north of the fault are modally distinct at the 90% confidence level, in regard to alkali feldspar and mafic mineral contents. Rocks north of the fault are systematically lower in color index and higher in alkali feldspar content than those south of the fault. Geophysical evidence (Sweeney, 1976) indicates vertical displacement along the fault, perhaps as much as a kilometer, with the south side moved up.

A vertical composition gradient within the pluton would be analogous to results reported for magma chambers that erupt as ash-flow tuffs (Ross and Smith, 1961; Smith and Bailey, 1966; Hildreth, 1980), where the inverted volcanic pile is interpreted to represent levels within the erupting magma chamber. Concentration of alkali feldspar toward the top and an increase in mafic mineral content toward the base seems to be typical of these magma chambers.

The porphyritic zone is the richest in alkali feldspar of the units and the lowest in color index. Simple fractionation of quartz, plagioclase, and biotite by gravity settling could explain this result, as these minerals are denser than alkali feldspar and might sink faster than the lower-density alkali feldspar during the cooling of the magma that crystallized to form the granite.

The rocks of the Lucerne pluton (Figs. 8 and 9) are all granite (monzogranite) as defined by the IUGS classification scheme (Streckeisen, 1973). The fundamental variation seems to be toward the alkali feldspar apex, and implies that the process leading to the scatter is controlled by alkali feldspar. Observation of aggregated alkali feldspar crystals (Fig. 10) supports such an interpretation and indicates that alkali feldspar was one of the early phases to crystallize from the melt. The presence of biotite schlieren along the southeast margin of the body implies that biotite also was an early crystallizing phase.

Table 3 gives average analyses for granitic rocks from the three dominant facies of the Lucerne pluton. Samples submitted for chemical analyses weighed between 20 and 50 kg. Chemical analyses were performed by laboratories of the U.S. Geological Survey in Reston, Virginia, using "rapid rock" methods as outlined by Shapiro (1975). CIPW normative calculations compare well with the average modal analyses. Both results demonstrate that the northern part of the pluton is enriched in K_2O and is depleted in TiO_2, Al_2O_3, and MgO as compared to the southern part.

Geophysical data

Gravity data, obtained by Sweeney (1975, 1976), show a Bouguer anomaly of about −30 mgal over the pluton (Fig. 11). Sharp gradients that coincide with the boundaries of the pluton imply a steep contact with the country rocks, a relatively flat base for the pluton, and a lower density than that of the surrounding rocks. In Figure 3, the configuration of the Lucerne pluton at depth is taken from Sweeney's (1976) interpretation of the gravity anomaly.

Alkali feldspars have a positive volume of mixing (Wright and Stewart, 1968). In the Lucerne pluton, the alkali feldspars have an average bulk composi-

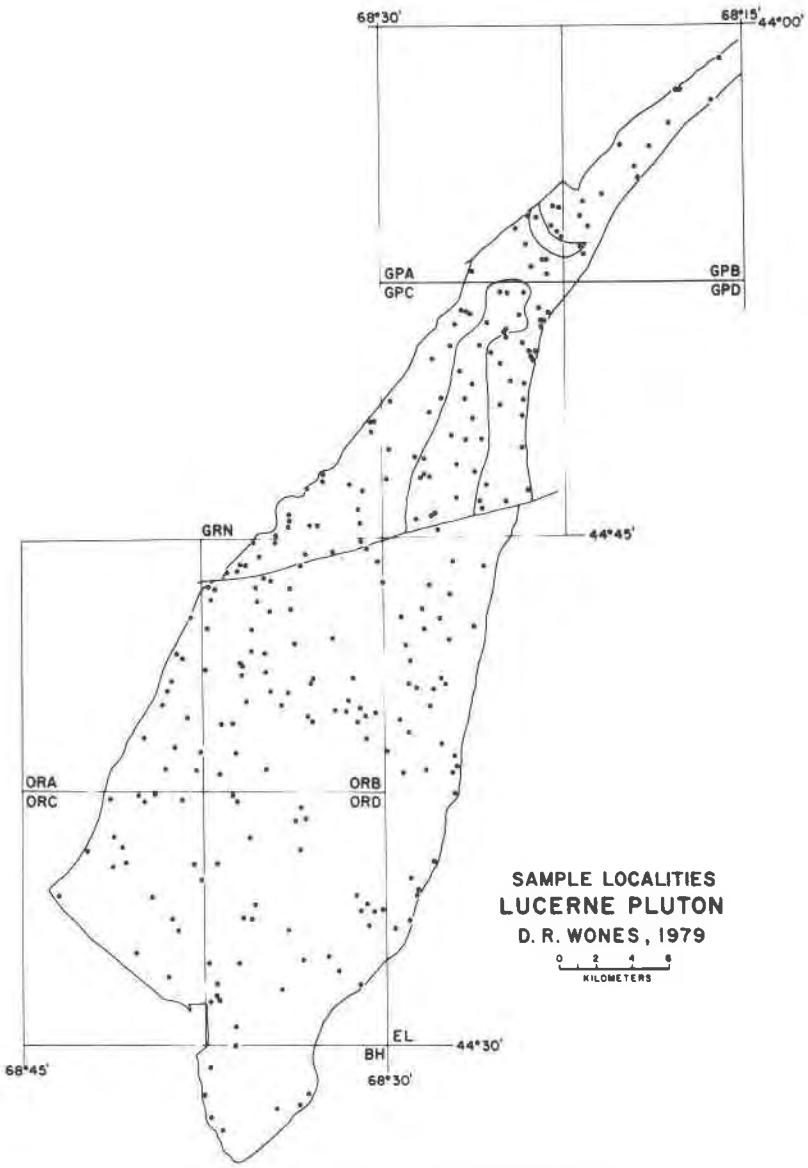

Fig. 7. Sample localities for modal analysis.

tion of $Or_{70}Ab_{30}$ and have exsolved to form microperthite. Thus, additional void space existing within the feldspars lowers the overall rock density. The turbid nature of the feldspars is due, in part, to these voids.

The porphyritic zone in the northern part of the pluton contains miarolitic cavities. Although small and dispersed, these cavities also lower the effective density of the pluton. Measured bulk densities of the granite range from 2.55 to 2.65, while the calculated densities range from 2.61 to 2.66. Our knowledge of the feldspars, as evidenced from the session preceding this address (Geol. Soc. Amer. Abstracts with Programs, v. 11, p. 349), permits us to make estimates of the densities of granitic rocks and to explain the observed discrepancies.

The fault which separates the northern third from the southern two thirds of the pluton may be equivalent to the Sunnyside fault described by Bickel (1976) in the Belfast Quadrangle to the southwest. This fault has displaced the east and west contacts of the pluton about 300 m. The gravity data interpretation by Sweeney (1976) suggests that the fault has about a kilometer of vertical motion, and that the southern

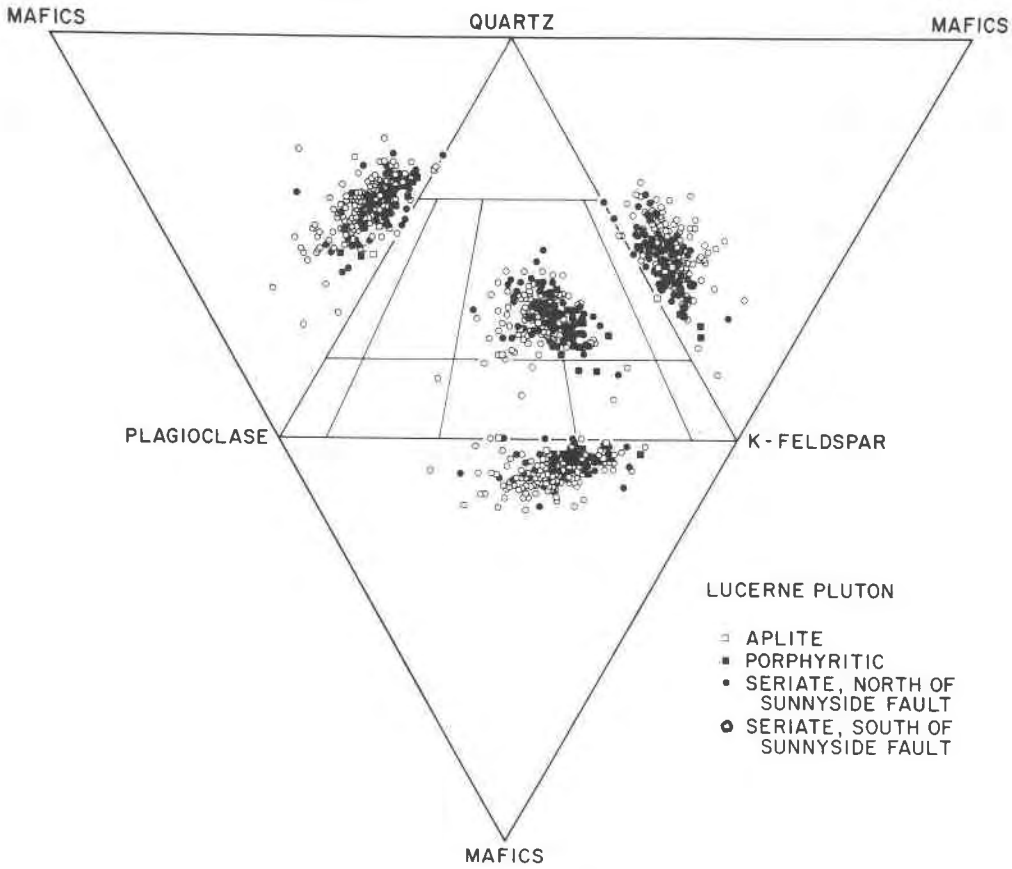

Fig. 8. Modal analyses of the Lucerne pluton.

part of the pluton represents a deeper level than the northern part of the pluton.

Magnetometer data show that the Lucerne pluton has a distinct signature. Use of a truck-mounted magnetometer (Kane *et al.*, 1971) demonstrated that the relatively uniform, magnetite-free granites of the Lucerne pluton produce a flat and relatively uninteresting magnetic profile. The Vassalboro and Penobscot Formations and the Ellsworth Schist all contain sufficient magnetite (Ellsworth) or pyrrhotite (Vassalboro and Penobscot) to give a significant contrast. Representative magnetometer traces across the contacts are shown in Figure 12. The magnetic contrast is readily explained by the fact that the pluton contains no magnetite, except in the mylonitized zones in the northern portion. There are a few tenths of a percent modal ilmenite and the major ferromagnesian mineral in the granite is biotite.

Much of the southernmost portion of the pluton is covered by glacial-outwash deposits, and the contacts are not exposed. The truck-mounted and backpack-mounted magnetometers permitted a close resolution of the contacts in the southern portions of the pluton. An understanding of the mineralogy of the pluton and the host rocks permits a more detailed interpretation of the geophysical data.

Geomorphology and glacial geology

Landsat images (Fig. 13) of the terrain that contains the Lucerne pluton show a number of striking features. The Lucerne pluton, containing quartz and feldspar, is more resistant to erosion than the carbonate and layer-silicate-rich country rocks that it intrudes. Thus, the Lucerne pluton forms a range of hills (although in Maine we fondly think of these as mountains) that rise 330 m above the surrounding country that is essentially at sea level. A pronounced topographic rise along the western contact is part of the Penobscot lineament discussed by O'Leary *et al.* (1976). This prominent feature is the contact between the hornfelsed rocks of the contact aureole of the Lucerne, made up of quartz, plagioclase and biotite, and the lower grade metamorphic rocks predominantly made up of quartz, calcite, muscovite, and chlorite.

The southeastern terminations of the larger lakes

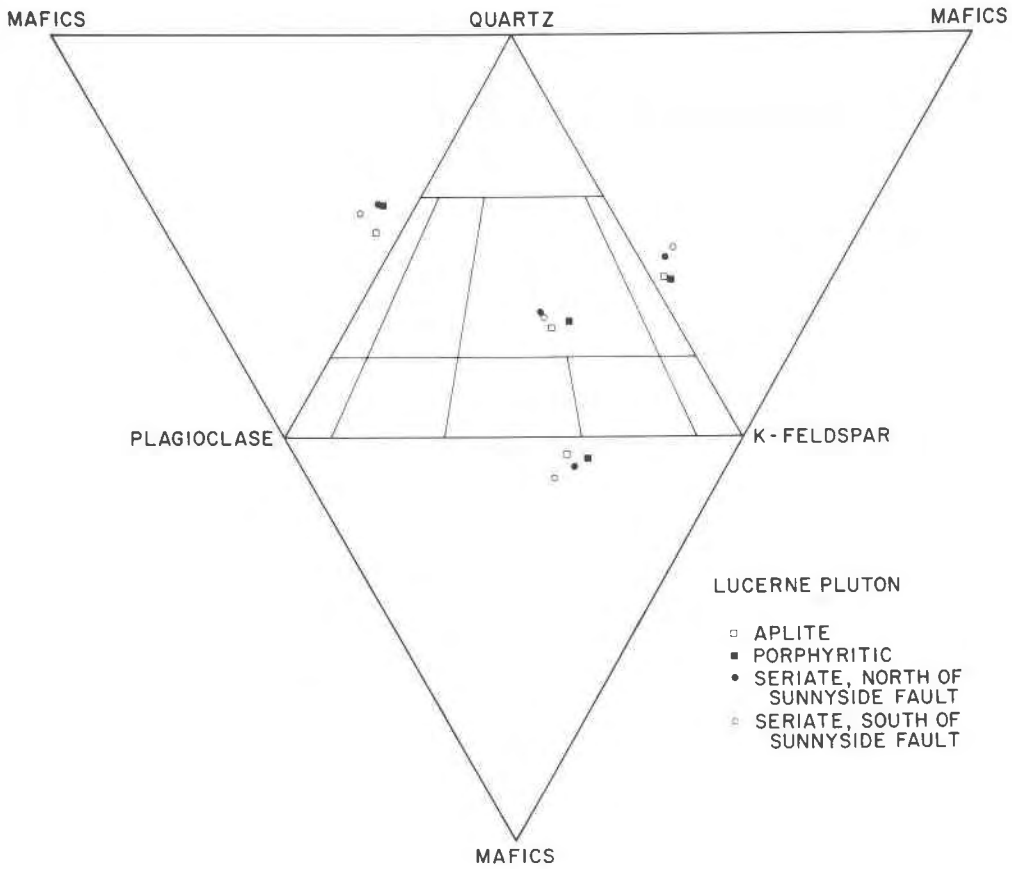

Fig. 9. Average modal analyses of the three facies of the Lucerne pluton.

found within the borders of the Lucerne pluton coincide with the eastern contact of the pluton against the metamorphic rocks in the aureole. Apparently glacial scouring took place more easily in the granite than in the hornfels, so that glacial erosion formed linear SE-striking basins which are dammed by the hornfels.

On the Bubbles, in Acadia National Park, is a large glacial erratic named Balanced Rock. This erratic is coarse-grained, contains large alkali feldspars, and has a modal composition within the range of the granite of the Lucerne pluton. Glacial striae in the rocks in and around the Bubbles indicate that glacial movements were S20E to S15E. Projecting this trajectory for Balanced Rock, we find that it coincides with the Lucerne pluton. This case, although rather simplistic, demonstrates that detailed knowledge of the petrology and mineralogy of plutonic rocks in New England can aid our understanding of glacial transport in this region.

Petrography

The coarse grain size, a prominent feature of the granites of the Lucerne pluton, makes study of the rocks in thin section difficult. In this study the relationships among the major minerals were determined from the examination of the stained slabs used for modal analysis. Measurements were made of the maximum and minimum diameters of the major minerals, and observations were made of their morphology.

The Lucerne pluton is predominantly coarse-grained granite with hypidiomorphic seriate texture. Quartz grains are often in aggregates and are subhedral to anhedral; alkali feldspar crystals often occur as Carlsbad twins and range from anhedral to euhedral; plagioclase crystals are usually subhedral. Sizes of these three minerals are seriate, within the ranges given in Table 1. The biotites are more uniform in grain size and are subhedral.

Another prominent petrographic feature of the pluton is the presence of plagioclase mantles, on about 5 percent of alkali feldspar crystals (Fig. 4b, c, e). Forty-one percent of the slabs of seriate granite south of the fault showed this texture, and of that group 13 percent of the alkali feldspar crystals were mantled. Of the seriate and porphyritic rocks north

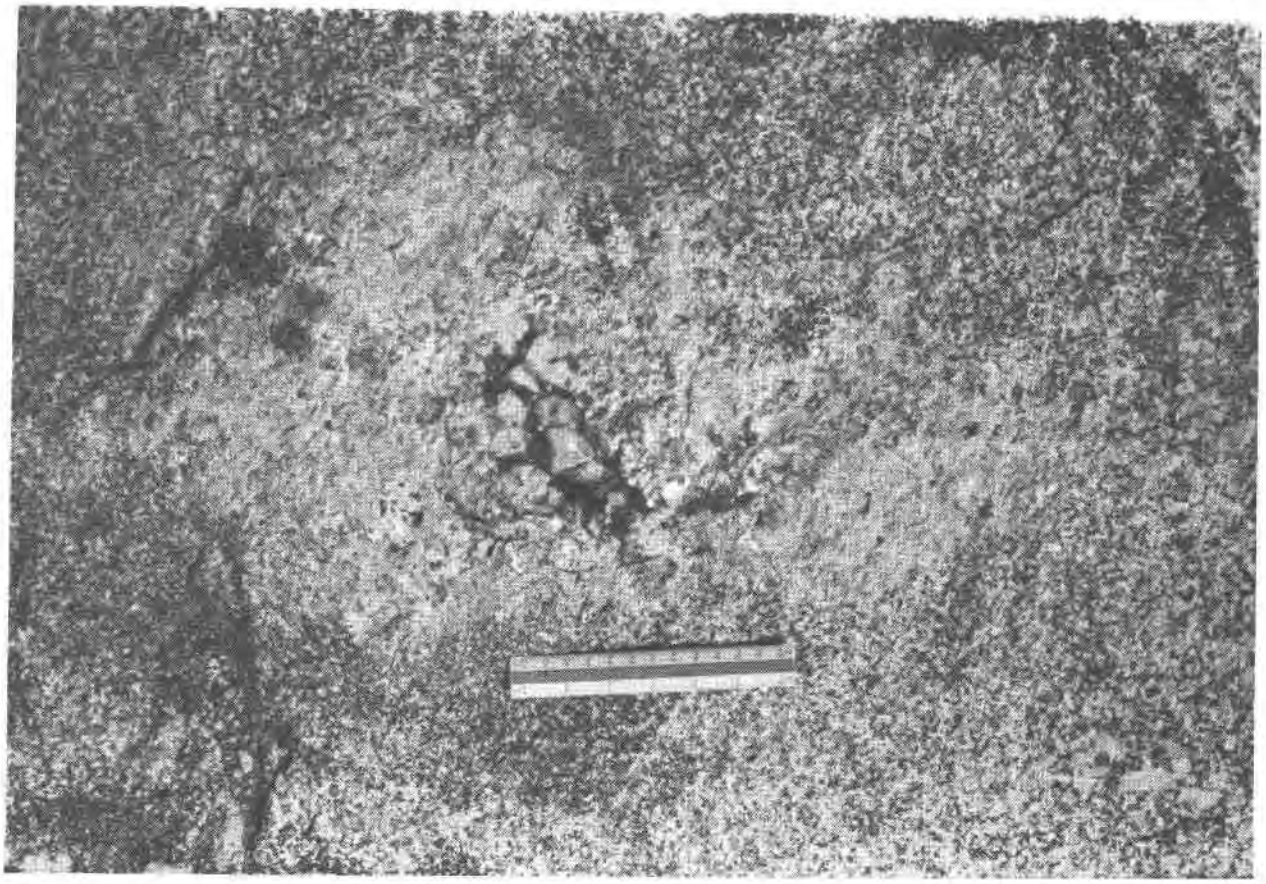

Fig. 10. Alkali feldspar aggregates and miarolitic cavity observed in road cuts, Route 1, near Upper Patten Pond. Scale is 6 inches long.

of the fault zone, 48 percent of the slabs contained mantled feldspars, and in those slabs, 15 percent of the feldspars larger than 1 cm were mantled in the seriate rocks and 10 percent of the phenocrysts in the porphyritic rocks. There is no significant difference in the percentage of mantled alkali feldspars among the three facies. I interpret these observations to indicate that, in spite of the modal differences among the three facies, the early crystallization histories were nearly the same.

Table 2. Average modal analyses for granitic rocks of the Lucerne pluton

	1		2		3	
Quartz	27.99 ± 5.7 (s.d.)		29.45 ± 5.2		27.43 ± 5.8	
Alkali Feldspar	39.02	7.1	41.48	6.7	46.22	6.3
Plagioclase	26.06	5.2	24.48	4.5	22.56	2.7
Mafics (Biotites)	6.72	2.7	4.85	2.4	3.92	1.7

1. Average of 124 analyses of seriate granitic rocks south of Sunnyside Fault.

2. Average of 72 analyses of seriate granitic rocks north of Sunnyside Fault.

3. Average of 24 analyses of porphyritic rocks north of Sunnyside Fault.

Sequence of crystallization

Sequence of crystallization can best be determined by examining mutual grain boundaries and inclusions; for the Lucerne pluton, the sequence is not obvious. The euhedral to subhedral character of the alkali feldspar tends to give that mineral a "primary" appearance, which is belied by the presence of quartz, plagioclase, and biotite inclusions within alkali feldspar grains. Biotite is a ubiquitous inclusion in all minerals, and the presence of the schlieren and flow banding discussed earlier lends credence to the hypothesis that biotite is the primary phase among the major minerals.

Because only 5 percent of the alkali feldspar is mantled, this must have been an early event in the crystallization of the Lucerne magma, and it is of interest to note that the boundary between the alkali feldspar core and the plagioclase rim is decorated with quartz and biotite. Rare euhedral grains of

Table 3. Average chemical analyses and CIPW norms for granitic rocks of the Lucerne pluton

	1		2		3	
SiO_2	71.95 ± 2.14 (s.d.)		73.20 ± 1.82		73.48 ± 1.93	
TiO_2	0.29	0.07	0.22	0.03	0.16	0.03
Al_2O_3	14.76	0.97	13.89	0.82	13.92	0.86
Fe_2O_3	0.66	0.28	0.59	0.22	0.64	0.15
FeO	1.49	0.31	1.46	0.24	1.20	0.14
MnO	0.04	0.03	0.03	0.01	0.06	0.04
MgO	0.28	0.13	0.16	0.05	0.09	0.01
CaO	1.06	0.31	0.96	0.19	0.84	0.19
Na_2O	3.23	0.23	3.02	0.17	3.38	0.22
K_2O	5.28	0.39	5.52	0.50	5.45	0.54
P_2O_5	0.15	0.11	0.06	0.01	0.13	0.05
H_2O	0.88	0.37	0.66	0.11	0.65	0.05
CO_2	0.02	0.02	0.02	0.02	0.02	0.01
Q	29.91		31.65		30.75	
C	2.21		1.40		1.29	
Or	31.17		32.69		32.20	
Ab	27.31		25.61		28.60	
An	4.15		4.25		3.19	
En	0.70		0.40		0.22	
Fs	1.79		1.89		1.52	
Mt	0.96		0.86		0.93	
Il	0.55		0.42		0.30	
Ap	0.36		0.14		0.31	
D. I.	88.38		89.94		91.55	

All analyses performed by Branch of Analytical Laboratories, U.S. Geol. Survey, Reston, Vriginia, using Rapid Rock Methods (Shapiro, 1975), H. Smith, Analyst.

1. Average of 10 analyses of seriate granitic rocks south of Sunnyside Fault
2. Average of 9 analyses of seriate granitic rocks north of Sunnyside Fault.
3. Average of 6 analyses of porphyritic rocks north of Sunnyside Fault.

plagioclase containing 5 to 10 percent biotite inclusions also appear to be early phases.

The porphyritic core is presumed to represent a quench event and therefore captures for us the early-crystallized phases: biotite, quartz, alkali feldspar, and plagioclase. Alkali feldspar crystals predominate, but the others are all present, biotite both as phenocrysts and as inclusions within the other phases. Plagioclase inclusions within the alkali feldspars may be partly exsolution products.

The crystallization sequence appears to be biotite preceding plagioclase, quartz, and alkali feldspar. Relations among the others are indeterminate.

Mineralogical data

Mineralogical studies have used a combination of methods: optical, X-ray powder diffraction, X-ray fluorescence, and electron microprobe. Most of the effort has been placed on the characterization of the major minerals, and relatively little work has been

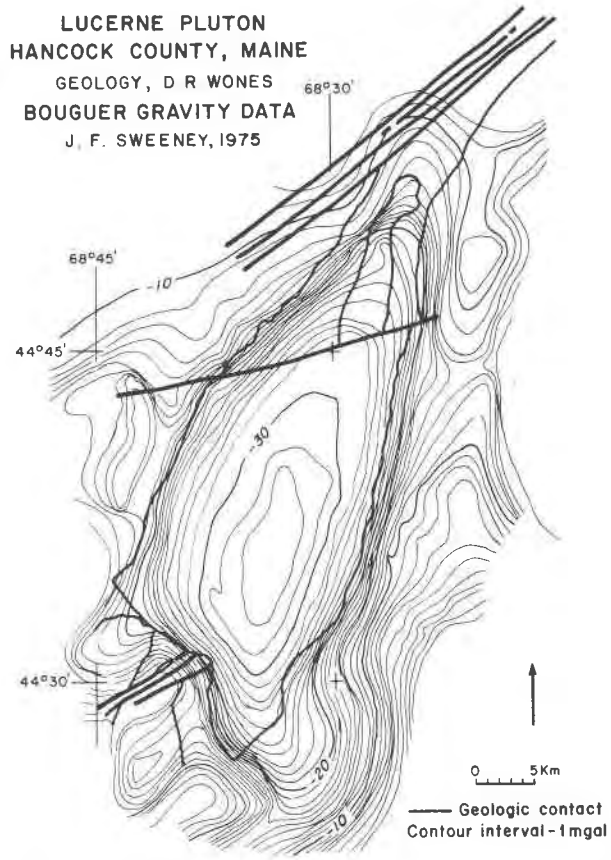

Fig. 11. Bouguer gravity anomaly associated with the Lucerne pluton. Gravity data are from Sweeney (1975, 1976). Geologic contacts are from Fig. 2.

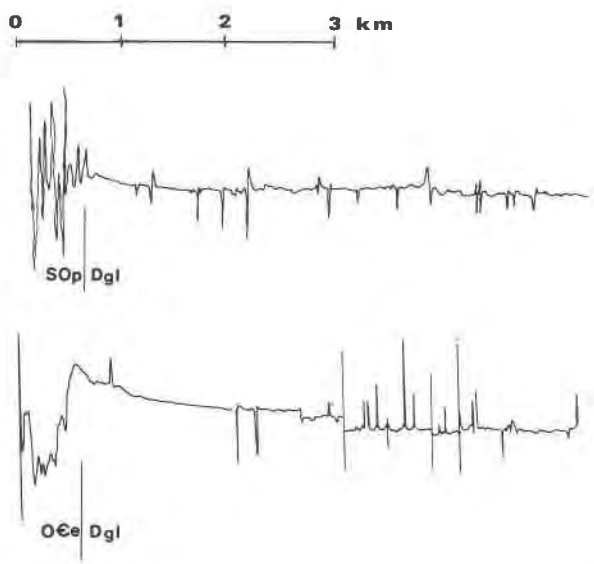

Fig. 12. Ground-level magnetometer tracings across contacts of the Lucerne Pluton. Dgl, Lucerne pluton; SOp, Penobscot Formation; OCe, Ellsworth Schist.

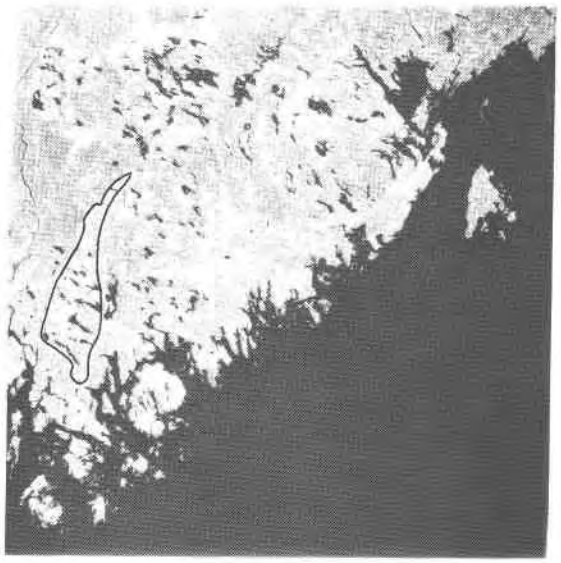

Fig. 13. Landsat image of eastern coastal Maine, with the outline of the Lucerne pluton superposed.

expended on the accessories, with the exception of apatite.

Plagioclase

Plagioclase occurs in four typical habits in the granites of the Lucerne pluton. It usually occurs as subhedral to anhedral polysynthetically-twinned crystals of An_7 to An_{30} composition scattered throughout the matrix of the granitic rocks. The most calcic plagioclases observed are An_{35}; these are found in the southern facies of the pluton. Most plagioclases are sericitized and weakly zoned. Plagioclase crystals also occur as inclusions within alkali feldspar crystals. These have not been extensively studied, but the available analyses indicate that they rarely exceed An_{20} in composition and are commonly $An_{7\text{-}15}$. The plagioclase mantles in the viborgite (rapakivi) feldspars range from An_{24} to An_{20}. Plagioclase lamellae in the perthitic alkali feldspar vary between An_3 and An_0.

Alkali feldspar

Alkali feldspar occurs as coarse- to medium-grained euhedral to subhedral crystals. The crystals are exsolved to lamellae of low albite about 0.05 mm thick within a matrix of maximum microcline of composition Or_{96} to Or_{100}. The structural state was established by X-ray diffraction using the method of Wright (1968). Bulk compositions of the alkali feldspars were determined by removing single crystals from rock samples and analyzing them by X-ray fluorescence methods. They were also sanidinized by crushing, pelletizing, and heating to 950°C for several days. Bulk compositions were then determined using the methods of Wright and Stewart (1968). The two methods are compared in Figure 14. The sanidization procedure always gives estimates of bulk composition as more Or-rich than the values determined by X-ray fluorescence. This is probably due to the inclusions of An_5 to An_{15} plagioclase that occur in the alkali feldspar. This material is not homogenized into the alkali feldspar during the sanidization procedure but is included in the XRF analysis. I have not attempted to determine the composition by modal analysis of perthite after microprobe analysis of the host and lamellae within the perthite. Because of the size of the lamellae, I did not use the "broad beam" microprobe technique reported by Whitney and Stormer (1976). The bulk composition of the perthites ranges from Or_{80} to Or_{60}. The compositions of mutually coexisting plagioclase and alkali feldspar are shown in Figure 15.

Biotite

Biotite occurs as subhedral crystals that range from 0.1 to 0.2 cm in diameter. They frequently contain inclusions of apatite, zircon, and in some cases, fluorite. Some of the included minerals are often found in a spiral pattern and are interpreted as "decorations" on a crystal of biotite forming by spiral

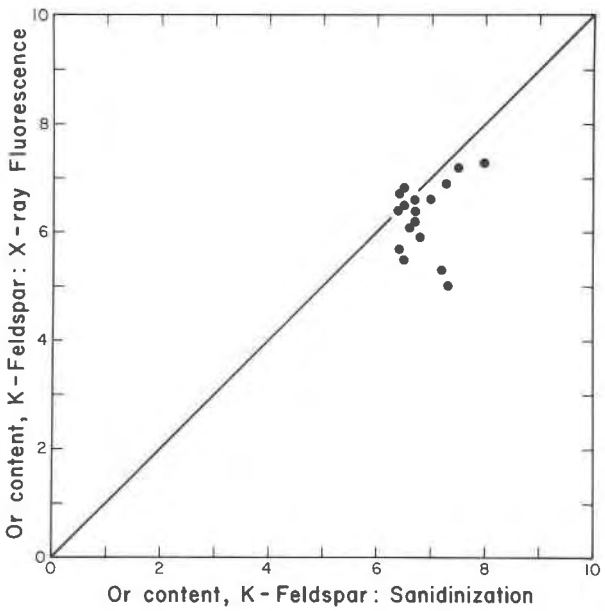

Fig. 14. Comparison of the Or content (in mole percent) of alkali feldspars of the Lucerne pluton determined by X-ray fluorescence of bulk feldspar grains with that determined by X-ray powder diffraction after sanidinization.

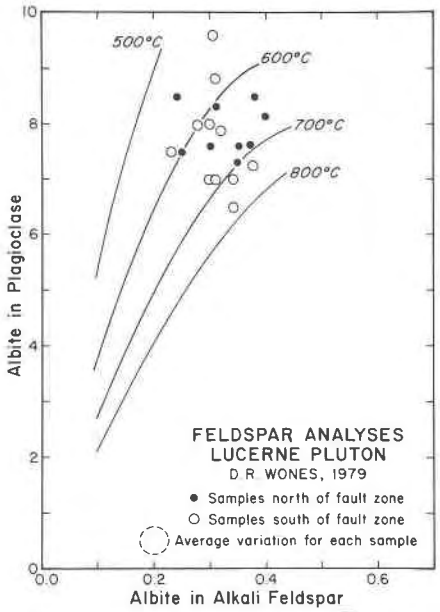

Fig. 15. Albite contents (in mole percent) of plagioclase plotted against albite content of coexisting alkali feldspar. Isotherms for coexisting sanidine and plagioclase at 1 kbar are from Stormer (1975). The size of the dashed circle is representative of the uncertainty at each data point.

growth. Biotite, in turn, occurs as inclusions in all of the other major minerals of the Lucerne pluton.

Biotite compositions [obtained to date] have been determined by microprobe. Li and Fe_2O_3 contents are unknown, although they can be estimated from bulk rock chemistry. This indicates that 25 to 35 percent of the Fe in the biotites occurs as Fe^{3+} and that maximum Li contents are 1000 ppm. Average biotite structural formulae are given in Table 4, and individual data are plotted in Figures 16–20. There is clearly a range of values, but the range within a single thin section is frequently as great as the total range expressed in the figures. The only systematic variation in biotite compositions with respect to location within the pluton is in the Fe/(Fe + Mg) values. These values are systematically higher in rocks found north of the Sunnyside fault, as opposed to those found south of the fault. This variation mimics the bulk composition of the rocks.

The variation in Al content in the octahedral layers (Al^{VI}) is much greater than that of Fe/(Fe + Mg) (Fig. 16).

The percent variation in Ti content (Figs. (17–19) is not as great as that of Al but is greater than that of Fe/(Fe + Mg). The substitution of Ti^{4+} in biotites for $(Fe,Mg)^{2+}$ can be compensated in a variety of ways:

$$Ti^{VI} + 2Al^{IV} = Mg^{VI} + 2Si^{IV} \quad (1)$$

Table 4. Average structural formulae for biotites of the Lucerne pluton

	1	2	3	4
Si^{IV}	2.81 ± .05	2.84 ± .02	2.86 ± .05	2.77 ± .05
Al^{IV}	1.19 .05	1.16 .02	1.14 .05	1.23 .05
Al^{VI}	0.33 .07	0.29 .12	0.35 .17	0.53 .03
Ti	0.20 .02	0.19 .02	0.17 .03	0.17 .03
Fe	1.85 .12	1.96 .16	1.92 .23	1.54 .12
Mn	0.03 .01	0.03 .01	0.02 .003	0.01 .002
Mg	0.36 .08	0.30 .04	0.25 .09	0.50 .10
Ca	0.01 .01	0.03 .02	0.004 .002	0.006 .005
Na	0.01 .01	0.003 .003	0.005 .003	0.004 .005
K	0.91 .05	0.91 .01	0.88 .02	0.83 .05
F	0.11 .07	0.10 .01	0.12 .03	0.09 .05
Cl	0.02 .01	0.02 .01	0.02 .01	0.02 .01
Σoct. cations	2.77	2.77	2.71	2.75
X_{Fe}	0.62	0.65	0.64	0.51
Fe/(Fe + Mg)	0.86	0.87	0.88	0.75

1. Average of biotites from seriate rocks south of Sunnyside Fault
2. Average of biotites from seriate rocks north of Sunnyside Fault
3. Average of biotites from porphyritic rocks north of Sunnyside Fault
4. Average of biotites filling a vein in feldspar

$$Ti^{VI} + \square = 2Mg^{VI} \quad (2)$$

$$Ti^{VI} + 2O^{2-} = (Fe, Mg)^{VI} + 2OH^- \quad (3)$$

In Figure 18, Ti is plotted against Si^{IV} and Fe, and there does not appear to be any correlation with either. Figure 19 does not appear to show any correlation with total octahedral cations, a relationship which should reflect coupling of Ti substitutions with a vacancy. The most likely type of substitution is apparently the TiO_2 for $(Fe,Mg)(OH)_2$ substitution.

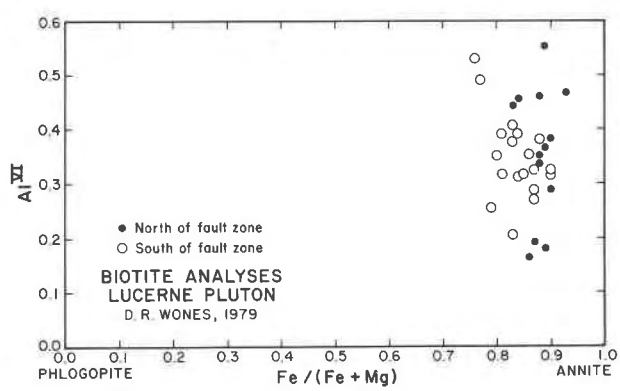

Fig. 16. Fe/(Fe + Mg) of biotites of the Lucerne pluton plotted against octahedral aluminum (Al^{VI}).

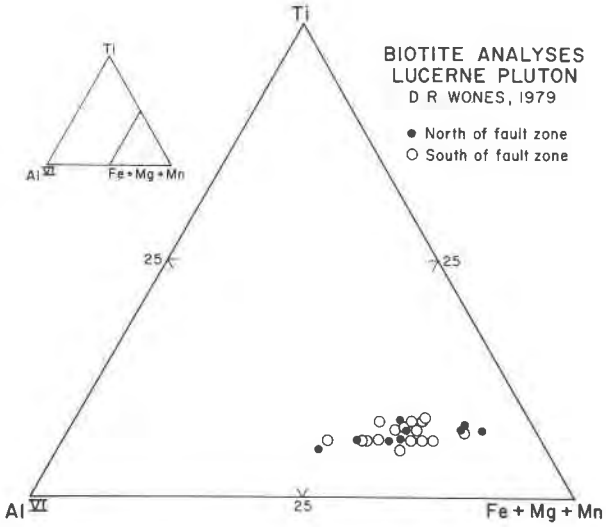

Fig. 17. Ternary plot of octahedral Al, Ti, and (Fe + Mg + Mn) contents of biotites of the Lucerne pluton.

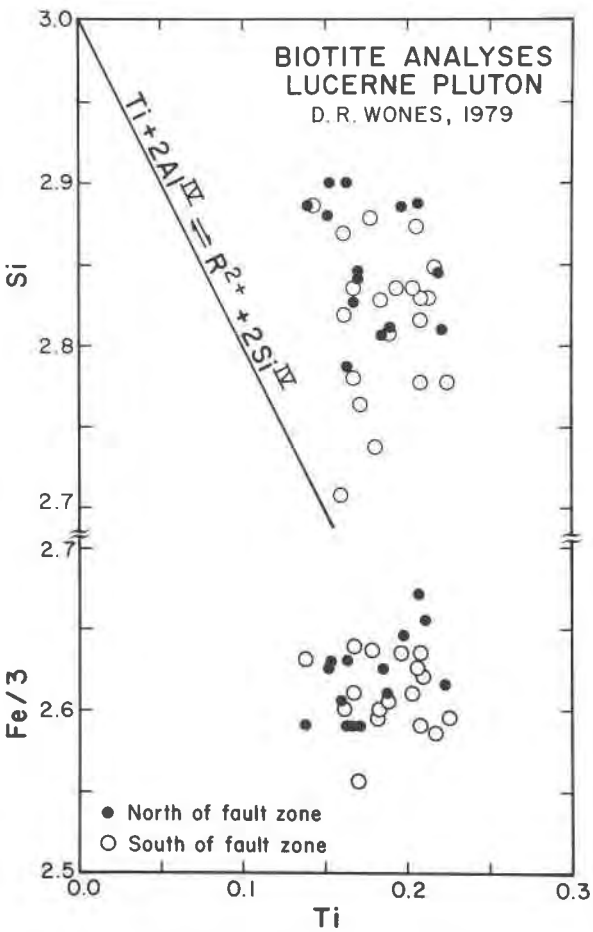

Fig. 18. Octahedral Ti in biotites from the Lucerne pluton plotted against Si content (upper figure) and mole fraction Fe in the octahedral layer (lower figure).

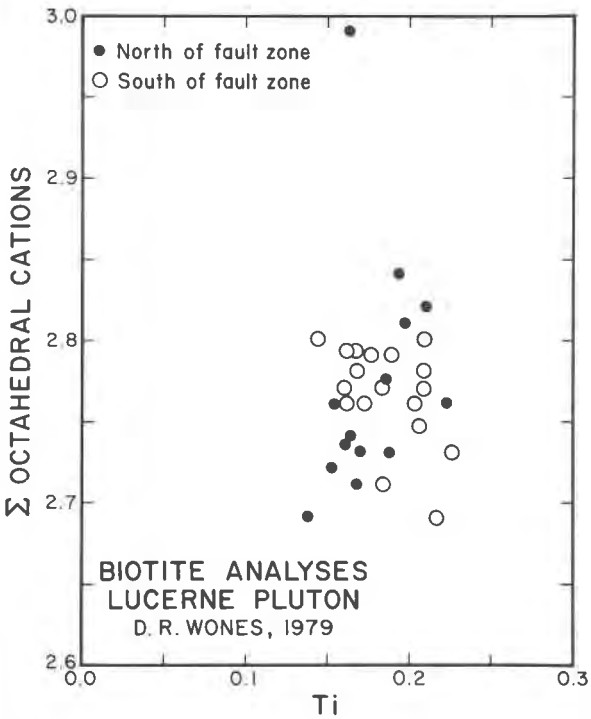

Fig. 19. Octahedral Ti in biotites from the Lucerne pluton plotted against total octahedral cations.

This result is contrary to those of Czamanske and Wones (1973) for biotites from the Finnmarka complex in Norway.

High Al content is characteristic of biotites that coexist with aluminosilicates (muscovite, cordierite,

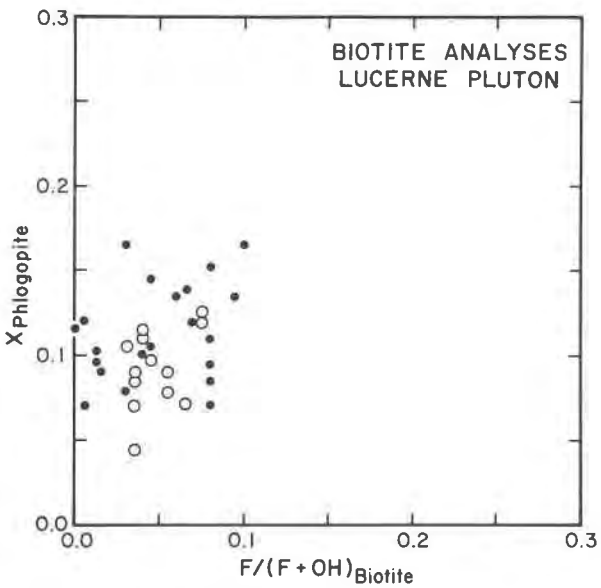

Fig. 20. $X^{phlogopite}$ (mole fraction Mg in octahedral layer) plotted against F/(F + OH) of biotites from the Lucerne pluton.

garnet, sillimanite) in granitic rocks. None of these aluminosilicates have been observed in the Lucerne pluton, but the Lucerne biotites are clearly more aluminous than those that occur with olivine, pyroxene, or amphiboles (Nockolds, 1947).

The alkali contents of the Lucerne biotites are notable because the Na contents are low, and the biotites seem to contain small but finite quantities of Ca. Using the same analytical techniques employed in this study, no Ca was detected in analyzed biotites that contain no Ca; hence the Ca contents of the Lucerne biotites appear to be real. The Na contents are low. The experimental results of Rutherford (1969) indicate that biotites crystallizing with alkali feldspars of compositions comparable to those of the Lucerne should contain higher amounts of Na. The low values observed may be due to the Al contents or may result from solidus reequilibration.

F and Cl contents are finite, and low (Table 4, Fig. 20). They are characteristic of biotites found in many orogenic belts but lower than those from alkalic or anorogenic terranes (Ludington, 1974; Ludington and Munoz, 1975).

Ilmenite

Representative ilmenites were analyzed for Fe, Ti, Al, Cr, Mg, Si, and Mn. The results, plotted in Figure 21, show that there is a slightly higher concentration of Mn in the ilmenites from the southern part of the pluton and that all of the ilmenites tend to be more enriched in Fe than in Ti. This implies that there is 3 to 5 mole percent $MnTiO_3$ (pyrophanite) component, and 0 to 9 mole percent Fe_2O_3 (hematite) component in the ilmenite. Ilmenite most commonly occurs as inclusions included in all other minerals as well. Biotites that include ilmenite do not appear to be richer in TiO_2 than those that do not.

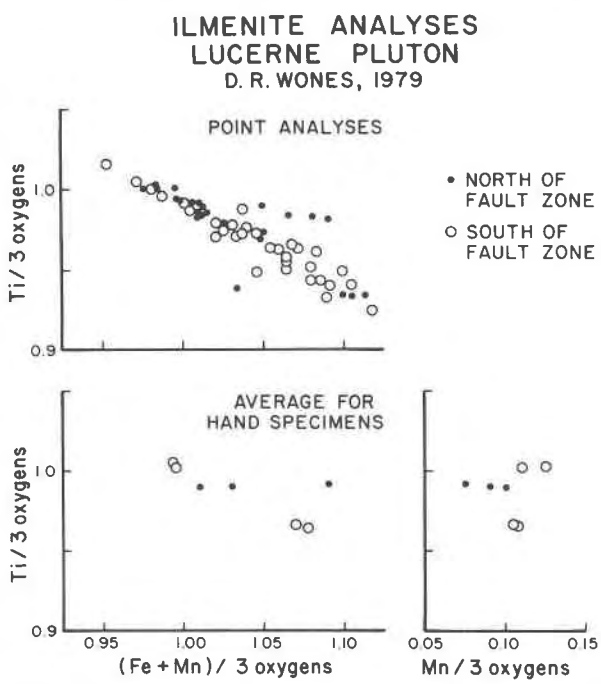

Fig. 21. Ti *vs.* (Fe + Mn) and Mn contents of ilmenites from the Lucerne pluton. Upper diagram shows scatter between analytical points. Lower diagram shows scatter between averaged hand specimens.

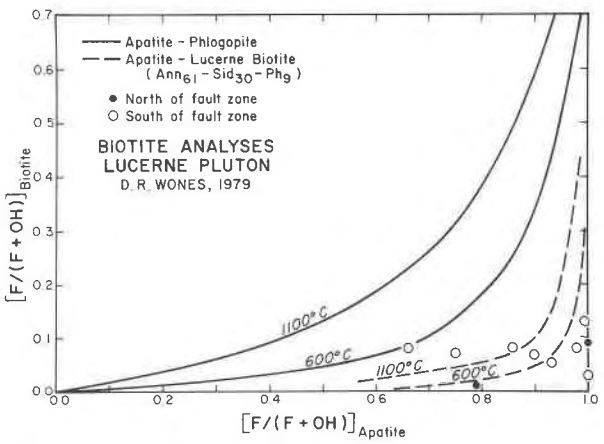

Fig. 22. F/(F + OH) of biotites plotted against F/(F + OH) of coexisting apatites from the Lucerne pluton. Heavy lines are 1100° and 600°C isotherms for pure phlogopite; dashed lines are isotherms calculated for biotite from the Lucerne pluton, based on Ludington (1978).

Magnetite

Magnetite is only found in areas of mylonitization where it is always associated with chlorite in pseudomorphs after biotite. These grains are almost pure Fe_3O_4. No magnetite has been observed in a primary textural relationship with any primary mineral.

Chlorite

Small amounts of this secondary mineral occur interleaved with biotite in nearly every rock. In mylonitized rocks, most of the biotite grains have been altered to chlorite, sphene and, rarely, epidote. The chlorite is more aluminous than the biotite and nearly always preserves the Fe/(Fe + Mg) value of the associated biotite. Chloritization is much more intense in the porphyritic zone of the pluton, as is the development of secondary sphene.

Sphene

This mineral only occurs in chlorite pseudomorphs after biotite.

Apatite

Apatite nearly always occurs as fine-grained subhedra usually associated with biotite. Microprobe analyses were performed on the apatites to explore the F and Cl fractionation between apatite and biotite (Stormer and Carmichael, 1971; Ludington, 1978). The analyses are not stoichiometric and imply that there are other substituent anions such as carbonate and sulfate as well as excess F in the apatite. Figure 22 is a plot of the F/(F + OH) of biotite against that of apatite. The irregular fractionation of F between the biotites and apatites indicates some disequilibrium between the two and may be due to subsolidus loss of F from the biotite.

Tourmaline

This mineral occurs in sprays on Springy Pond Mountain, near the NW boundary of the porphyritic facies of the pluton. Tourmaline also occurs in the single outcrop of pegmatite observed near the western margin of the pluton 800 m north of Moose Brook. Aplite dikes observed at the Craig Brook Fish Hatchery and on Blackcap Mountain contain tourmalines. Trace amounts of tourmaline have been observed in 2 samples of the seriate facies of the pluton. The Fe/(Fe + Mg) ratio varies between 0.65 and 0.69.

Amphibole

This mineral was observed in only one thin section.

Zircon

The mineral is ubiquitous, and nearly always occurs associated with biotite.

Fluorite

This mineral was observed in only one specimen as thin lamellae interleaved with biotite.

Contact metamorphism

Novak (1979) determined that the thermal effects of the Lucerne pluton on its host rocks extend about 1 km from the contacts. The major effect is recrystallization of the Vassalboro Formation from quartz–calcite–muscovite–chlorite assemblages characteristic of the regional grade to plagioclase–biotite assemblages, similar to the situation at the Togus plutons to the southwest (Ferry, 1976). Quartz–calcite veins, deformed into tabular masses, react at higher grades to form assemblages that contain tremolite, diopside, and zoisite. The more pelitic layers within the Vassalboro react to form andalusite- and corundum-bearing assemblages. Novak did not observe sillimanite or garnet in any of the metamorphic assemblages, even those adjacent to the pluton at the contacts.

The inferred composition of the gas phase present during the prograde metamorphism of the Vassalboro is relatively CO_2-rich. However, the later reaction of calcite–plagioclase assemblages to zoisite (or epidote) indicates a late-stage gas phase that was H_2O-rich.

The granite of the Wallamatogus pluton, which lies a few hundred meters SW of the Lucerne pluton and predates the Lucerne, contains garnet and sillimanite as accessory minerals and is confined to the Penobscot Formation. Novak found that biotite–cordierite assemblages within the Penobscot Formation probably represent an earlier metamorphism that predated the intrusion of the Lucerne pluton.

The sequence of events as worked out by Novak is: (1) a prograde metamorphism of the Vassalboro Formation that generated CO_2-rich fluids, followed by (2) the introduction of aqueous fluids into the metamorphic rocks. Ferry (1978) suggested a similar sequence for the Togus plutons, followed by the incorporation of fluids into the crystallized granite pluton. In the Lucerne pluton there is little evidence for large-scale introduction of fluids into the granite after its crystallization. There is some deuteric alteration and minor silicification along joints, but no extensive metasomatism and retrograde reaction. Finally, restricted mylonitization and deformation took place within specific portions of the pluton.

Intensive variables

One of the great accomplishments of experimental petrology during the past two decades has been the development of a number of mineralogical methods of determining the values of intensive parameters during geological events. Such parameters have traditionally been pressure and temperature, but now we can make approximate determinations of the activities or fugacities of chemical components. Current work may establish values for reaction rates, strain rates, and thermal histories as well.

Granitic rocks are the result of a long cooling history beginning with a magma of uncertain origin. The total crystallization interval of such a magma could range from 400° (Carmichael, 1967) to only a few tens of degrees. This could be followed by subsolidus recrystallization. Thus the mineral assemblages that we observe in the rocks today are the re-

sult of a long integrated history of different temperatures, pressures, and fluids. These problems have been repeatedly encountered in studies applying the ilmenite–magnetite geothermometer–oxybarometer of Buddington and Lindsley (1964) to granitic rocks (Haggerty, 1976).

System Ab–An–Q–H_2O

One of the earliest suggestions for establishing temperatures and pressures of granitic magma crystallization was that of Tuttle and Bowen (1958), namely that the composition of the liquid coexisting with alkali feldspar, quartz, and a vapor phase in the system Ab–Or–Q–H_2O had unique values, and that the residual liquids in a crystallizing magma might be modeled after the synthetic system. Recent additions to this study by Luth *et al.* (1964), Steiner *et al.* (1975), and James and Hamilton (1968) show that high pressure, low activities of H_2O, and the addition of the anorthite component can modify the compositions of the melt coexisting with two feldspars, quartz, and gas.

Normative compositions of selected samples of the Lucerne pluton are projected onto the Q–Ab–Or ternary diagram in Figure 23. Also plotted on the figure are the compositions of the ternary minimum liquids as determined by Tuttle and Bowen (1958) and the composition of liquids coexisting with quartz, plagioclase, alkali feldspar, and vapor at 1 kbar as determined by James and Hamilton (1968) for An_3 and An_5 compositions in the more general system Q–Ab–An–Or–H_2O. Most of the samples from the Lucerne pluton plot within the alkali feldspar region rather than on the phase boundary between quartz and feldspar. The most siliceous rocks plot near the three-phase boundary at 500 bars total pressure or near the four-phase boundary at An_3 composition at 1 kbar. As can be seen from Table 3, the porphyritic facies of the Lucerne pluton contains about 3 weight percent An component.

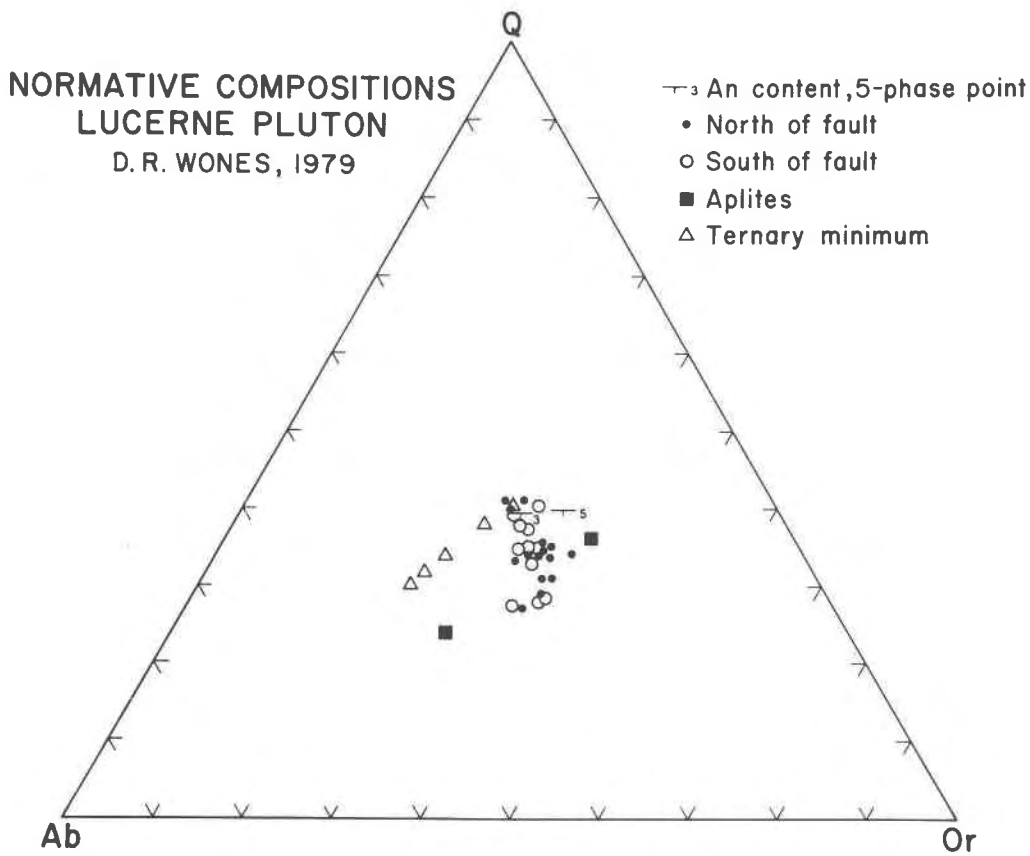

Fig. 23. Ternary projection of normative Q–Ab–Or contents of the rocks of the Lucerne pluton. Also plotted are minimum melting compositions (triangles) for the system Q–Ab–Or–H_2O of Tuttle and Bowen (1958) at 0.5, 1.0, 2.0, 3.0, and 4.0 kbar (from right to left) and for the composition of the melt coexisting with quartz, plagioclase, alkali feldspar and vapor at An_3 and An_5 compositions at 1 kbar (after James and Hamilton, 1968).

The normative data are projected onto the An–Ab–Or ternary (Fig. 24), as is the boundary curve between plagioclase and alkali feldspar given by James and Hamilton (1968) for 1 kbar. Compositions of the plagioclases and alkali feldspars observed within the Lucerne pluton are given as well. The rocks of the Lucerne pluton plot near the four-phase boundary.

The porphyritic facies of the Lucerne pluton contains miarolitic cavities. This fact, and the porphyritic texture, suggest that this facies of the pluton may have partially crystallized in the presence of a gas phase. Porphyritic texture can result from the exsolution of gas from a phenocryst-bearing melt as the H_2O pressure within the crystallizing magma exceeds the ambient pressure.

Abbott (1978) and Cherry and Trembath (1978) have examined the available information concerning the coexistence of the two feldspars and liquid. They have suggested that viborgitic (rapakivi) texture is due to a change in ambient conditions, rather than the result of peritectic reaction as suggested by Stewart and Roseboom (1962). Such an event, if their analysis is correct, would have taken place when 5 percent of the alkali feldspar had crystallized, would have been effective throughout all the presently exposed part of the pluton, and could have happened when the magma moved into its present position. The porphyritic core region would have been the last part of the pluton to crystallize and would have accumulated the residual H_2O from the rest of the system during crystallization of the anhydrous quartz and feldspar.

Two-feldspar geothermometry

The use of the two-feldspar geothermometer has been recently enhanced by the formulation of Stormer (1975) and the applications by Whitney and Stormer (1976). Although the formulation was done originally for sanidine, recent data are available for microcline (Whitney and Stormer, 1977). The habit of the alkali feldspars in the granites of the Lucerne Pluton is monoclinic, so that I have plotted the isotherms for coexisting plagioclase and alkali feldspars as originally given by Stormer (1975). Indicated tem-

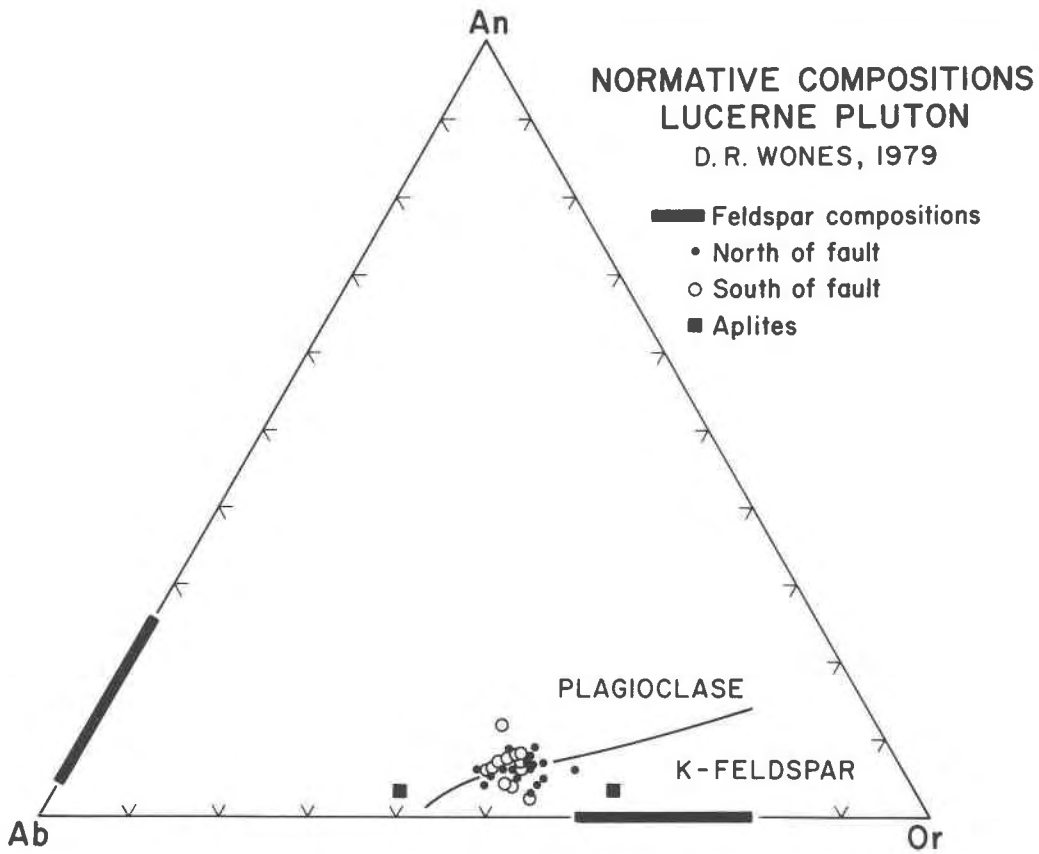

Fig. 24. Ternary projection of normative An–Ab–Or contents of the rocks of the Lucerne pluton. Boundary curve between alkali feldspar and plagioclase at 1 kbar after James and Hamilton (1968).

peratures of equilibration range from 775° to 550°C. The range in composition of the alkali feldspars is limited, so that the range in temperatures reflects the varying composition of plagioclase. The plagioclase and alkali feldspar must have undergone some reequilibration and subsolidus recrystallization during cooling. The lower inferred temperatures could reflect the decrease in the An content of the plagioclase due to sericitization and/or the reaction of plagioclase with exsolving albite during the formation of microcline perthite. The best estimate for the temperature of the feldspar mantling event is about 675°C.

Plotting the granite minimum melting curve at gas saturation as a function of pressure and temperature yields a value of about 1 to 3 kbar for the pressure at which the Lucerne pluton crystallized (Fig. 25). Also plotted in Figure 25 is the boundary curve between the Al_2SiO_5 polymorphs, andalusite and sillimanite, as determined by Holdaway (1971) and by Richardson *et al.* (1969). The lack of sillimanite in the contact metamorphic rocks near the Lucerne pluton has two interpretations. If we assume that the data on the quartzo-feldspathic phases are correctly interpreted, then the andalusite–sillimanite curve established by Holdaway must be at too low a pressure, and the curve of Richardson *et al.* is more nearly correct. On the other hand, if Holdaway's determination is correct, it appears that the temperature estimates of the Lucerne magma at low pressures are too high, and that the actual curve of the granite minimum is not a good estimate of the minimum melting conditions of the Lucerne magma. This entire analysis assumes that the rocks immediately adjacent to the contact were heated to magmatic temperatures.

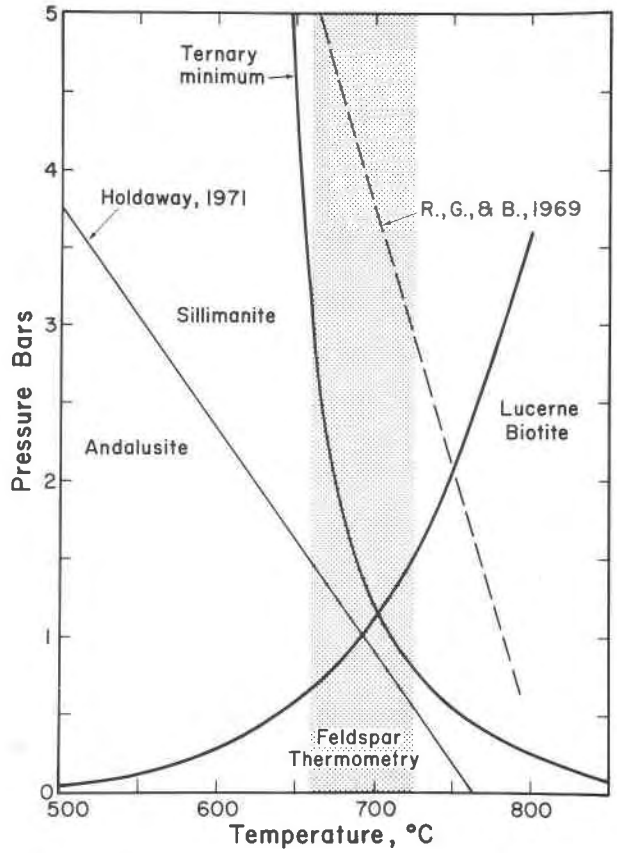

Fig. 25. Pressure *vs.* temperature plot for the ternary minimum at water saturation in the system Q–Ab–Or–H_2O after Tuttle and Bowen (1958). Boundary curves between andalusite and sillimanite after Holdaway (1971) (solid) and Richardson *et al.* (1969) (dashed). The stippled area is the estimated temperature range of the crystallization of the Lucerne magma. The curve labeled "Lucerne biotite" is the upper stability of biotites in the Lucerne pluton at oxygen fugacities defined by the quartz–magnetite–fayalite assemblage (Hewitt, 1978). See text and Fig. 26.

Oxygen fugacity estimates

The use of magnetite–ilmenite pairs to estimate temperatures and oxygen fugacities is not applicable to the Lucerne pluton as no magmatic magnetite has been observed. The occurrence of ilmenite with a composition of $Ilm_{85}Py_{10}Hm_5$ gives a range of oxygen fugacity–temperature values that approximate those of the assemblage fayalite–magnetite–quartz (Lindsley, 1976, 1978; Hewitt, 1978; Chou, 1978). If we assume that the oxygen fugacity–temperature range of the magma approximates the FMQ assemblage, then we can calculate an f_{H_2O}–T curve for the stability of the biotites found in the Lucerne (Fig. 25). These in turn can be expressed in P_{H_2O}–T diagrams and superposed on the data for the quartzo-feldspathic components. With the data of Wones and Eugster (1965), as modified by Wones (1972), we can calculate a curve on the assumption that the Fe in the biotites is all Fe^{2+}.

The biotites within the Lucerne pluton are limited in mole fraction of Fe^{2+} in the structural formula to 0.51 to 0.71 of the octahedral constituents. In this treatment, vacancies were counted as constituents, as were Ti and Al; the ratio, Fe/(Fe + Mg), is not appropriate. The stability curve calculated for these aluminous biotites lies close to that determined by Rutherford (1969) for the stability of synthetic aluminous ferruginous biotites. In Figure 25, the calculated biotite stability curve intersects the granite minimum curve of Tuttle and Bowen (1958), within the range of the feldspar temperature estimates, and at about 1 kbar pressure. The P_{H_2O} values of this curve are for biotites coexisting with magnetite. Actual P_{H_2O}

values for the Lucerne magma would be lower, as magnetites are not present as magmatic phases.

Carmichael (1967; personal communication) has suggested that the TiO_2 contents of biotites coexisting with ilmenite or sphene are a function of temperature. Czamanske and Wones (1973) showed that this was true for the rocks of the Finnmarka complex. TiO_2 contents of the biotites from the Lucerne pluton are comparable to those of the granites of the Finnmarka complex, for which Czamanske and Wones estimated a crystallization temperature between 675° and 700°C. These data are also comparable with those of Robert (1976) for synthetic Mg-biotites.

If we assume that the total pressure of the crystallizing Lucerne magma was about 1 kbar, then we can assume H_2O pressures near that value and plot oxygen fugacity *vs.* temperature (Fig. 26) for the Lucerne biotites as if they coexisted with a spinel (magnetite). The biotite stability is limited by two curves, one for the reaction to sanidine and spinel (magnetite) and one of biotite plus quartz to sanidine and fayalite, orthopyroxene, or cordierite depending upon the Fe–Mg–Al ratios. The first curve puts a boundary on the oxygen fugacity, the second on temperature. Both are plotted in Figure 26 for the two limiting biotite compositions. The maximum calculated temperatures for biotite stability are given by the intersection of the two curves. This constraint shows good agreement with the temperature estimates made from the two-feldspar thermometer and from the system Q–Ab–Or–An–H_2O.

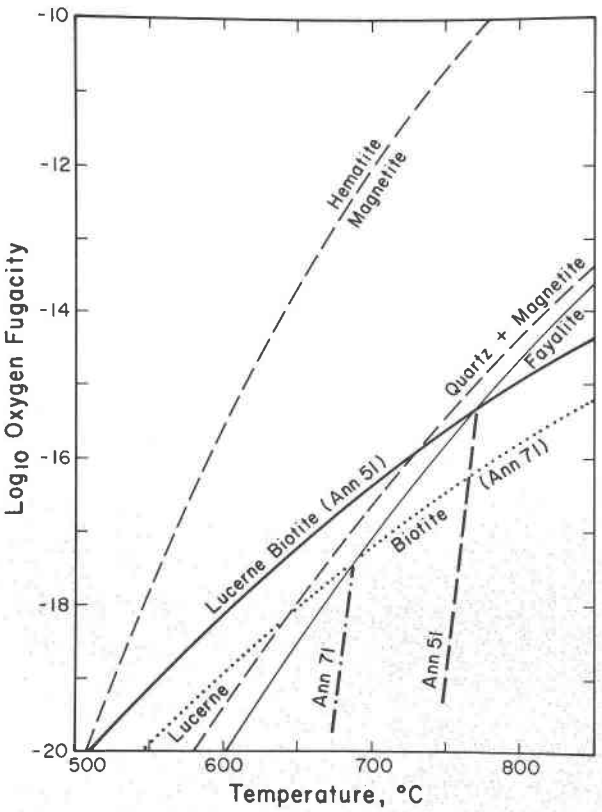

Fig. 26. Log_{10} oxygen fugacity *vs.* temperature. Dashed boundary curves for hematite–magnetite and quartz–magnetite–fayalite are from Chou (1978). Solid curve for the quartz–magnetite–fayalite assemblage is after Hewitt (1978). The heavy line labeled Ann 51 is the stability curve of a biotite in equilibrium with sanidine and magnetite that contains 51 mole percent Fe in the octahedral layers. The dotted curve is the equivalent for 71 mole percent Fe. The dash–dot curve is the estimated upper stability of the biotite + quartz assemblage for Ann 71, and the heavy dashed line is the equivalent curve for Ann 51.

Crystallization sequence

Another approach is to use the data of Whitney (1975) and of Maaloe and Wyllie (1975) that relate the sequence of crystallization of the minerals to the temperature, pressure, and water content of the magma. Biotite was the primary phase of the essential minerals, and the occurrence of biotite-rich schlieren within the pluton indicates that it must have been a stable liquidus phase at the time of intrusion.

The occurrence of the miarolitic cavities in the porphyritic core zone indicates that the magma did not reach saturation with a vapor phase until well over 90 percent of the presently exposed surface had crystallized. Thus, there was a gas-undersaturated magma in which biotite was stable, and in which the quartz, plagioclase, and alkali feldspar begin to crystallize simultaneously. On the basis of the biotite and ilmenite data, the oxygen fugacity of the melt must have been relatively reducing, but exact limits cannot be determined.

Maaloe and Wyllie (1975) established crystallization sequences for a granitic magma for a series of H_2O contents. They used the Ni–NiO buffer to establish oxygen fugacities in their experiments, and had magnetite as the early crystallizing phase. As a consequence, their data for biotite stability probably yield temperatures that are too low for direct application to the Lucerne pluton. The Fe/(Fe + Mg) values for their granite are lower than the values for the Lucerne pluton. Their data for quartz and the feldspars should be applicable. Whitney (1975) collected similar data for a synthetic sample that did not contain ferromagnesian constituents but was close to the composition of the Lucerne pluton in terms of the quartzo-feldspathic components.

These combined data suggest that the Lucerne magma, upon intrusion at its present level, must have been saturated with quartz, plagioclase, alkali feldspar, and biotite but undersaturated with water. We have observed that the amount of water or other volatiles within the magma could not have been great, because of the large volume of the pluton that crystallized before the formation of the porphyritic core facies. From Figure 25 we see that the magma must have contained a finite amount of H_2O corresponding to an H_2O pressure of 1 to 2 kbar. However, if the magma contained another volatile substance that promoted lower melting temperatures, then the biotite stability and the water contents could be more compatible.

Boron as a possible component

Chorlton and Martin (1978) have demonstrated that B_2O_3 will lower the solidus of granitic magmas. Accessory tourmaline within the Lucerne pluton and late quartz and tourmaline veins indicate that boron was present in the magma. Boron would make the magma less viscous, and because of its tendency to break up silica polymers within the melt could suppress crystal nucleation and lead to the coarse grain size of the pluton.

Boron might also influence the position of the boundary curves between the feldspars. Mantling of alkali feldspar by plagioclase could be the result of enriching the residual melt in B_2O_3 during crystallization of quartz and feldspar, thus shifting the phase boundary toward alkali feldspar.

Origin of the Lucerne magma

Mineralogical studies can place a surprising number of constraints on the origin of granitic magmas, although geochemical studies are essential for the best resolution of such a problem. The magma clearly originated from a potassium-rich source, had its water content controlled by reactions involving biotite, and was intruded from greater depths to its present level. The Al-rich biotites of the Lucerne pluton have not come to equilibrium with each other in regard to Ti and Al contents and may represent a biotite residuum from the source or disaggregated inclusions. The presence of tourmaline suggests a boron-enriched source. A quartz–plagioclase–biotite gneiss derived from the metamorphism of a graywacke-type sediment is a most likely source material.

An earlier metamorphic event that could have depleted the source in muscovite and H_2O would have made such a gneiss even more appropriate as a source material. The Lucerne magma, once formed, would have carried residual quartz, plagioclase, alkali feldspar, and biotite to the site of the intrusion.

These concepts essentially follow the models that White and Chappell (1977) have proposed for granites derived from a sedimentary source ("S" granites), and are in great contrast to the model proposed by Barker *et al.* (1975) for the Pikes Peak Batholith. The Lucerne pluton is one tenth the size of the Pikes Peak Batholith, contains more plagioclase, and crystallized biotite at an earlier stage. According to the model of Barker *et al.* (1975), the Lucerne pluton must have formed in a less mature continental crust than did the Pikes Peak Batholith.

Summary

I have attempted to demonstrate how studies of mineralogy permit us to map rocks, to interpret their history and deformation, to define conditions of magma crystallization, to constrain source regions of magmas, and even to understand geomorphic and glacial processes better. I am confident that many other applications await us, once we have the vision to see them.

Acknowledgments

A large number of people have contributed to the data I have summarized herein, and I would like to acknowledge their contributions. I thank the U.S. Geological Survey and the National Science Foundation for their support. The pluton was mapped under the auspices of the U.S. Geological Survey, and some of the recent mineralogical and chemical work was obtained through National Science Foundation Grant EAR 78-03655.

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Douglas G. Brookins and Robert E. Zartman have contributed to the resolution of the geochronology of the Lucerne pluton.

My understanding of the local geology has been aided immeasurably by long discussions with P. H. Osberg, Olcott Gates, Arthur M. Hussey, and Allan Ludman, although they disagree with some of my interpretations. I owe a special debt to my colleague, David B. Stewart, who originally suggested that the Lucerne pluton was appropriate for study. Stewart has mapped the Blue Hill and Castine quadrangles that include the southern lobe of the Lucerne pluton (Stewart, 1974; Stewart and Wones, 1974).

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Finally, I would like to acknowledge the inspiration and challenge that Paul C. Bateman of the U.S. Geological Survey has given me. Paul patiently took me through a mutual project in the Sierra Nevada (Bateman and Wones, 1972a,b) and challenged me to produce data for New England that would complement the data that he and his colleagues have put together for the Sierra Nevada batholith (Bateman *et al.*, 1963; Bateman and Clarke, 1974; Bateman, 1979). This study is part of the answer to that challenge.

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