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METALLOGENY OF GRANITOID ROCKS IN THE CANADIAN SHIELD

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ABSTRACT

Granitoid rocks ranging in age from 1.0 to 3.76 Ga are the dominant component of the Canadian Shield but are variable in abundance, composition, mode and depth of emplacement, magma genesis, and degree of deformation among the seven structural provinces and within provinces. Most plutons are syntectonic, mesozonal diapirs, but the plutons vary in tectonic setting from pretectonic and subvolcanic to late- or post-tectonic and epizonal. The oldest granitoid units, which are volumetrically minor, 2.8–3.76-Ga-old deformed and gneissic tonalite–granodiorite, are present in most structural provinces and probably formed a basement for Late Archean supracrustal sequences. In the Late Archean, 2.55–2.75 Ga, a major granite-producing event resulted in craton stabilization when large composite batholithic complexes ranging in composition from tonalite to granite (dominantly granodiorite) intruded volcanic–sedimentary supracrustal sequences; both trondhjemitic and calc-alkaline trends are present. Late Archean plutons are more abundant and generally more sodic in greenstone-belt subprovinces than in paragneiss subprovinces and were derived largely by anatexis of lower crust and mantle; upper crustal anatexis is rare, and is most common in paragneiss subprovinces. In the Churchill and Grenville provinces, most granitoid plutons, apparently Archean in age, were metamorphosed, deformed, remobilized and partly melted by Proterozoic orogenic events. Proterozoic granitoid plutons are not abundant except in areas of Proterozoic greenstone-belt volcanism. Proterozoic granitoid plutons in areas away from greenstone belts are generally more potassic than Archean plutons.

Mineral deposits are sparse in and adjacent to granitoid plutons but include porphyry Cu–Mo, nonporphyry Cu–Mo, vein and porphyry Au–Ag, U–Th in pegmatites and larger plutons and aureoles of Be–Li–Cs–Nb–Ta–REE-bearing pegmatites. Except for the pegmatites, the genetic relationship of mineralization and plutons and the nature of the parent plutons are poorly documented. Cu, Mo, Au and Ag deposits are concentrated in small subvolcanic to epizonal, tonalite–granodiorite plutons in greenstone-belt terranes, particularly in the southern Superior Province. Cu and Mo appear to be genetically related to the host plutons, but for many Au–Ag deposits the plutons are favorable hosts but are apparently not genetically related to the mineralization. Syenitoid plutons appear to be an equally favorable host for Au–Ag deposits. Pegmatite deposits are widespread in the Superior, Slave, Churchill and Grenville provinces, but appear to be most abundant in paragneiss–granitoid terranes of the Superior Province. Churchill and Grenville provinces are characterized by U–Th-enriched anatectic pegmatites and by a relative paucity of pegmatites related to granitoid intrusions. In contrast, Be–Li–Cs–Ta-bearing pegmatite swarms, fractionated from late-tectonic silicic leucogranites, are abundant in the Superior and Slave provinces. Abnormally high concentrations of U–Th also occur dispersed in large and commonly pegmatitic granite plutons in the Superior, Churchill and Grenville provinces.

Keywords: Canadian Shield, granitoid plutons, metallogeny, porphyry deposits, pegmatites, Cu, Mo, Au, Ag, U, Th, Li, Rb, Cs, Be, Ta, Nb, REE.

SOMMAIRE

Les roches granitoïdes, mises en place il y a 1.0 à 3.76 milliards d'années, forment la partie dominante du bouclier Canadien. Ces roches varient en abondance, composition, mode et profondeur de mise en place, origine du magma et degré de déformation entre les sept provinces structurales, voire

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à l'intérieur d'une même province. Dans la plupart des cas, les plutons sont des diapirs syntectoniques mésozonaux, mais leur environnement varie de prétectonique et subvolcanique à post-tectonique et épizonal. Les unités les plus anciennes occupent un volume restreint; ce sont des tonalites et granodiorites déformées, gneissiques, vieilles de 2.8 à 3.76 Ga, présentes dans la plupart des provinces structurales, où elles forment un socle pour les séquences supracrustales de l'Archéen supérieur. A cette époque, entre 2.55 et 2.75 Ga, un important événement a produit quantité de plutons granitiques qui a stabilisé le craton. C'est alors que les vastes complexes batholitiques, tonalitiques à granitiques, mais surtout granodioritiques, ont été mis en place dans les séquences supracrustales volcano-sédimentaires; on y trouve les deux lignées trondhjémitique et calco-alcaline. Ces plutons sont plus abondants et généralement plus sodiques dans les ceintures de roches vertes que dans les domaines paragneissiques; ils doivent leur origine surtout à l'anatexie de la croûte inférieure et du manteau. L'anatexie de la croûte supérieure est un phénomène rare que l'on rencontre surtout dans les domaines paragneissiques. Dans les provinces du Churchill et du Grenville, la plupart des plutons granitoïdes sont apparemment d'un âge archéen; ils ont été métamorphisés, déformés, remobilisés et partiellement fondus lors d'événements orogéniques protérozoïques. Les plutons d'âge protérozoïque ne sont pas communs, sauf dans les secteurs de volcanisme protézoroïque du type "ceinture de roches vertes". Les plutons plus éloignés des ceintures de roches vertes sont généralement plus potassiques que les plutons archéens.

Les gîtes minéraux ne sont que rarement associés aux plutons granitoïdes: on y trouve des gisements de Cu–Mo (associés ou non à des porphyres, une minéralisation Au–Ag en filons ou associée à des porphyres, une minéralisation U–Th dans les pegmatites et les grands plutons, et les auréoles de pegmatites à Be–Li–Cs–Nb–Ta–terres rares. Sauf dans le cas des pegmatites, on connaît mal la relation entre la minéralisation et la filiation des plutons-parents. Les gisements de Cu, Mo, Au et Ag sont concentrés dans de petits plutons subvolcaniques ou épizonaux de tonalite–granodiorite dans les ceintures de roches vertes, surtout celles dans la partie sud de la province du Supérieur. Cu et Mo semblent liés génétiquement aux plutons-hôtes; pour plusieurs gisements Au–Ag, les plutons sont des hôtes favorables mais ne semblent pas liés à la minéralisation. Les plutons syénitiques offrent aussi des sites favorables à la minéralisation Au–Ag. Les gîtes pegmatitiques sont répandus dans les provinces du Supérieur, de l'Esclave, de Churchill et du Grenville, mais tout particulièrement dans les domaines à paragneiss–granite de la province du Supérieur. Les pegmatites anatectiques enrichies en U–Th et sans lien apparent aux plutons granitoïdes caractérisent les provinces de Churchill et du Grenville. Par contre, les essaims de pegmatites fractionnées de magmas leucogranitiques siliceux tardi-tectoniques abondent dans les provinces du Supérieur et de l'Esclave. Des concentrations anormalement élevées de U + Th se trouvent dispersées dans les plutons de granite pegmatitiques des provinces du Supérieur, de Churchill et du Grenville.

(Traduit par la Rédaction)

Mots-clés: bouclier Canadien, plutons granitiques, métallogénie, gisement du type porphyre, Cu, Mo, Ag, Au, U, Th, Li, Rb, Cs, Be, Ta, Nb, terres rares.

INTRODUCTION

Granitoid rocks of various compositions and types are the dominant component of the Precambrian Canadian Shield, but are largely *terra incognita* in terms of composition, magma genesis, emplacement mechanisms, structural setting and metallogeny. This paucity of data reflects a number of factors, including the vast size of the granitoid terrane, inaccessibility, lack of economic incentive because of lack of known mineral deposits and, until recently, an apparent lack of appreciation of the importance of granitoid rocks in modeling early crustal evolution.

Intensive investigations of large granitoid terranes have been undertaken only recently (*e.g.*, Ayres 1974, Breaks *et al.* 1978, Davidson 1972b, Dimroth *et al.* 1973, 1974, Ermanovics *et al.* 1979, McCrank *et al.* 1981, Schwerdtner & Lumbers 1980, Schwerdtner *et al.* 1979) and interest in the granitoid terranes has been increasing markedly. Thus, the time is ripe for a review of the granitoid terrane and its potential for mineral exploration. Previous reviews have been given by various authors listed in Price & Douglas (1972) and by Stockwell *et al.* (1970). In any review of this magnitude, the data and conclusions are, of necessity, generalized, but there are always exceptions to the generalizations. We recognize that in petrogenetic or metallogenic modeling, the exceptions may be just as important as the general trends. Accordingly, where data permit, we have attempted to present both general trends and anomalies, particularly anomalies of regional significance. Unfortunately, lack of systematic field, petrographic, structural and geochemical data, except for localized areas, prohibits comprehensive treatment of the granitoid plutons. Discussion of various subjects and areas in this paper is uneven, but this is a reflection of the data base.

SETTING AND TERMINOLOGY

The Canadian Shield is the geological core of North America (Fig. 1). It has an outcrop area

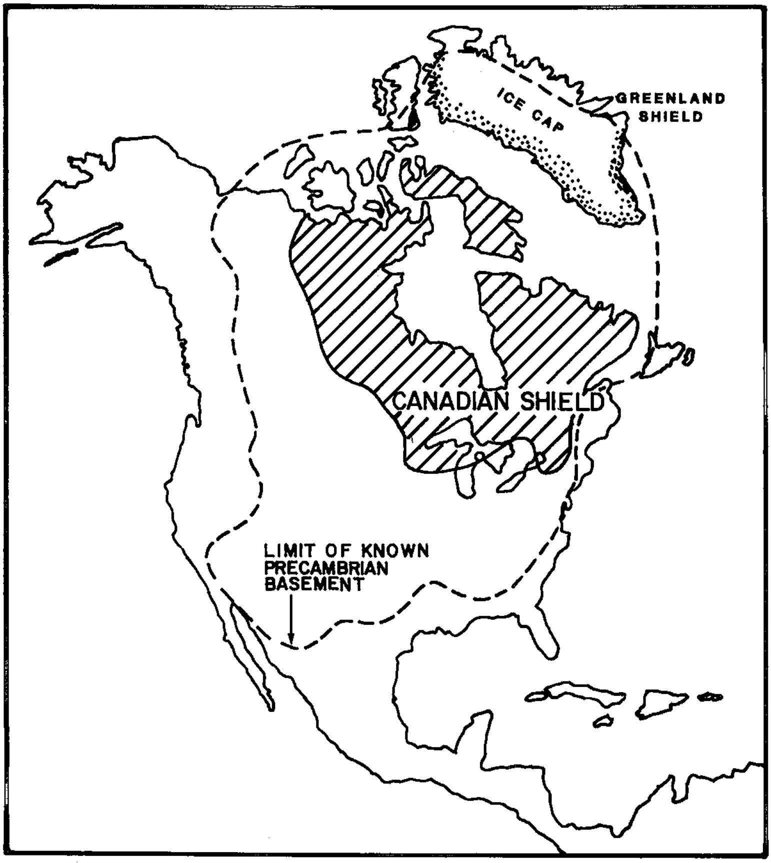


FIG. 1. Outcrop area of the Canadian Shield (lined pattern) in relationship to the Greenland Shield (dot pattern) and Phanerozoic rock units (unpatterned).

of about 4,780,000 km^2, mainly in Canada, but it extends beneath the relatively flat-lying Phanerozoic strata of the Interior Plains of Canada and the United States, the Canadian Arctic, and the inliers of the Hudson Bay and Foxe basins. It also extends beneath the inner parts of the Appalachian, Cordilleran and Innuitian orogenic regions. Outliers of the Shield are exposed in tectonically uplifted areas within and on the margins of the orogenic regions.

The outcrop area of the Shield forms almost half of Canada. On the south, it extends for a limited distance into the United States in the Lake Superior and Adirondack regions. On the northeast, it is essentially contiguous with Precambrian rocks of the Greenland Shield. In this contribution, we will consider only the contiguous parts of the Canadian Shield that outcrop in Canada. Furthermore, we will restrict our discussion to intrusive magmatic units of alkali feldspar granite, granite, granodiorite, tonalite (including trondhjemite), quartz monzonite, quartz monzodiorite and quartz diorite composition [fields 2, 3, 4, 5, 8*, 9*, and 10* of Streckeisen (1976)]. These granitoid plutons range from fresh and undeformed to high-grade metamorphosed orthogneiss. We have excluded granitoid gneisses derived from probable sedimentary or uncertain protoliths, and the minor granitoid phases of largely mafic plutons. Time terminology is summarized in Figure 2.

Mineral resources are widespread and economically important in the Canadian Shield, but are confined largely to weakly or moderately metamorphosed volcanic and sedimentary sequences and mafic plutons. For example, most of the iron, nickel, gold, silver, uranium and platinum-group metals and a large proportion of the copper and zinc produced in Canada come from these shield rock-units. The are-

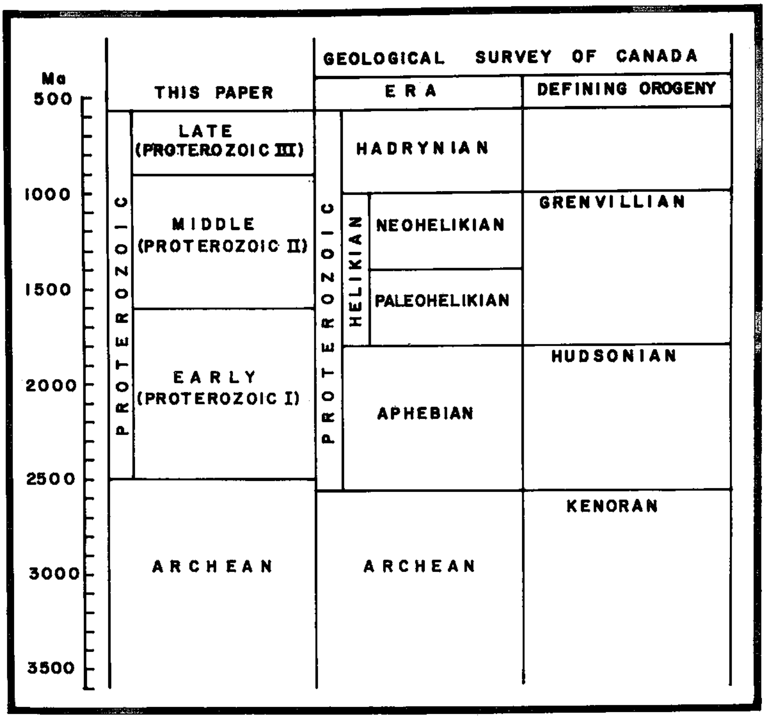


FIG. 2. Time classification of the Precambrian used in this paper compared to that of the Geological Survey of Canada (Stockwell 1961, 1973). Time boundaries used in this paper follow those recommended by the International Subcommission on Precambrian Stratigraphy (Sims 1980) but the recommended terms Proterozoic I, II and III have not been used. Instead we have used the terminology early, middle and late proposed by Harrison & Peterman (1980). The orogenies are those defined by Stockwell (1961) as marking the last period of important widespread deformation, metamorphism and plutonism in the type structural province. The end of these orogenies mark important time-boundaries.

ally more abundant granitoid rocks, on the other hand, contain only sparse mineral deposits. Uranium, thorium, tantalum, cesium, lithium, beryllium, rare-earth elements, copper, molybdenum, gold and silver deposits have been documented, but most of these are currently uneconomic. The rarity of mineral deposits in granitoid rocks of the Canadian Shield in part reflects a genuine scarcity, but in part may reflect a low intensity of mineral exploration and research.

Mineral deposits associated with granitoid plutons are generally in or near small plutons rather than the vast granitoid batholithic complexes that are the dominant rock-unit in much of the Shield. Concentrations of some elements, particularly uranium, thorium, tantalum, cesium, niobium, lithium, beryllium and lanthanide elements, which are mainly in pegmatites, appear to be a direct result of the magmatic evolution of granitic systems. For copper, molybdenum, gold and silver, however, there is some uncertainty about mechanisms of concentration. The major question is whether the elements are derived from the granitoid magma and concentrated by crystallization processes or by postcrystallization redistribution, or whether the plutons are simply favorable hosts for concentrating elements scavenged from adjacent strata by circulating aqueous solutions. Granitoid plutons of certain types could also be a direct factor in concentration of elements that formed volcanogenic gold–silver, massive sulfide and iron deposits.

SUBDIVISIONS OF THE CANADIAN SHIELD

The Canadian part of the Shield has been

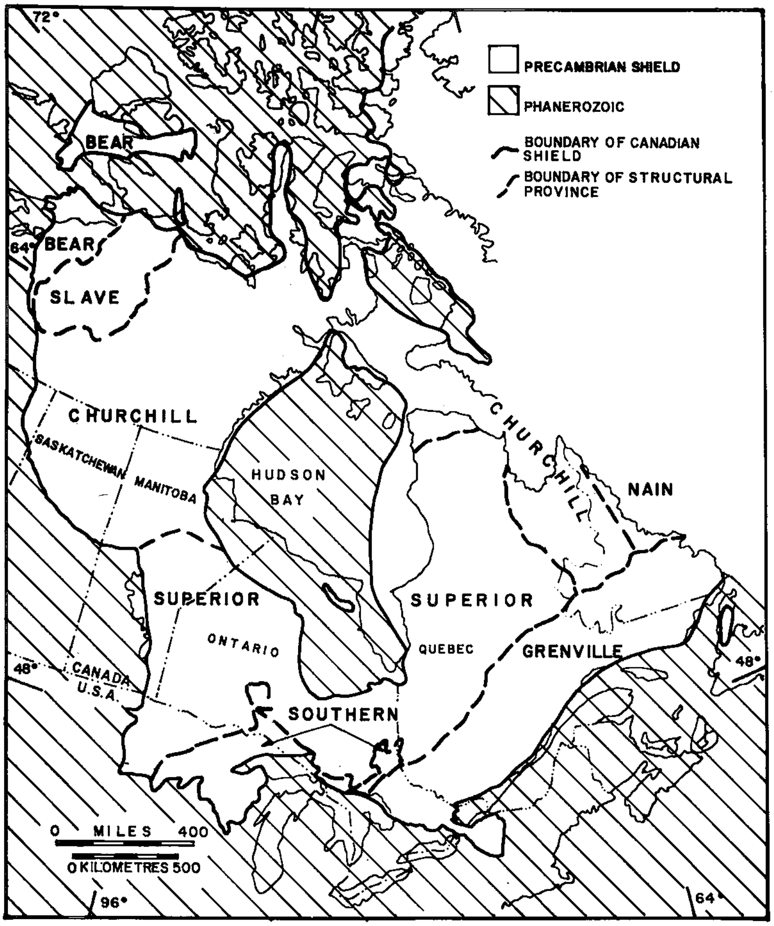


FIG. 3. Subdivisions of the Canadian Shield.

divided into seven structural provinces on the basis of contrasting structural trends, style of deformation and isotopic ages (Fig. 3, Table 1). The provinces were originally defined from structural trends (Wilson 1939, Gill 1949, Wilson 1949). This was subsequently augmented by recognition of several orogenies that affected different provinces more or less contemporaneously and that could be isotopically dated (Stockwell 1961, 1964). The provinces thus defined also show lithologic and metamorphic differences.

Most provinces are now known to be composite and to include several deformational events varying in intensity and widely spaced in time. Consequently, in several provinces, although various events can be dated, there is some controversy regarding the age of the deformational event that defines the province. In spite of this uncertainty, the provinces can be grouped into three broad age-categories. From oldest to youngest, these are (Table 1): Archean (Superior, Slave and Nain or Nutak), Early Proterozoic (Southern, Churchill and Bear) and Middle Proterozoic (Grenville).

Except for the Nain Province, the defining elements in each province are a series of broadly contemporaneous, interrelated events that were initiated by the deposition of thick volcanic and sedimentary sequences on sialic or oceanic basement, and that culminated with deformation, metamorphism and plutonism. The deformation, which was termed *orogeny* by Stockwell (1961, 1964), established the subparallel structural grain of the province and, in places, stabilized the province as part of the craton. The deformation intensity, metamorphic grade and amount of plutonism, as indicated by the present surface of erosion, are variable both within and between provinces; the deepest levels of

TABLE 1. SUMMARY OF MAJOR ROCK UNITS, EVENTS, AND GRANITOID PLUTONS IN THE SEVEN STRUCTURAL PROVINCES OF THE CANADIAN SHIELD IN CANADA

Province	Area^{1} (x10^{5} km^{2})	Major lithologies	Relative abundance of granitoid plutons^{2}	Regional stratigraphic-plutonic-deformational events^{3}	Nature and composition of granitoid plutons	Regional structural trends	Metamorphic grade	Late events^{4}	Major references^{5}
Grenville	6.4	quartzo-feldspathic gneiss of uncertain protoliths; paragneiss; metavolcanic-meta-sedimentary sequences; anorthosite-quartz monzonite-granite batholiths; nepheline syenite; granitoid plutons	uncertain; probably 20-50^{+}%	>3.0 Ga - tonalitic orthogneiss		north-easterly	greenschist to granulite facies	diabase dikes; alkalic and locally granitoid plutons; block faults	Wynne-Edwards (1972)
				2.5-2.7 Ga - Superior and Nain Province basement; dominant rock unit in most of province (?)	unknown				
				1.5-2.5 Ga - Sedimentation and minor volcanism and granitoid plutonism of the Southern and Churchill Provinces. Deformed during Hudsonian Orogeny	granodiorite-quartz monzonite dike swarms, sheets, stocks, and batholiths (1.5-1.7 Ga); includes an early pegmatite phase; now gneissic and recrystallized as a result of superimposed deformation and metamorphism				
				1.1-1.5 Ga - Anorthosite-granite plutons, in part remobilized	quartz monzodiorite-quartz monzonite-granite forming separate stocks and batholiths as well as being associated with anorthosite; now largely gneissic and recrystallized as a result of superimposed deformation and amphibolite to granulite facies metamorphism. Emplacement models range from syntectonic to extensional rift environment.				
				1.0-1.5 Ga - Volcanism and sedimentation of Grenville Supergroup; mafic, alkalic and granitoid plutonism; deformation of Grenvillian Orogeny (Stockwell et al. 1970) which affected all pre-existing rock units	early tectonic, in part subvolcanic, epizonal to mesozonal, tonalite-granodiorite stocks and batholiths (1.25 Ga); syntectonic, catazonal granodiorite-granite stocks and batholiths (1.125 Ga); late tectonic granite-alkali feldspar granite-monzonite-syenite dikes, stocks and batholiths (1.0-1.2 Ga) that are locally peralkaline; ubiquitous pegmatite dikes				
Southern	2.56	clastic and minor carbonate sedimentary and metasedimentary units; basalt and rhyolite metavolcanic rocks; gabbro and granitoid plutons	<5%	2.55-2.75 Ga - Superior Province basement; 2.8-3.6 Ga in the United States	as in Superior Province			mafic to felsic, calc-alkalic and alkalic plutonism; sedimentation; faults	Card et al. (1972)
				<1.9->2.2 Ga - Huronian and Animikie sedimentation, minor volcanism, mafic and granitoid plutonism, metamorphism, and deformation (Penokean Orogeny)	syntectonic granodiorite-granite stocks		?		
				1.6-1.75 Ga - granitoid plutonism, metamorphism and deformation (Hudsonian Orogeny of Stockwell 1961).	syntectonic tonalite-granodiorite-granite batholiths	easterly	diagenetic to amphibolite facies		
				1.1-1.4 Ga - Keweenawan volcanism, sedimentation, mafic and felsic plutonism, metamorphism, and tilting	subvolcanic granite sills, dikes, irregular plutons, and composite gabbro-granite plutons	easterly	zeolite facies		
Churchill	22	metavolcanic-metasedimentary (greenstone belt) sequences; paragneiss sequences; granitoid plutones; undivided granitoid gneiss and granulite	unknown; probably >50% but most of these are part of the Archean basement	2.8-3.5 Ga - granitoid plutonism	poorly documented tonalite-granodiorite plutons	?	?	Middle Proterozoic sedimentation and minor volcanism; gabbro and diabase stocks, dikes, and sills of several ages; anorthosite-granite batholiths; syenite stocks; lamprophyre dikes; block faults	Davidson (1972a)
				2.55-2.75 Ga - volcanism, sedimentation, deformation, metamorphism and granitoid plutonism of Kenoran Orogeny (extensive basement terrane)	subvolcanic dikes, sills, and irregular plutons; and epizonal, mesozonal, and catazonal, syntectonic to late tectonic composite stocks and batholiths of tonalite-granodiorite-granite and minor gabbro and diorite. Largely metamorphosed to amphibolite and granulite (in part retrograded) facies with development of pronounced gneissosity and local charnockite				

TABLE 1. (Continued)

Churchill (Continued)				1.7-2.4 Ga- volcanism and sedimentation within intracratonic and craton-margin mobile belts of different ages. Deformation, metamorphism, remobilization of basement, and granitoid plutonism at several periods from 1.7-2.2 Ga culminating with Hudsonian Orogeny	highly variable depending on location; includes subvolcanic dikes, sills, sill complexes and stocks of tonalite-granodiorite-granite; syntectonic, epizonal to catazonal, simple to composite tonalite-granodiorite-granite dikes, sheets, mushroom-shaped plutons, and batholiths that are locally charnockitic; syntectonic anatectic sills of tonalite-granodiorite; late tectonic, sills, stocks, and batholiths of tonalite-granodiorite-granite-leucogranite; post-tectonic stocks of fluorite-bearing leucogranite that are in part related to post-orogenic volcanism	northeasterly in west and north; northwesterly in southeast	greenschist to granulite facies		
Bear	1.3	clastic and carbonate sedimentary and metasedimentary units;mafic to felsic volcanic and metavolcanic sequences; granitoid plutons	30-50% in Wopmay Orogen; absent elsewhere	2.55-2.7 Ga -volcanism, sedimentation, deformation, metamorphism, and granitoid plutonism (Slave Province basement)	as in Slave Province	?	greenschist to granulite facies	sedimentation;flood basalt volcanism; gabbro and diabase dikes, sheets, and layered complexes; faults. Covers northern half of province	Fraser et al. (1972), Hoffman & McGlynn (1977), Hoffman (1980)
				1.8-2.1 Ga - sedimentation and volcanism, granitoid plutonism, deformation, and metamorphism of Hudsonian Orogeny	Hepburn subprovince - tonalite-granodiorite-granite-pegmatite stocks, batholiths, and migmatization; porphyroblastic granodiorite stocks, batholiths, and gneiss domes of reactivated Archean basement Great Bear subprovince - subvolcanic and epizonal dikes, stocks, and batholiths of granite and minor granodiorite and tonalite	northerly	unmetamorphosed to amphibolite facies		
Superior	13	metavolcanic metasedimentary (greenstone belt) sequences; paragneiss sequences; granitoid batholiths; granitoid gneiss and granulite terranes	40-60%	2.85-3.05 Ga - mafic to felsic volcanism and tonalite plutonism (Lac Seul Event of Goodwin 1977); in some plutons age is metamorphic and plutons originally emplaced 3.3-3.6 Ga	composite gneissic tonalite-granodiorite plutons of unknown extent; metamorphosed to amphibolite and possibly granulite facies during Kenoran Orogeny	?	greenschist, amphibolite, and possibly granulite facies	minor mafic and alkalic stocks, diabase dikes, faults	Goodwin et al. (1972), Ayres (1978)
				2.55-2.75 Ga - mafic to felsic volcanism and concomitant sedimentation; early deformation and metamorphism was an outgrowth of crustal loading by the volcanoes; late deformation and metamorphism associated with diapiric emplacement of large granitoid batholithic complexes (Kenoran Orogeny of Stockwell 1961)	subvolcanic stocks, dikes, sills, and sill complexes; syntectonic, simple, zoned and composite stocks and batholiths within greenstone belts and paragneiss sequences; syntectonic batholithic complexes (areas >1000 km^2) that form the margins of greenstone belts and paragneiss sequences; late tectonic stocks within and outside of batholithic complexes. Composition mainly tonalite-granodiorite with some quartz diorite, quartz monzodiorite, quartz monzonite, and granite	easterly	subgreenschist to granulite facies; lowest grades occur in greenstone belts		
Slave	1.9	metasedimentary and less abundant metavolcanic sequences of Yellowknife Supergroup; mixed gneisses, migmatites, and granitoid gneisses derived from metasediments; granitoid plutons	30-45%	2.94-3.15 Ga-tonalite-granodiorite-granite plutonism	massive to gneissic plutons of unknown extent	?	?	granodiorite-granite stocks and batholiths (in part peralkaline) related to development of Bear Province; diabase dikes and sheets; rare alkalic stocks;faults; sedimentary units of the Kilohigok Basin (Bathurst Subprovince)	McGlynn & Henderson (1972); Thompson (1978); Henderson (1981)
				2.55-2.7 Ga - mafic to felsic volcanism and concomitant to younger sedimentation; deformation and metamorphism associated with, and older than emplacement of granitoid batholiths (Kenoran Orogeny)	subvolcanic stocks, dikes, and sills; syntectonic or late tectonic, mesozonal tonalite-granodiorite batholiths; late tectonic granodiorite-granite-leucogranite-pegmatite stocks and batholiths	northerly	greenschist to amphibolite facies		

TABLE 1. (Continued)

Nain	0.4	Metavolcanic-metasedimentary sequences; gneissic to massive granitoid plutons; undivided gneissic rocks	? (insufficient data)	3.6-3.8 Ga -volcanism, minor sedimentation, and granitoid plutonism; three pulses of deformation and metamorphism	tonalite-granodiorite and minor granite	?	amphibolite and granulite facies	Proterozoic metavolcanic and metasedimentary sequences of uncertain age; post-tectonic granite stocks (1.3-2.4 Ga); anorthosite-granite plutons (1.4-1.5 Ga); peralkaline granite stocks; diabase dikes; faults	Taylor (1972, 1979); Collerson & Bridgwater (1979)
				3.0->3.0 Ga - volcanism, sedimentation, mafic plutonism, deformation, and metamorphism	anatectic granite sheets and migmatitic veins	?	?		
				2.5-2.8 Ga - volcanism, granitoid plutonism, deformation, and metamorphism of the Kenoran Orogeny	syntectonic tonalite-granodiorite; post-tectonic potassic granite	northerly but diverse and chaotic	amphibolite and granulite facies		
				1.6-1.8 Ga - volcanism, sedimentation, granitoid plutonism, deformation, and metamorphism of the Hudsonian Orogeny (Makkovik Subprovince)	pre-tectonic, syntectonic, and post-tectonic granodiorite-granite stocks and batholiths	north-easterly	amphibolite and locally greenschist facies		

[1] Approximate area of outcrop within Canada, including extrapolations beneath lakes and various bays and channels of the Arctic.

[2] Estimated percentage of area of province. This figure is approximate because a) the scale and intensity of mapping is highly variable, b) in some areas granitoid plutons have not been separated from granitoid gneisses derived from supracrustal protoliths, and 3) the protoliths of some granitoid gneisses are controversial with both supracrustal and plutonic origins having been proposed for some units.

[3] Ages come from a variety of sources cited in text but are mainly Rb-Sr isochron and U-Pb zircon ages.

[4] Not including uplift, erosion, events related to marginal overlap of an adjacent province, or Phanerozoic events.

[5] Stockwell et al. (1970) is a major reference to all provinces. References to specific events and age dates are cited in text.

deformation are recorded in the Nain, Churchill and Grenville provinces, where multiply deformed basement terranes are exposed.

Older sedimentation, volcanism, plutonism and deformational events of varied extent are recognized in each province. In most provinces, these older events have been partly to largely obscured by the main orogenic pulse, but in the Churchill Province, there are extensive older volcanic–sedimentary sequences, such as the Archean Rankin–Ennadai belt of the Kaminak Subprovince, that have been affected only weakly by the younger Proterozoic events. Post-orogenic events include uplift, erosion, block faulting, emplacement of minor mafic and alkalic plutons, and development of localized sedimentary basins.

Boundaries between provinces vary from stratigraphic to deformational and metamorphic; some may be plate boundaries or sutures (Baragar & Scoates 1981, Dewey & Burke 1973, Gibb & Walcott 1971, Gibb & Thomas 1977, Irving *et al.* 1972). In most areas, province boundaries were probably originally stratigraphic, with sedimentary and volcanic units overlapping onto or overlying the cratonic areas of older provinces. Some of the younger provinces were apparently continental margins, whereas others were intracratonic. Subsequent deformation affected both the basement and cover rocks and, in many areas where deep erosion has stripped off the deformed cover rocks, the deformational and metamorphic boundary is entirely within the basement.

Superior Province

As presently exposed, this is the second largest (Fig. 3, Table 1) and one of the best documented provinces. It is characterized by metavolcanic–metasedimentary sequences that define greenstone belts, paragneiss sequences, granitoid batholithic complexes and heterogeneous granitoid gneiss and granulite terranes. The distribution of the major lithologies define thirteen generally east-trending subprovinces (Fig. 4) that differ in lithology, structural style, metamorphic grade, and abundance and nature of granitoid rocks, but are broadly equivalent in age. The oldest dated events are volcanism and plutonism at 2.85–3.05 Ga (Clark *et al.* 1981, Corfu *et al.* 1981, Goodwin 1977, Nunes & Thurston 1980, Nunes & Woods 1980), but these have been identified at only a few widely scattered localities. Most of the volcanism, plutonism, metamorphism and deformation took place in the interval 2.55–2.75 Ga (Goodwin 1977). Although systematic Rb–Sr whole rock and U–Pb zircon age-data have been obtained from only a few areas, most of the volcanism appears to be in the interval 2.7–2.75 Ga (Corfu *et al.* 1981, Davis *et al.* 1980, Nunes & Jensen

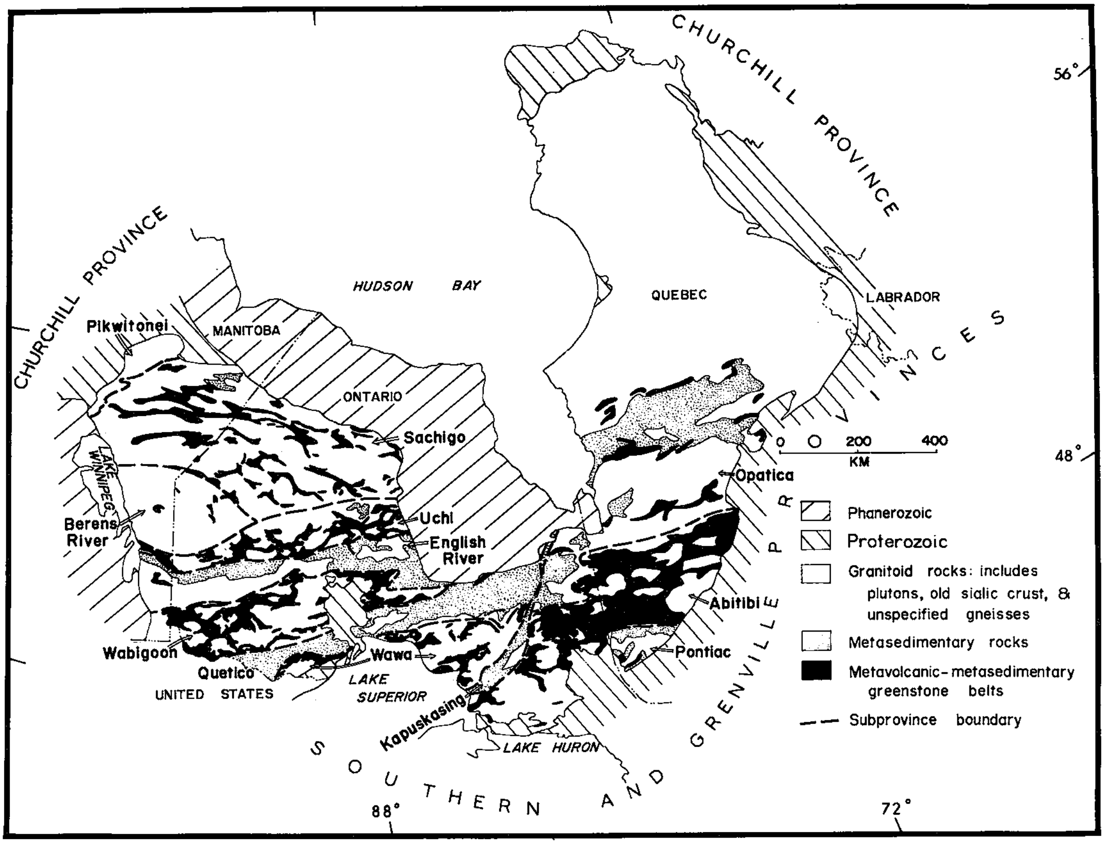


FIG. 4. Major lithological units and subprovinces of the Superior Province (modified from Douglas 1969).

1980, Nunes & Pyke 1980, Nunes & Thurston 1980, Nunes & Wood 1980), but plutonism spans the longer interval of 2.55–2.75 Ga (*e.g.*, Birk 1979, Birk & McNutt 1981, Corfu *et al.* 1981, Davis *et al.* 1980, Gower & Clifford 1981, Krogh *et al.* 1976, Turek *et al.* 1981, Wooden 1978). The regional deformation event, which may not have been synchronous in all parts of the province, has been termed the Kenoran Orogeny (Gower & Clifford 1981, Stockwell 1961). Late events that range in age from Archean to Phanerozoic include intrusion of widespread swarms of diabase dykes of several ages, intrusion of mafic and alkalic stocks including numerous carbonatites, and formation of faults (Goodwin *et al.* 1972).

Plutons emplaced during the 2.85–3.05 Ga event are deformed and metamorphosed to amphibolite facies and are now orthogneiss of quartz diorite, tonalite and locally granodiorite composition (Breaks *et al.* 1978, Clark *et al.* 1981, Ermanovics 1981, Ermanovics *et al.* 1979, Harris & Goodwin 1976, Hillary & Ayres 1980, Verpaelst *et al.* 1980). They commonly form enclaves in 2.55–2.75 Ga plutons, and their original size and extent are unknown. Some of the plutons were exposed to erosion prior to and during the 2.7–2.75 Ga volcanism, but it is not known whether these plutons are remnants of an older, dismembered but originally extensive cratonic basement or localized cratonic islands, not all of which are necessarily identical in age (Clark *et al.* 1981). The reported ages of some plutons may date the time of metamorphism rather than emplacement. For example, in northern Quebec, Verpaelst *et al.* (1980), using ^{87}Sr/^{86}Sr, have proposed that gneissic tonalite which has a Rb–Sr isochron age of 3.06 Ga was originally formed about 3.6 Ga. Similarly in northwestern Ontario, Hinton & Long (1979), using ion-microprobe U–Pb data from single grains of zircon, have concluded that zircon in gneissic tonalite, which Krogh *et al.* (1976) determined to be 3.04 ± 0.04 Ga, are actually 3.3 ± 0.1 Ga. These 3.3–3.6 Ga ages are comparable to the oldest granitoid units

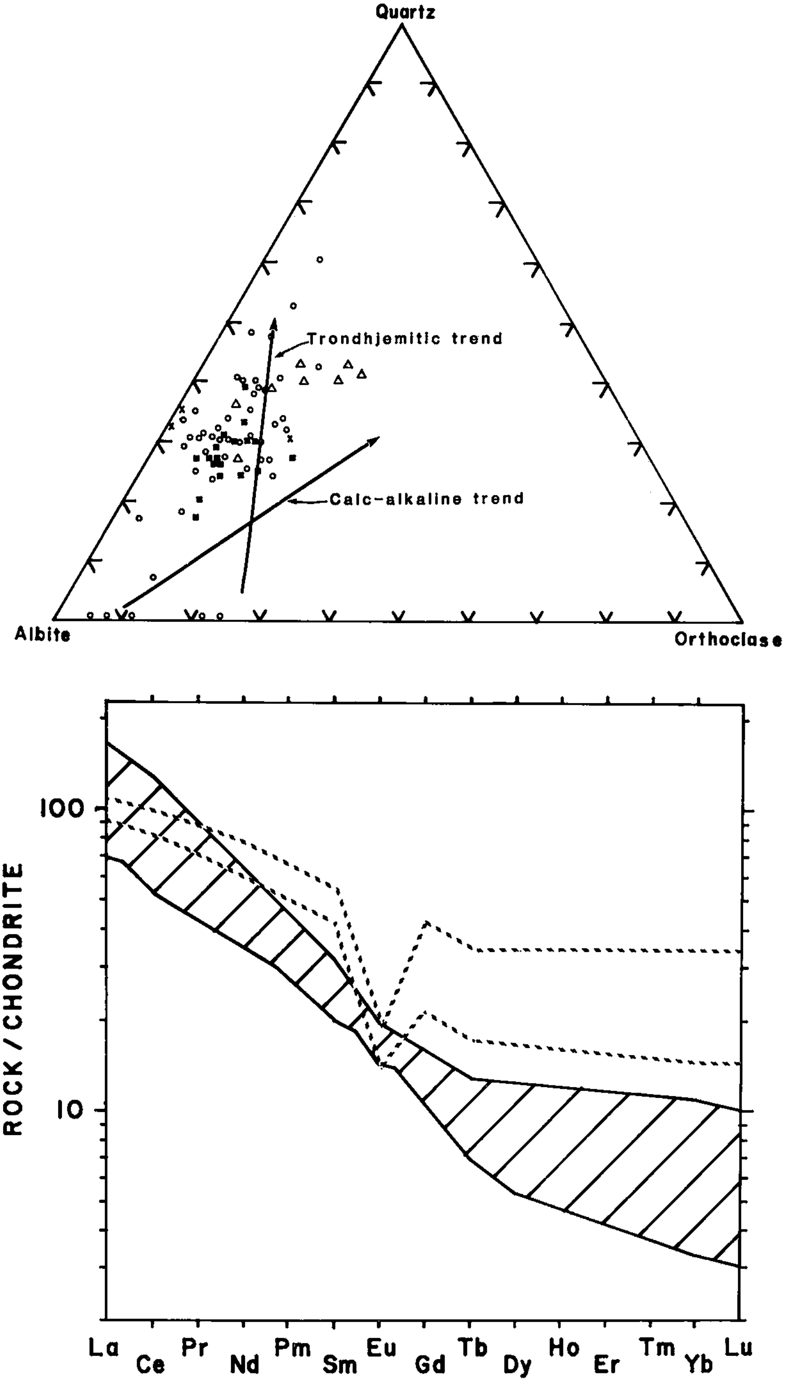


FIG. 5. a) Plot of normative quartz–albite–orthoclase for basement (2.85–3.05 Ga) plutons of the Sachigo (■ Hillary & Ayres 1980), Berens River (○ Ermanovics *et al.* 1979) and English River subprovinces (× Harris & Goodwin 1976, △ Clark *et al.* 1981). Trend lines after Barker & Arth 1976). b) Chondrite-normalized REE patterns for 2.85–3.05 Ga basement plutons of the western Superior Province. Lined area is the envelope of variation for six samples of high-Al_2O_3 tonalite from the English River Subprovince (Chou 1978) and Sachigo Subprovince (Hillary & Ayres 1980). The two individual REE trends represent low-Al_2O_3 tonalite from the English River Subprovince (Chou 1978).

reported from the Southern and Nain provinces (Table 1).

In the western Superior Province, the original plutonic origin of the orthogneiss can be determined from relict magmatic plagioclase (Clark *et al.* 1981, Hillary & Ayres 1980) and zircon textures (Harris & Goodwin 1976) and by preserved, discordant, intrusive relationships among phases (Clark *et al.* 1981), which show, in turn, that some of these older plutons were originally composite. Chemically, the older plutons are characterized by a high value of Na/K, which results in a trondhjemitic trend (Fig. 5a; *cf.* Barker & Arth 1976). Most samples have enriched light-REE and flat, slightly depleted heavy-REE patterns (Fig. 5b) that are similar to those of high-Al_2O_3 trondhjemites (*cf.* Arth & Barker 1976), except for the absence of a positive Eu anomaly. A few samples, however are similar to Arth's & Barker's (1976) low-Al_2O_3 trondhjemite with flat REE patterns, a negative Eu anomaly and enriched heavy REE (Fig. 5b). The REE patterns of the high-Al_2O_3 tonalite suggest that the magmas may have been derived by partial melting of an older amphibolite, which implies a still older crustal event (Hillary & Ayres 1980). The REE patterns of the low-Al_2O_3 tonalite, on the other hand, may be due to "metamorphic segregation of a low-temperature felsic component" (Chou 1978, p. 153).

The subprovinces can be broadly grouped into 3 categories: 1) greenstone–granodiorite (Sachigo, Uchi, Wabigoon, Wawa, Abitibi) (Fig. 4), 2) paragneiss–granitoid (English River, Quetico, Pontiac), and 3) a variable group that includes gneissic to massive granitoid and granulite terranes of both plutonic and supracrustal protoliths (Pikwitonei, Berens River, Kapuskasing, Opatica, Northern Quebec). Metallogenically, the greenstone–granodiorite subprovinces are the most important and are the best documented, but reported mineral deposits occur mainly in the greenstone belts.

In the greenstone–granodiorite subprovinces, the greenstone belts appear to be isoclinally folded, partly dismembered remnants of subaqueous to subaerial, basaltic to rhyolitic volcanoes. The volcanoes had flanking volcaniclastic sedimentary aprons and formed coalescing, east-trending linear chains of islands in the Archean ocean (Ayres 1978). They were apparently erupted on a submerged sialic to simatic crust that developed during the Lac Seul (Table 1; Goodwin 1977) and possibly younger events [using zircon, Nunes & Thurston (1980) have dated volcanism in the Uchi Subprovince at 2.96, 2.8 and 2.74 Ga]. The metavolcanic–metasedimentary sequences are best preserved in the Abitibi Subprovince (Fig. 4), where they are more than 35 km thick (Jensen 1978). Regional metamorphic grade varies from subgreenschist to amphibolite facies.

Metamorphosed, calc-alkaline, subvolcanic to epizonal stocks, dykes, sills, and sill complexes (Table 1) are a ubiquitous but areally minor component of most greenstone belts, particularly of the more felsic upper portions, but are important metallogenically. They vary in texture from porphyritic to locally equigranular and from aphanitic to medium grained. Their composition ranges from gabbro to granite, but most are leucocratic tonalite (trondhjemite) or granodiorite. Quartz-poor syenitoid plutons are common in some greenstone belts, particularly in the Abitibi Subprovince. These are not generally considered to be part of the granitoid suite but will be considered briefly in this contribution because of their spatial association with gold and silver deposits. Subvolcanic sills occur below many syngenetic stratiform Cu–Zn–Ag deposits, and are apparently genetically related to these deposits (Campiglio & Darling 1976, Franklin & Thorpe 1982).

Syntectonic and late tectonic plutons are the dominant component of these subprovinces (Table 1). They range in size from small stocks to immense batholithic complexes, but most are magmatically or mechanically emplaced diapirs (Fyson *et al.* 1978, Schwerdtner *et al.* 1979) that resulted in deformation and dismemberment of the volcanic–sedimentary sequences. The plutons are typically medium-grained, equigranular to porphyritic, locally zoned (*e.g.*, Birk & McNutt 1981, Wolhuter 1973) mesozonal intrusions. In some plutons, microcline megacrysts apparently developed after emplacement by volatile autometasomatism (Birk *et al.* 1979). The larger plutons are commonly variable in composition and are composite, with individual phases forming sills, sheets, stocks, small batholiths, dyke swarms and crescentic plutons. They include early gneissic quartz diorite – tonalite – granodiorite phases and later, more massive and commonly more leucocratic tonalite – granodiorite – granite phases (Card 1979, 1982, Cimon 1979a, Ermanovics *et al.* 1979, Ermanovics & Davison 1976, Gower & Clifford 1981, Sage *et al.* 1975, Schwerdtner *et al.* 1979, Ziehlke 1975); pegmatite and aplite are ubiquitous late phases. Hornblende and biotite are the dominant mafic constituents; muscovite is present in the more leucocratic potassic phases but muscovite granite is rare. The fabric of the various phases resulted from a combination of magmatic, deformational and cooling processes (Ayres 1978, Schwerdtner *et al.* 1979, Schwerdtner & Lumbers 1980). In many areas much of the deformation appears to be related to emplacement of younger phases and diapiric rise rather than to later superimposed events, although Park (1981) has proposed major post-emplacement deformation. Gower & Clifford (1981) have observed isoclinal to tight folds in some of the early gneissic units and related this to a combination of regional deformation and emplacement of younger phases. Percival (1981) and Schwerdtner *et al.* (1979) have proposed that prior to diapirism, the early quartz diorite – tonalite – granodiorite phases were discontinuous, horizontal sheetlike bodies beneath volcanic – sedimentary sequences.

Except where bounded by greenstone belts, many of the batholithic complexes have poorly defined boundaries. Thus, the impression given by generalized maps such as Figure 4 is a large irregular granitoid terrane that has the form of a flat sheet, 10–20 km thick (surface to base of upper crust), interrupted by vertically dipping greenstone belts. However, emplacement of such a granitoid pluton as a single unit is difficult to envisage. Furthermore, detailed mapping has shown that the granitoid terranes are composed of numerous discrete plutons that have a considerable age range (*e.g.*, McCrank *et al.* 1981, Schwerdtner *et al.* 1979). and that were emplaced by a series of magmatic pulses. Schwerdtner & Lumbers (1980) have suggested that such piecemeal emplacement occurred beneath a volcanic–sedimentary cover at some depth below the present level of the plutons. Subsequent diapiric rise of the batholithic complexes to their present structural level occurred in response to a ductility decrease between the gradually heating metavolcanic–metasedimentary roof rocks and the gradually cooling pluton (Schwerdtner & Lumbers 1980). Hillary & Ayres (1980) have documented such progressive heating of 2.91 Ga trondhjemite by piecemeal pluton emplacement.

Chemically the granitoid rocks are varied in both composition and evolutionary trends but, except in small areas, insufficient data are available to document meaningful geographic or temporal variations. The deficiency is particularly pronounced for trace-element data from well-documented batholithic complexes. In general, the plutons have an average composition of sodic granodiorite. There is a general tendency for younger phases to be more potassic and silicic and deficient in magnesium and iron compared to older phases, but there are numerous reversals and interruptions in this trend. Both trondhjemitic and calc-alkaline trends have been identified in the batholithic complexes (Ermanovics *et al.* 1979). As an example of the variation, data from several batholithic complexes in the Favourable Lake area of the Sachigo Subprovince of northwestern Ontario are presented in Figure 6. Both parts of this figure show the general temporal trend and the interruptions and reversals in this trend. On the normative quartz–albite–orthoclase plot (Fig. 6b), the North Trout Lake batholithic complex has a trondhjemitic trend, with potassium enrichment in the more silicic phases. This trend, however, does not represent the progressive evolution of a single body of magma, because there are several sodic and potassic phases that were emplaced into the batholithic complex at different times (Fig. 6b). The two complexes on the south side of the greenstone belt have a more calc-alkaline trend.

The most comprehensive geochemical study of granitoid rocks has been made in the western Wabigoon Subprovince (Birk 1979, Birk & McNutt 1981, Birk *et al.* 1979, Goldich & Peterman 1978, Longstaffe & Birk 1981, Longstaffe *et al.* 1980, Sutcliffe 1978). The work of Birk and coworkers was concentrated on a group of 12 small, apparently coeval, late tectonic stocks within a greenstone belt; the stocks include both homogeneous and zoned types and range in composition from monzodiorite to granite. Oxygen- and strontium-isotope data for both the stocks and a nearby batholithic complex indicate that the granitoid magmas were derived from lower crust or upper mantle sources and not from supracrustal metasedimentary rocks (Birk 1979, Birk & McNutt 1981, Longstaffe & Birk 1981, Longstaffe *et al.* 1980). REE patterns are light-REE-enriched and commonly lack a Eu anomaly (Fig. 7; Birk *et al.* 1979); there is a general decrease in REE abundances with increasing SiO_2 content (Fig. 7). Birk *et al.* (1979) stressed that many Archean granites of the Superior Province lack a Eu anomaly, whereas post-Archean granites and Archean granites elsewhere commonly have a negative Eu anomaly of varying magnitude (*cf.* Condie 1981). The lack of a Eu anomaly has been related to high Ba and Sr contents, which prevent Eu depletion by plagioclase crystallization except in the last differentiates (Birk *et al.* 1979).

The paragneiss subprovinces appear to represent, at least in part, major linear sedimentary troughs that developed between the chains of volcanic islands of the greenstone subprovinces

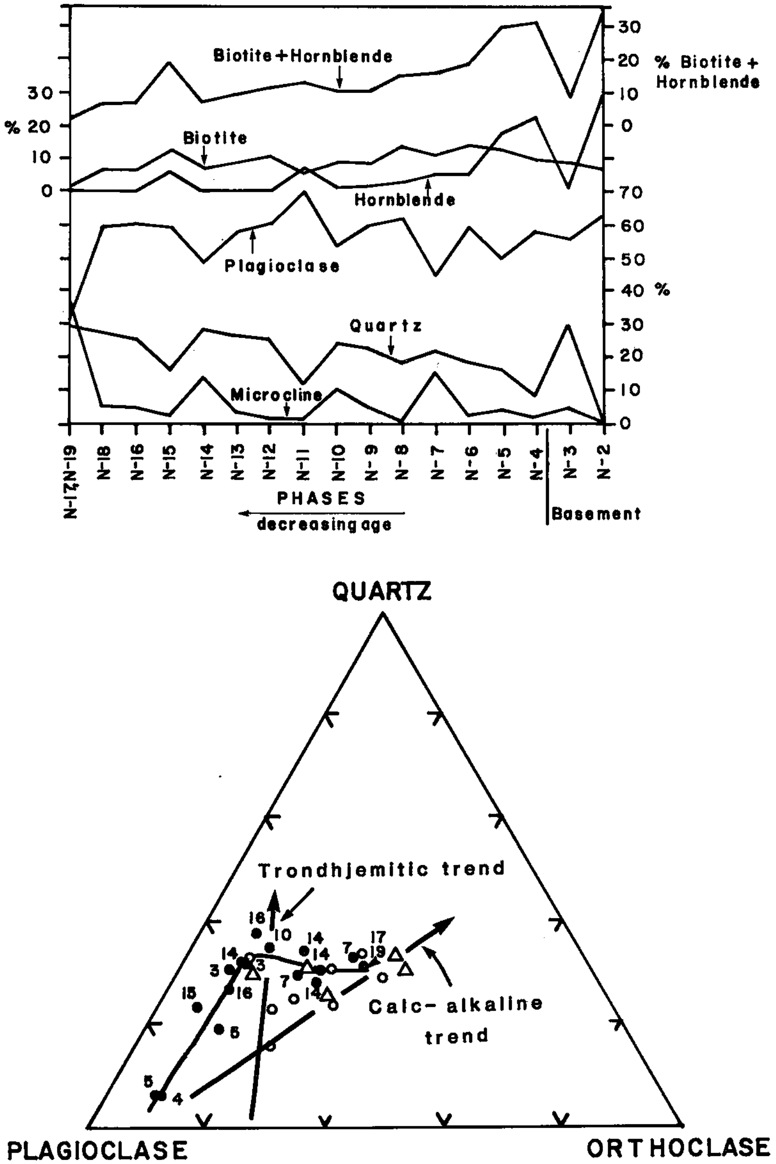


FIG. 6. a) Modal variations in part of the North Trout Lake batholithic complex of the Sachigo Subprovince, northwestern Ontario [mean data for each phase from Ayres (1974) and unpublished]. In this complex, 20 phases have been identified in a 200-km^2 area and are numbered from N–1 (oldest) to N–20 (youngest). Phases N–1 to N–3 represent 2.9 Ga basement, whereas the other phases were emplaced during the younger Kenoran Orogeny. b) Plot of normative quartz–albite–orthoclase for selected samples from various phases of the North Trout Lake batholithic complex (●), located on the north side of the 13-km-wide Favourable Lake greenstone belt, and the Setting Net Lake (○) and Bear Head Lake (△) batholithic complexes, on the south side of the greenstone belt [data from Ayres (1974) and unpublished]. The North Trout Lake and Setting Net Lake batholithic complexes are in the Sachigo Subprovince but the Bear Head Lake complex is in the Berens River Subprovince. The contact between the two subprovinces in this area is a fault. Trondhjemitic and calc-alkaline trends after Barker & Arth (1976).

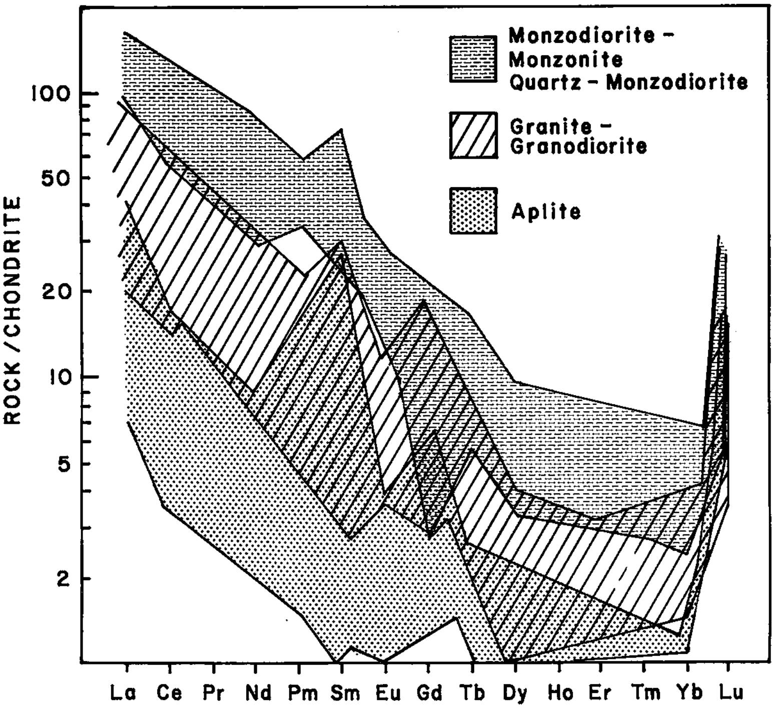


FIG. 7. Composite plot of REE variations for various granitoid rock-types from three homogeneous and two zoned stocks within a greenstone belt, western Wabigoon Subprovince (modified from Birk *et al.* 1979). The three lithological groups show the general relationship between composition and REE abundances. The high Lu of some samples is associated with autometasomatic development of microcline megacrysts.

(Ayres 1978). They are characterized by a lower abundance of granitoid plutons and a higher metamorphic grade, with the metasedimentary component and some of the early plutons metamorphosed to amphibolite and, locally, granulite facies. Although data are sparse, the granitoid rocks appear to have a somewhat more potassic bulk composition than granitoid rocks of the greenstone subprovinces (Ermanovics *et al.* 1979). Smith & Williams (1980) have further suggested that the granitoid rocks have a greater compositional range than granitoid rocks of the greenstone subprovinces, reflecting a more varied magma source, but their data-base is small and may not be representative.

The granitoid rocks comprise both *in situ* diatexite and a varied suite of plutons. The diatexite grades into migmatitic paragneiss and is mainly medium-grained to pegmatitic granite, but includes some granodiorite and tonalite (Breaks *et al.* 1978, Pirie & Mackasey 1978). The plutons are most abundant and best documented in the English River Subprovince, where they are commonly composite and variable both in composition and in fabric. They comprise 1) strongly recrystallized, pretectonic gneissic quartz diorite – tonalite with local granodiorite; 2) less recrystallized, pre- to syntectonic sills, stocks and composite batholiths of foliated, medium-grained, equigranular to porphyritic quartz diorite – tonalite – granodiorite; and 3) unrecrystallized, syn- to post-tectonic dyke swarms, sills, stocks and composite batholiths of massive, medium-grained to pegmatitic equigranular to porphyritic granodiorite – granite (Breaks *et al.* 1978, Ermanovics *et al.* 1979). In places, the gneissic suite is metasomatized and migmatized by injection of younger phases, local *in situ* anatexis and development of microcline porphyroblasts (Breaks *et al.* 1978, Ermanovics *et al.* 1979). It includes both 2.85–3.05 Ga basement (Clark *et al.* 1981, Harris & Good-

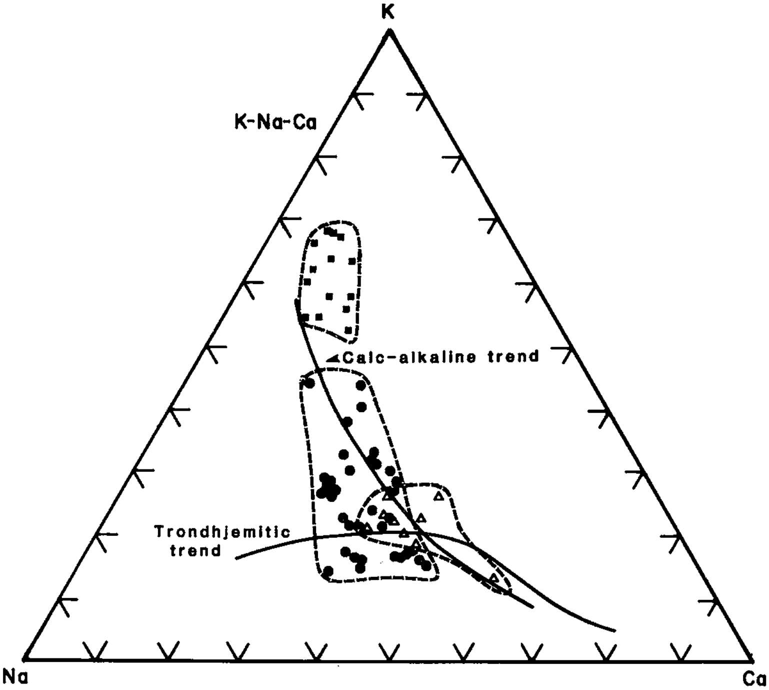


FIG. 8. K–Na–Ca variation of pretectonic gneissic suite (△), pre- to syntectonic foliated suite (●), and syn- to post-tectonic massive suite (■) of the English River Subprovince (after Breaks *et al.* 1978). Trend lines after Barker & Arth (1976).

win 1976, Krogh *et al.* 1974, 1976) and younger catazonal plutons (Breaks *et al.* 1978) that are probably an early phase of Kenoran plutonism. In general, there is a temporal progression in the granitoid rocks toward more leucocratic and more potassic phases (Fig. 8).

Some trace element and REE data have been presented by Breaks *et al.* (1978), Chou (1978), Smith & Williams (1980) and Williams (1978), but the only systematic study is that of Černý *et al.* (1981), who examined granitoid rocks in and adjacent to the Bird River greenstone belt, Manitoba, the only large greenstone belt within the English River Subprovince. This greenstone belt is metallogenically important because of the presence of pegmatites; its geochemistry is discussed in more detail in the section on pegmatites. Unlike the granites of the Wabigoon greenstone–granodiorite Subprovince, many of the granites of the English River and Quetico subprovinces have a negative Eu anomaly (Černý *et al.* 1981, Chou 1978, Williams 1978). The Eu anomaly is most pronounced in silicic leucogranite with low Ba and Sr contents (*cf.* Figs. 31, 32; Goad & Černý 1981).

In the Pontiac Subprovince, a composite tonalite–granodiorite batholithic complex has been investigated by Dimroth *et al.* (1973, 1974). It appears to be different from those in the greenstone–granodiorite subprovinces and is described as a stockwork batholith that was emplaced by slow opening and expansion of fractures and their gradual filling by a multitude of dykes and sills.

The five granite and granulite subprovinces include a wide variety of lithologic units. They have been grouped together because existing reconnaissance mapping hampers more detailed subdivision and comparison. The Berens River and Opatica subprovinces are mainly mesozonal to catazonal, gneissic to massive, composite batholithic complexes that range in composition from quartz diorite to granite and, in part, are recrystallized and metasomatized (Ermanovics & Davison 1976). In the Berens River Subprovince, an early trondhjemitic trend is succeeded

TABLE 2. ARITHMETIC MEAN VALUES OF LITHOPHILE TRACE ELEMENTS IN 63 COMPOSITE GRANITOID SAMPLES FROM THE SUPERIOR PROVINCE (MULLIGAN 1980)

K_2O %	Rb ppm	K/Rb	Li ppm	Cs ppm	Sn ppm	Be ppm	Mo ppm	W ppm	F %
3.1	153	168	22	5	3	2.8	2.2	1.7	0.04

by a later calc-alkaline trend with potassium enrichment (Ermanovics *et al.* 1979). Rocks of the Pikwitonei and Kapuskasing subprovinces have been metamorphosed to the granulite facies. The Pikwitonei consists mainly of metatonalite and metagranodiorite plutons (Weber & Scoates 1978), whereas the Kapuskasing is mainly a metavolcanic-metasedimentary sequence (Thurston *et al.* 1977) with some gneissic and xenolithic tonalite (Percival 1981). Northern Quebec is an unsubdivided assemblage of metavolcanic, metasedimentary and granitoid rocks of amphibolite- and granulite-facies metamorphic grade (Eade 1966, Herd 1978, Stevenson 1968).

Lithophile trace elements have been determined for 63 composite samples of granitoid rocks collected from several subprovinces (Table 2; Mulligan 1980). In general, K/Rb, which ranges from 150 to 400, is higher and lithophile element abundances lower than in Canadian Phanerozoic granitoid rocks. The Li content of muscovite granite associated with lithium-bearing pegmatite is 5–10 times higher than the mean value (Mulligan 1973). There is a poor negative correlation between K/Rb and K and Li contents, but no correlation with Sn (Mulligan 1980).

Slave Province

Although smaller and less well documented than the Superior Province (Fig. 3), the Slave Province is lithologically similar and records the same deformational–plutonic events, but with different structural trends (Table 1). However, unlike the Superior Province, the Archean units do not define distinctive subprovinces, the ratio of metasedimentary to metavolcanic rocks is much higher, granitoid plutons are less abundant, and granulite-facies rocks are rare (Fig. 9, Table 1; McGlynn & Henderson 1972, Thompson 1978). In addition, the timing of emplacement of granitoid plutons relative to deformation and metamorphism, and the nature of emplacement may be different (Fyson & Frith 1979, Thompson 1978).

Tonalite–granodiorite and granite basement units with zircon and Rb–Sr ages between 2.94 and 3.15 Ga have been identified at several localities, but the extent and nature of these plutons are largely unknown (Frith *et al.* 1977a, Henderson & Easton 1977, Henderson 1981, Jenner *et al.* 1981, Krogh & Gibbins 1978, McGlynn & Henderson 1972). Frith & Roscoe (1980) have proposed that basement is associated with most of the greenstone belts, and Henderson (1981) has suggested that the late Archean volcanism and sedimentation were related to extensional faulting and graben development in a 2.94–3.15 Ga granitoid crust that originally underlay the Slave Province. Much of this basement has been destroyed by emplacement of late Archean plutons. In places, the preserved basement-units are much less deformed than comparable units in the Superior Province (Henderson & Easton 1977), but elsewhere they were affected by pre-Kenoran metamorphism and metasomatism (Frith 1978). Massive to gneissic granite, which forms an undetermined amount of the basement (Henderson 1981, Jenner *et al.* 1981), is the most potassic early Archean basement unit described to date in the Canadian Shield.

Subvolcanic granitoid plutons are relatively rare and poorly documented. They are mainly dykes, sills and small irregular to lenticular stocks of porphyritic tonalite – granodiorite with an aphanitic to fine-grained groundmass (Bostock 1980, Henderson & Brown 1966, Moore 1956).

Early syntectonic to late-tectonic mesozonal batholiths are the dominant granitoid unit in the Slave Province; these mainly consist of medium-grained, equigranular to porphyritic plutons (Davidson 1972b, McGlynn & Henderson 1972). They range in composition and fabric from early gneissic to foliated to locally massive quartz diorite – tonalite – granodiorite to late massive to foliated granodiorite – granite and minor tonalite; pegmatite is a major constituent of many of the late muscovite-bearing granite plutons (Bostock 1980, Frith & Loveridge 1982, Frith *et al.* 1977a, 1977b, Green & Baadsgaard 1971, McGlynn & Henderson 1972). Early plutons tend to be concordant with regional structure and stratigraphy, whereas younger more potassic plutons are more discordant (Fyson 1981). Early syntectonic emplacement of the Keskarrah granodiorite batholith (2.642 ± 0.015 Ga) in the central part of the Slave Province is indicated by intrusion of the batholith into the lower part of the volcanic greenstone-belt sequence but incorporation of clasts derived from the unroofing of the batholith in later conglomerate of the greenstone belt (Bostock 1980). Associated with the batholiths are large

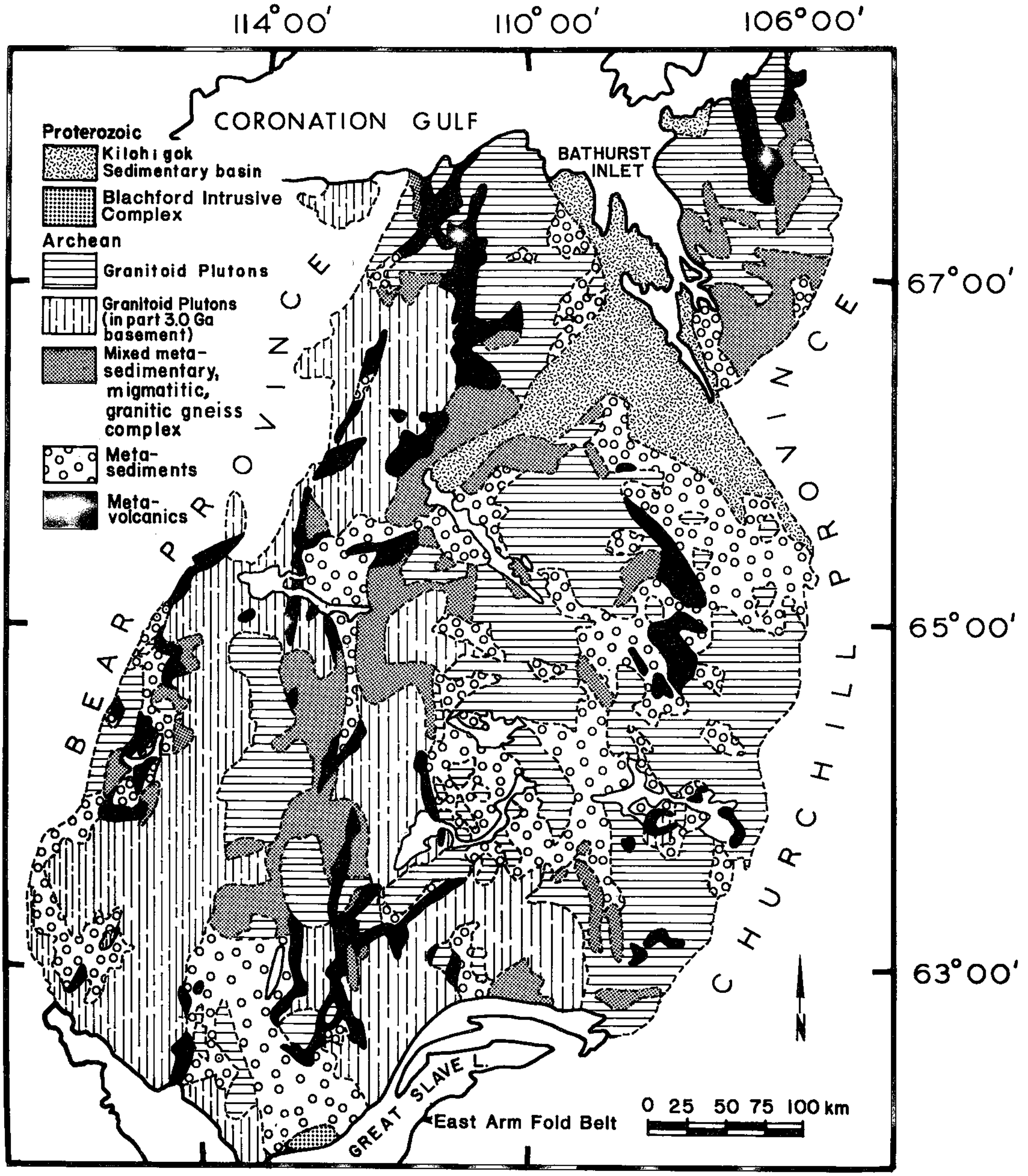


FIG. 9. Major lithological units of the Slave Province [modified from Henderson (1981), McGlynn & Henderson 1972)].

areas of "mixed gneisses, migmatites, and granitic gneisses that appear to be highly metamorphosed and granitized equivalents" of the metasedimentary sequence (McGlynn & Henderson 1972, p. 519).

There is some controversy about the mechanism of emplacement of the plutons. Drury (1977) and other authors have proposed that most plutons were diapirically emplaced during deformation of the supracrustal sequences and

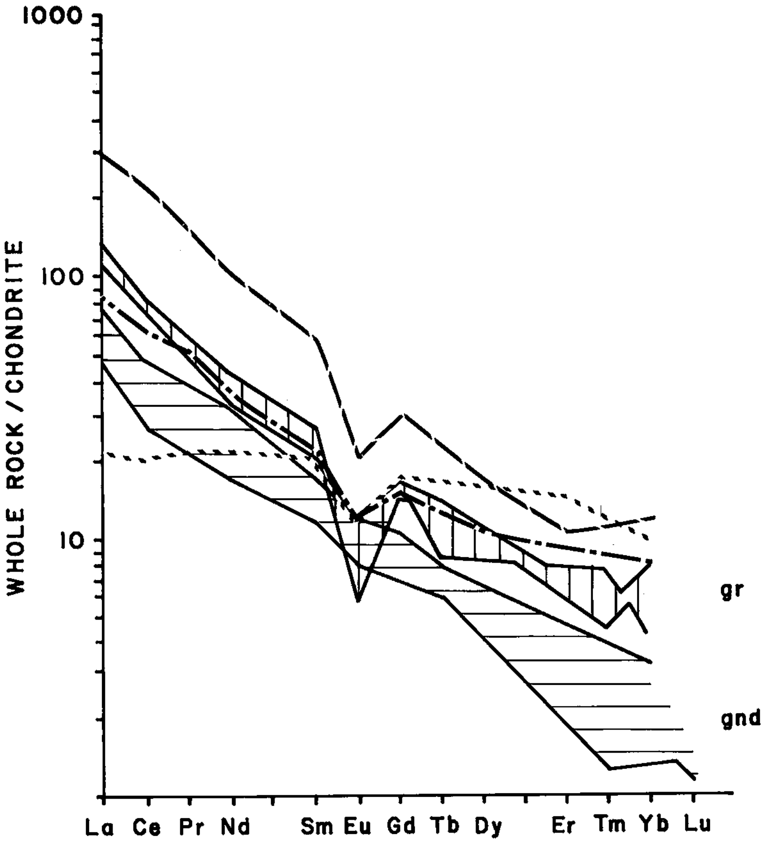


FIG. 10. Envelopes of variation of chondrite-normalized REE patterns for syntectonic granodiorite (gnd) and late-tectonic granite (gr) of the Slave Province (data from Drury 1979). The three individual REE trends are for samples of isotopically undated gneissic granite that may be basement to the greenstone-belt sequences (Jenner *et al.* 1981).

were the cause of this deformation. Fyson (1978, 1980, 1981) and Fyson & Frith (1979), on the other hand, have proposed that plutons were emplaced at various times during the deformational history and were not the sole cause of the deformation. According to these authors, many plutons postdate the development of major folds, but pluton emplacement modified earlier folds. Using metamorphic and structural data, Frith (1978) and Thompson (1978) have argued also that pluton emplacement postdated the culminations of both metamorphism and deformation.

Drury (1979) has shown that syntectonic granodiorite plutons have lower abundances of REE, particularly heavy REE, than late-tectonic granite plutons, which also have a negative Eu anomaly (Fig. 10). Isotopically undated gneissic granites of possible basement origin have varied REE abundances, but REE patterns are in part similar to those in the late-tectonic massive to foliated granites (Fig. 10; Jenner *et al.* 1981). The difference in REE between the plutons has been interpreted to indicate different sources for the magmas, the basement (?) granite magma being derived by partial melting of an intermediate to felsic source, the granodiorite magma by partial melting of mafic units at mantle depths, and the granite magma by partial melting of metasedimentary rocks (Drury 1979, Jenner *et al.* 1981). Strontium-isotope data (Green & Baadsgaard 1971) also support a mantle derivation for some of the granitoid magmas. The negative Eu anomaly of the granites constitutes a distinction with the granites from the greenstone–granodiorite subprovinces of the Superior

Province (Fig. 7).

Post-tectonic plutons include 1) the 2.15 Ga Blachford Lake Complex on the shore of Great Slave Lake adjacent to the East Arm Fold Belt of the Churchill Province (Fig. 3; Badham 1979, Davidson 1978, 1982), 2) several small, 1.9–2.9-Ga granodiorite stocks near the boundary with the younger Bear Province on the west, which are related to plutonic events within the Bear Province (Frith *et al.* 1977a) 3) five periods of emplacement of Proterozoic diabase dykes and sheets (McGlynn & Henderson 1972), and 4) a single alkalic stock. Of particular interest is the Blachford Lake Complex, a batholith that is partly peralkaline in character and contains Nb, Ta, Y, Th, U and REE mineralization (Davidson 1982). The intrusive sequence in the complex is early alkalic gabbro followed by ferrodiorite, quartz syenite, granite, peralkaline perthite granite and late peralkaline syenite; the peralkaline units form the bulk of the complex (Davidson 1978). Emplacement of the

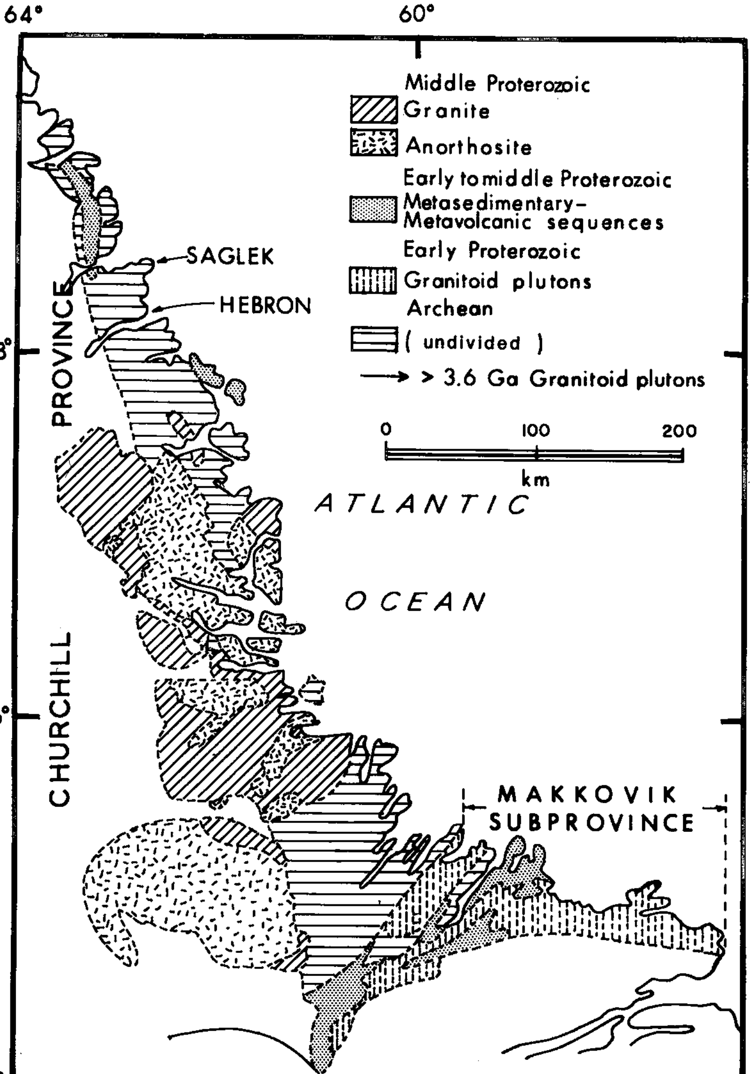


FIG. 11. Major lithological units of the Nain Province [modified from Taylor (1972), Emslie (1978) and Ermanovics & Raudsepp (1979)].

complex was apparently related to early development stages of the adjacent East Arm Fold Belt (Davidson 1982).

In the northeastern part of the province, the Archean is covered by Early to Middle Proterozoic (Aphebian and Helikian) clastic and carbonate sedimentary rocks of the Kilohigok Basin (Fig. 9; Campbell & Cecile 1981). This has been referred to as the Bathurst Subprovince (McGlynn & Henderson 1972, Stockwell *et al.* 1970), but it is not comparable to the subprovinces as defined in the Superior Province.

Nain Province

This is the smallest, most poorly documented, and possibly the most complex of the structural provinces (Fig. 3, Table 1; Collerson *et al.* 1976, Collerson & Bridgwater 1979, Taylor 1972, 1979). The Nain Province contains the oldest rock units identified to date in Canada (Wanless *et al.* 1979). Most of the province is Archean, but the Archean units range in age from greater than 3.76 to 2.5 Ga and have undergone at least five periods of Archean deformation, high-grade metamorphism and granitoid plutonism (Table 1; Baadsgaard *et al.* 1979, Collerson *et al.* 1976, Collerson & Bridgwater 1979). The youngest Archean deformational event was the Kenoran Orogeny (2.5–2.7 Ga). Early granitoid plutons are commonly metamorphosed to the granulite facies, in part retrograded to the amphibolite facies, and can be documented only by detailed mapping (Collerson & Bridgwater 1979, Collerson *et al.* 1976). In much of the province, the various Archean rock units and events have not yet been deciphered.

To compound the problem, Early Proterozoic (Aphebian) volcanism, sedimentation, metamorphism, deformation, and granitoid plutonism has been superimposed locally on the Archean units. This culminated with the Hudsonian Orogeny (Fig. 2; Cameron *et al.* 1981, Stockwell 1961) at about 1.8 Ga. Early Proterozoic units are best developed in the southeastern part of the province and characterize the Makkovik Subprovince (Fig. 11; Taylor 1972). Granite plutons resulting from six distinct magmatic pulses and ranging in age from 1.6 to 1.8 Ga have been identified in this subprovince (Clark 1979). They range from syntectonic, recrystallized gneissic plutons to late, massive plutons.

Post-tectonic plutons elsewhere include 1) Proterozoic granite stocks ranging in age from 1.3 to 2.4 Ga (Barton 1977) and 2) Middle

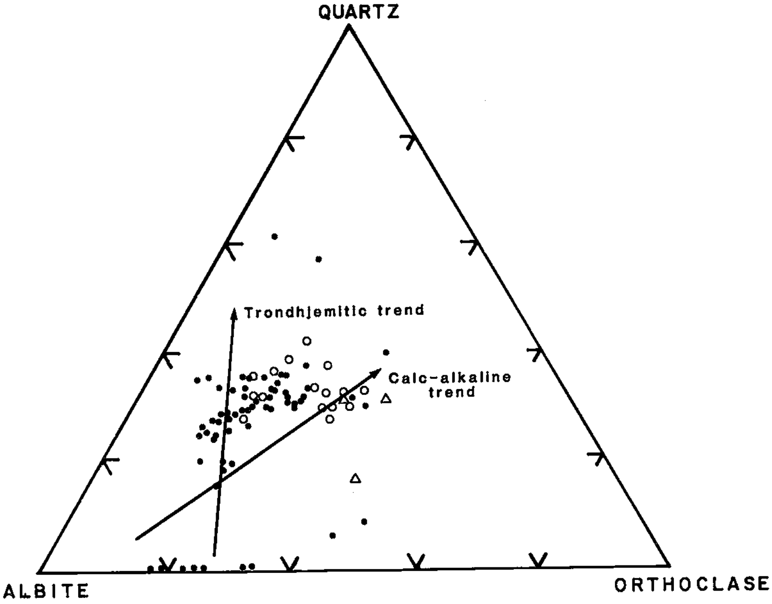


FIG. 12. Plot of normative quartz–albite–orthoclase for the Uivak gneissic plutons (> 3.6 Ga) of the Nain Province (Collerson & Bridgwater 1979); Uivak I ●, Uivak II ○, pegmatite △. Trend lines after Barker & Arth (1976).

Proterozoic (Paleohelikian) anorthosite – quartz monzonite – granite batholiths and layered troctolite – syenite plutons that were emplaced in the central part of the province at 1.4 –1.5 Ga (Fig. 11; Emslie 1978a). The anorthosite – granite batholiths hamper correlation of older units.

The pre-3.6 Ga plutons (Uivak Gneisses) are the best documented of the Archean units (Collerson & Bridgwater 1979). These plutons consist of two suites separated in time by a major period of deformation and metamorphism. The earlier Uivak I suite ranges in composition from gabbro to granite but is mainly tonalite – granodiorite. It has a distinct trondhjemitic trend, with potassium enrichment in the more silicic members (Fig. 12). Collerson & Bridgwater (1979) considered the potassium enrichment to be a metasomatic event produced during the deformation, and related to emplacement of the Uivak II plutons. The Uivak I suite is somewhat similar in composition to the 2.85–3.05 Ga granitoid units of the Superior Province (*cf.* Figs. 5, 12). The younger Uivak II suite ranges in composition from tonalite to granite and has higher potassium, iron and magnesium contents than Uivak I units with equivalent silica contents. Uivak II plutons were originally, at least in part, porphyritic and now consist of augen gneiss.

The anorthosite – quartz monzonite – granite batholiths are part of an extensive chain of similar plutons that extends southwesterly across the Churchill and Grenville provinces. However, unlike most anorthosite – granite batholiths elsewhere, those in the Nain Province have not been subjected to later metamorphism and deformation, and the relationship between the anorthosite and granite can be determined (Emslie 1978a, b). The plutons are mesozonal and were emplaced at depths of 10–20 km (Berg 1977, Emslie 1978a). The batholiths are distinctly bimodal, with only rare diorite, tonalite and granodiorite. The granite and quartz monzonite form large discrete plutons (Fig. 11) that intruded the anorthosite, and differ from calc-alkaline granite – quartz monzonite plutons in the presence of fayalite, inverted pigeonite, highly exsolved clinopyroxene and mesoperthite, all of which indicate a water-undersaturated and high-temperature magma, and the local presence of a rapakivi texture (Emslie 1978a, b). They also characteristically have lower SiO_2 contents, and are enriched in total iron relative to MgO, and in total alkalis relative to CaO, compared to calc-alkaline granitoid suites (Emslie 1978b). Phases with low quartz content, such as quartz monzonite and quartz monzodiorite, commonly predominate over granite, and the granitoid suite is commonly referred to as mangerite and quartz mangerite. At the south end of the Nain Complex (55°30′–56°N, Fig. 11), the granite – quartz monzonite has been intruded by stocks of equigranular to locally porphyritic peralkaline granite containing arfvedsonite–riebeckite (Hill 1980).

Although the precise genesis is controversial (Emslie 1978a, b), the anorthosite and granite – quartz monzonite appear to be genetically related but not necessarily comagmatic. Emslie (1978b) has proposed that rising, mantle-derived aluminous gabbroic magma, which formed the anorthosite by fractionation, caused partial melting of crustal rocks to produce the granite – quartz monzonite.

Southern Province

This province (Fig. 3) is mainly a variably deformed and metamorphosed, southward thickening, Early Proterozoic (Aphebian) clastic sedimentary and minor volcanic sequence that unconformably overlies the south part of the Superior Province in Ontario and adjacent parts of the United States. The Southern Province coincides with a major suture in the underlying Archean basement: to the north is a typical 2.55–2.75-Ga greenstone–granodiorite terrane of the Superior Province, but to the south, a 2.8–3.5-Ga gneissic terrane predominates (Sims *et al.* 1980); the gneissic units outcrop only in the United States. Rock units range in age from <1.9 to >2.2 Ga (Card *et al.* 1972). The youngest sedimentary units cannot be dated precisely; for example, an Rb–Sr age of 1.556±0.064 Ga for the uppermost formation is a minimum age reflecting diagenetic re-equilibration of Sr isotopes (Franklin *et al.* 1978). Several distinct deformational pulses (1.6–2.2 Ga) produced structures ranging from isoclinal to broad open folds (Table 1). In Canada, the sedimentary sequence is as much as 5 km thick and becomes younger and less deformed and metamorphosed westward (Card *et al.* 1972). However, when the entire Southern Province, in both Canada and the United States, is considered, there is no lateral change in intensity of deformation or metamorphism.

In the Lake Superior Basin, the Middle Proterozoic (Helikian) Keweenawan sequence unconformably overlies the northern boundary between the Early Proterozoic sequence and the Superior Province basement. The Keweenawan sequence ranges in age from 1.1 to 1.4 Ga and

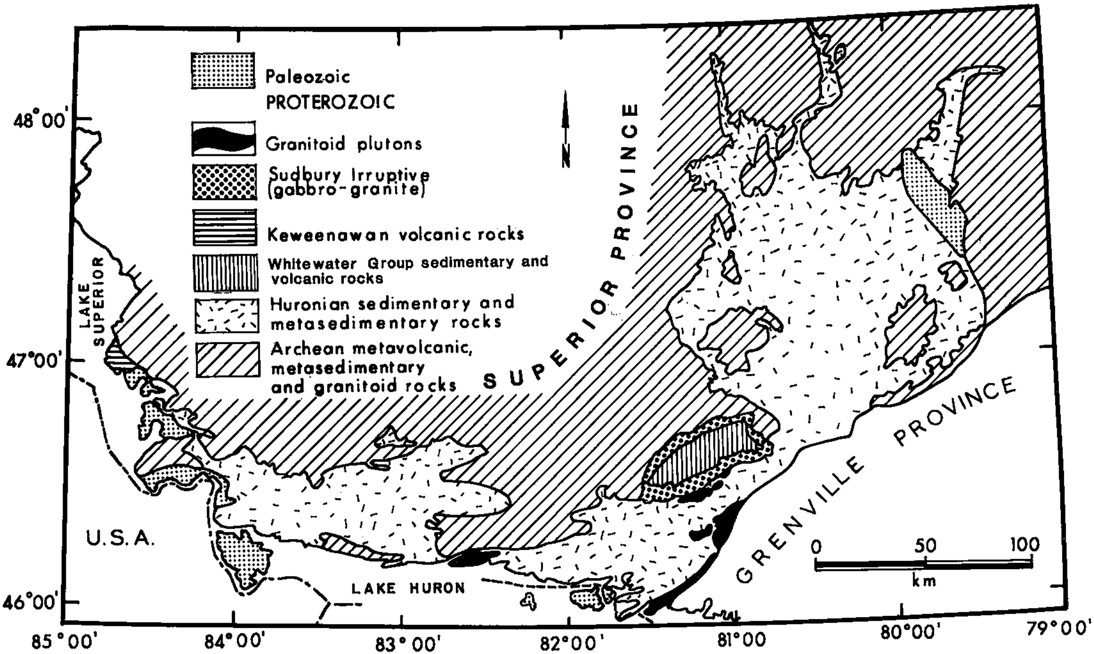


FIG. 13. Major lithological units of the eastern part of the Southern Province [modified after Ayres *et al.* (1971) and Card *et al.* (1972)].

comprises up to 15 km of flood basalt, rhyolite flows and clastic sedimentary units.

Pre- to post-tectonic gabbro dykes and sills are widespread and range in age from 1.1 to 2.15 Ga (Card *et al.* 1972, 1978). Some of the sills contain late-stage granophyric layers. The Sudbury Irruptive (1.85 Ga, Fig. 13) has a 1–1.5 km thick upper layer of granophyric granite (micropegmatite). This layer was injected into its present position late in the fractionation history of the original gabbroic magma, possibly as a result of subsidence of a central uplift produced by meteorite impact (Peredery & Naldrett 1975).

Granitoid plutons are rare in the Canadian portion of the Southern Province (Fig. 13), but are relatively abundant in a volcanic–plutonic terrane south of the sedimentary wedge in Wisconsin (van Schmus 1976). In Canada the plutons are variable in age and level of emplacement, and comprise 1) 2.2-Ga mesozonal, syntectonic, composite granodiorite – granite stocks (Dutch 1979), 2) 1.6–1.75-Ga syntectonic, epizonal to mesozonal, composite tonalite – granodiorite – granite batholiths (Cannon 1970, Lumbers 1975a), 3) a 1.47-Ga, post-tectonic, epizonal, gabbro – quartz monzodiorite – granite stock, and 4) 1.1-Ga subvolcanic granite plutons (Card *et al.* 1972).

The syntectonic plutons were emplaced at different crustal levels (epizone to deep mesozone) during two distinct pulses of deformation. In texture, they are medium grained and equigranular to porphyritic, with porphyritic varieties predominating. Pegmatite is rare except in the westernmost pluton (Fig. 13), which was emplaced passively into deep mesozonal metasediments by segregation of anatectic magma during deformation (Cannon 1970). Other plutons were forcefully emplaced, possibly as diapirs remobilized from the Archean (Superior Province) basement (Dutch 1979).

The 1.1-Ga subvolcanic granite plutons are restricted to the Keweenawan volcanic sequence of the Lake Superior area. They are commonly porphyritic, with aphanitic to fine-grained groundmasses, but locally consist of aphyric felsite or granophyre (Annells 1974). They form dykes, sills, irregular plutons and composite gabbro – granite stocks (Giguère 1975), all of which are intimately related to rhyolite volcanism.

Churchill Province

This is the largest (Fig. 3, Table 1), but the most poorly understood of the structural provinces. The restricted geological data-base is a function of the large size of the province, the reconnaissance nature of much of the mapping, inaccessibility except by aircraft, Arctic climate, paucity of exploitable mineral deposits in much of the province, generally high to medium metamorphic grade, and superposition of several major deformational, metamorphic and plutonic events (Table 1). The province is characterized by both intracratonic and possible craton-margin, Early Proterozoic (Aphebian) mobile belts. Several different mobile belts are present and apparently developed at different times during the Early Proterozoic (Davidson 1972a). The intracratonic mobile belts comprise linear, in part disrupted, metavolcanic – metasedimentary sequences that were deposited on Archean sialic crust similar to that now exposed in the Superior and Slave provinces. This basement was deformed and metamorphosed during the Hudsonian Orogeny (1.7–1.8 Ga, Table 1), and in much of the province the basement has been exhumed by deep erosion. In many areas, the amphibolite- and granulite-facies metamorphic grade hampers the distinction between Archean and Early Proterozoic rock-units and events (Fig. 14). Possible craton-margin metavolcanic-metasedimentary sequences are less deformed and metamorphosed, and rock-units and events can be more readily deciphered (Baragar & Scoates 1981). They also contain most of the known mineral deposits. Middle Proterozoic (Paleohelikian) undeformed sedimentary and volcanic sequences accumulated in two intracratonic basins (Fig. 14).

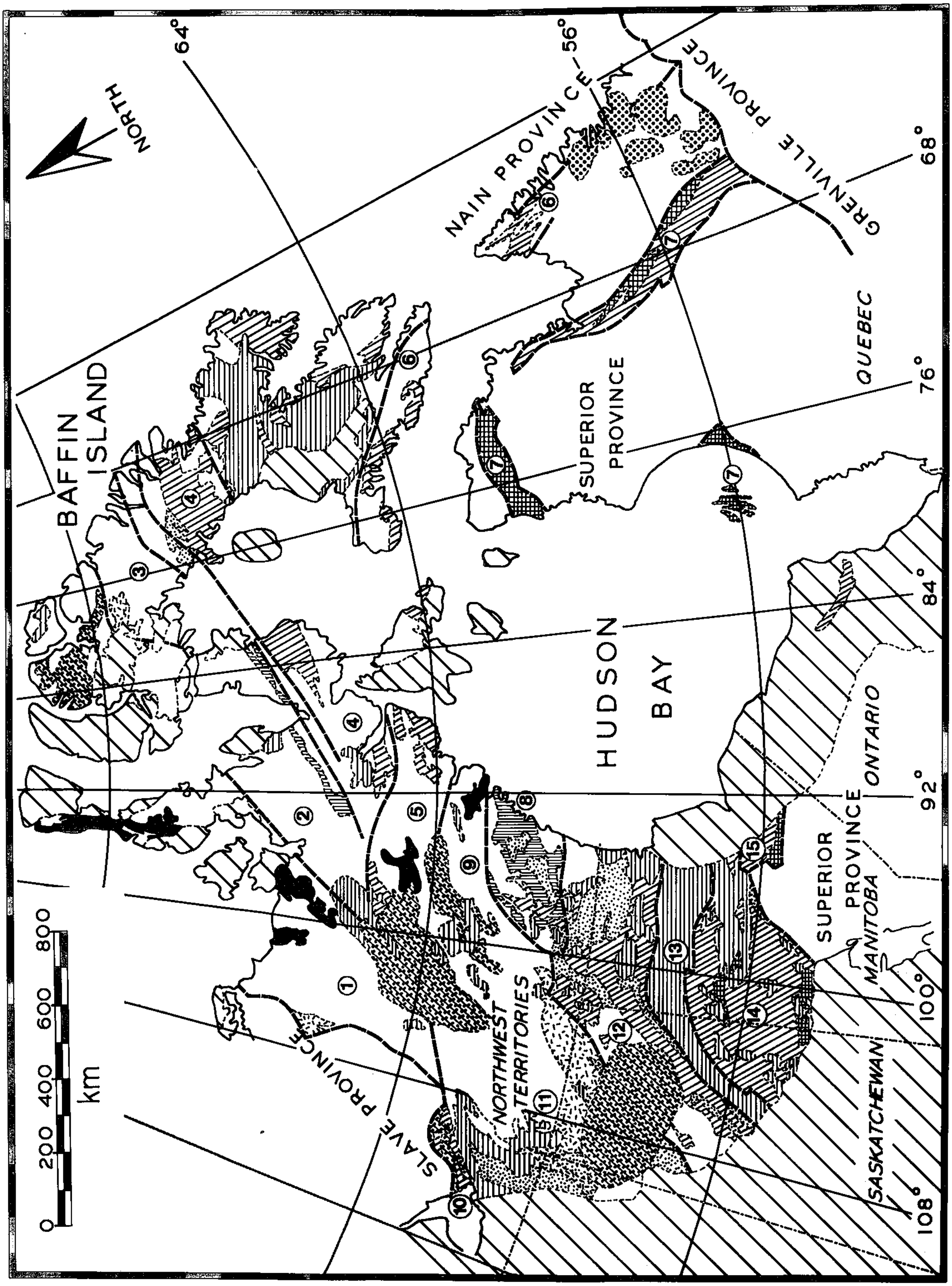
The boundaries between the Churchill and the older Nain, Superior and Slave provinces range from depositional to tectonic-metamorphic. The position of the boundary with the Nain Province in the east is controversial (Douglas 1972, Taylor 1971), but appears to be a fault (Taylor 1972) that probably represents late adjustment between two crustal blocks. The main boundary marker is the eastern limit of Early Proterozoic sedimentation, deformation and metamorphism.

The Churchill–Superior boundary is partly obscured by Phanerozoic deposits of the Hudson Bay Basin. On the east, in northern Quebec, the boundary is depositional with metasedimentary-metavolcanic strata of the Circum-Ungava Geosyncline (subprovince 7, Fig. 14) unconformably overlying Archean basement of the Superior Province (Dimroth *et al.* 1970, Dimroth & Dressler 1978). The depositional contact has been modified by Hudsonian deformation and metamorphism, the outer limit of which is now, at least in part, within the Superior Province basement (Brooks 1980, Dimroth & Dressler 1978).

On the west in northern Manitoba, an early deformational boundary is in part overlapped by younger metavolcanic-metasedimentary strata (Weber & Scoates 1978). The fault separates Early Proterozoic strata on the northwest (Southeastern Zone Subprovince; 14 on Fig. 14) from Archean basement on the southeast, but the southeastern limit of Early Proterozoic, 1.7–1.8-Ga Hudsonian deformation and metamorphism extends eastward beyond this faulted boundary (Weber & Scoates 1978). In the northeast, adjacent to the Phanerozoic cover of the Hudson Bay Basin, the fault boundary is unconformably overlain by the 1.7-Ga metavolcanic-metasedimentary sequence of the Fox River Belt (15 on Fig. 14). The Fox River sequence postdates the main Hudsonian deformation in this area but is itself deformed, possibly by late Hudsonian events. Variable ages of Hudsonian deformation are characteristic of the Churchill Province elsewhere; the province apparently evolved by a series of depositional and orogenic events that culminated at different times in different places (Davidson 1972a, Jackson & Morgan 1978). Gibb & Walcott (1971) and Baragar & Scoates (1981) have proposed that the Churchill–Superior boundary represents a fossil plate-boundary.

In most places, the Slave–Churchill boundary is a zone 5–10 km wide termed the Thelon Front, in which Archean rocks of the Slave Province become increasingly deformed and metamorphosed (Davidson 1972a). Major faults are common along the boundary and, in places, they mark an abrupt change in intensity of deformation. This boundary was originally thought to be the result of Hudsonian events. However, recent work by Henderson *et al.* (1982) along the boundary between the Slave Province and the Queen Maud Block (1 on Fig. 14) of the Churchill Province has shown that the rapid eastward increase in metamorphic grade, from greenschist to granulite facies, and change in structures, from curvilinear on the west to consistently northerly on the east, are the result of Archean events. Superimposed on this are Early Proterozoic cataclastic zones and intermediate-pressure metamorphism. The best defined of these cataclastic zones may be the province boundary (Henderson *et al.* 1982).

Gibb & Thomas (1977) have suggested that the Thelon Front may be a cryptic suture produced by Early Proterozoic collision of two Archean crustal blocks. Lewry & Sibbald (1980) have questioned the suture interpretation. They


NORTH
BAFFIN ISLAND
NAIN PROVINCE
GRENVILLE PROVINCE
SUPERIOR PROVINCE
QUEBEC
HUDSON BAY
SUPERIOR PROVINCE
ONTARIO
MANITOBA
SASKATCHEWAN
NORTHWEST TERRITORIES
SLAVE PROVINCE
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km
64°
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76°
84°
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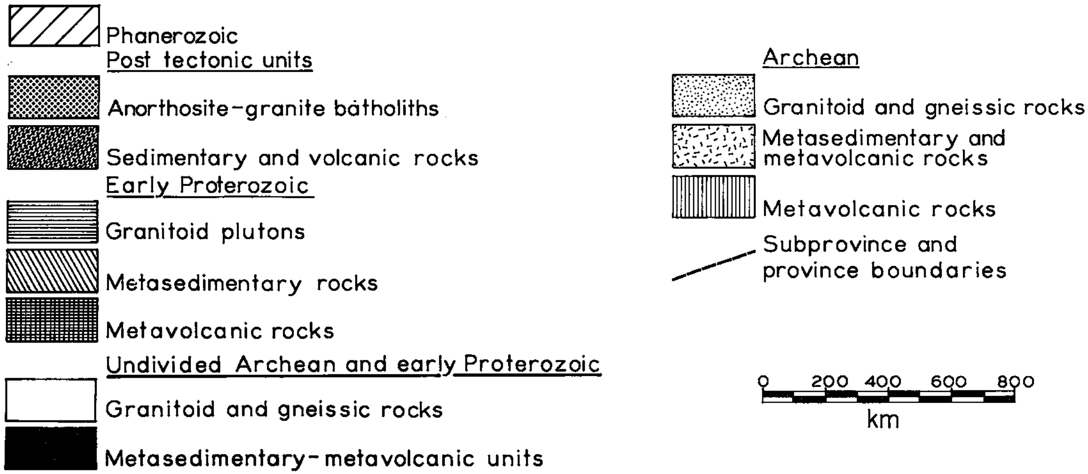


FIG. 14. Major lithological units and subprovinces of the Churchill Province [modified from Douglas (1969, 1974), Eade (1978), Fraser (1978), Godfrey & Langenberg (1978), Heywood & Schau (1978), Jackson & Morgan (1978), Jackson & Taylor (1972), Lewry *et al.* (1978), M.M.R.D. (1979), Schledewitz (1978) and Whitaker & Pearson (1972)]. Numbered subprovinces are 1. Queen Maud Block, 2. Committee Bay Block, 3. Committee Fold Belt, 4. Foxe Fold Belt, 5. Armit Lake Block, 6. Dorset Fold Belt, 7. Circum-Ungava Geosyncline, 8. Kaminak, 9. Ennadai Fold Belt, 10. East Arm Fold Belt, 11. Western Craton, 12. Cree Lake Zone, 13. Rottenstone–Chipewyan, 14. Southeastern Zone, and 15. Fox River Belt. Of these, the Western Craton, Cree Lake Zone and Southeastern Zone have been further subdivided into smaller domains that are not shown on this figure (M.M.R.D. 1979, Lewry *et al.* 1978, 1981). The northern part of the Churchill Province on Devon and Ellesmere Islands has not been subdivided and has been omitted from this figure.

proposed instead that the Western Craton Subprovince of the Churchill Province (11 on Fig. 14) is a continuation of the Slave Province craton. They further suggested that the major tectonic boundary lies well within the Churchill Province and is the junction of the Western Craton and Cree Lake Zone subprovinces (11 and 12 on Fig. 14; Lewry & Sibbald 1980).

In the south, the Slave and Churchill provinces are separated by the fault-bounded East Arm Fold Belt (10 and Fig. 14), which contains a weakly deformed unmetamorphosed, Early Proterozoic sedimentary sequence. This is probably an aulacogen related to the development of the Coronation geosyncline of the Bear Province to the west (Fraser *et al.* 1972, Hoffman 1973).

The Churchill Province has been partly divided into subprovinces (Fig. 14) that have been variously termed fold belts, zones, domains, blocks, tectonic belts, geosynclines and other names (Davidson 1972a, Godfrey & Langenberg 1978, Heywood & Schau 1978, Jackson & Taylor 1972, Lewry & Sibbald 1977, 1980, Lewry *et al.* 1978, 1981, M.M.R.D. 1979, Schledewitz 1978, Stockwell *et al.* 1970). The nomenclature and boundaries are still somewhat controversial, and names used herein (Fig. 14) generally reflect most recent usage. The subprovinces can be broadly grouped into five categories: 1) Archean greenstone – granodiorite terrane that has not been greatly modified by Hudsonian deformation (Kaminak, Committee Bay Block, Committee Fold Belt), 2) Archean gneiss and plutonic terrane that was variably reworked and remetamorphosed during the Hudsonian Orogeny [Queen Maud Block, Armit Lake Block, Western Craton, Ennadai Fold Belt (?); note that many of these subprovinces are as yet unnamed], 3) intracratonic (ensialic), Early Proterozoic mobile belts (East Arm Fold Belt, Foxe Fold Belt, Dorset Fold Belt, Cree Lake Zone), 4) possible craton-margin, Early Proterozoic mobile belts (Southeastern Zone, Fox River Belt, Circum-Ungava Geosyncline), and 5) Early Proterozoic granitoid plutons (Rottenstone–Chipewyan). Granitoid plutons differ in nature and abundance from subprovince to subprovince.

Granitoid, quartzofeldspathic and migmatitic gneisses of tonalite – granodiorite composition dated at 2.8–3.48 Ga by Rb–Sr isochron and zircon U-Pb methods (Cranstone & Turek 1976, Wanless 1979) have been found in several subprovinces. However, because of multiple deformation, the extent of gneisses in this age range and the nature of their protoliths are unknown. As in the Archean structural provinces (Table 1), the gneisses are probably basement to volcanic and sedimentary rocks formed during the main period of Archean volcanism and sedimentation (2.65–2.75 Ga; Wanless 1979).

Archean (2.55–2.75 Ga) metasedimentary and metavolcanic rocks and granitoid plutons that were lithologically similar to those in the adjacent Superior and Slave provinces may be the dominant rock-units in the Churchill Province. Some Archean units, such as the greenstone belt and associated granitoid plutons of the Kaminak Subprovince (8 on Fig. 14) and locally the Committee Bay Block (2 on Fig. 14), are well preserved (Ridler & Shilts 1974, Schau 1977). However, most of the Archean units have been affected by Early Proterozoic deformation and amphibolite- to granulite-facies metamorphism; the extent of the Archean terrane and of various lithologic units within this terrane are generally poorly defined, particularly in the Northwest Territories (Fig. 14). Numerous K-Ar ages have been obtained from the Churchill Province, but most of these date the Early Proterozoic Hudsonian deformation. The true extent of the Archean terrane is being realized only now as mapping progresses and as Rb–Sr isochron and U–Pb zircon ages become more abundant.

Greenschist-facies Archean units are extensively preserved in the Kaminak greenstone belt, which is the second largest known Archean greenstone belt in the Canadian Shield (Ridler & Shilts 1974). In the Kaminak belt, granitoid plutons comprise 1) porphyritic to equigranular, aphanitic to fine-grained, subvolcanic dykes, sills and irregular plutons (Davidson 1970b, 1972a, Eade 1974, Ridler & Shilts 1974); their compositions are unspecified but are probably tonalite – granodiorite – granite, and 2) epizonal to mesozonal, syntectonic to late tectonic, composite stocks and small batholiths within and on the margins of the belt; these are commonly medium-grained, equigranular to porphyritic, massive to gneissic, tonalite – granodiorite – granite plutons with minor gabbro and diorite phases (Davidson 1970a, b, c, 1972a). The general temporal sequence in the plutons is tonalite, followed successively by granodiorite and granite, but this sequence may be repeated in cyclic fashion (Davidson 1972a). The youngest phases are always the most potassic. Some plutons consist of an older gneissic granodiorite – granite unit, in part derived from supracrustal sequences, and younger massive granodiorite – granite phases (Eade 1974). Toward the margins of the Kaminak Subprovince, the Archean granitoid rocks become recrystallized, with development of a gneissic structure and a decrease in grain

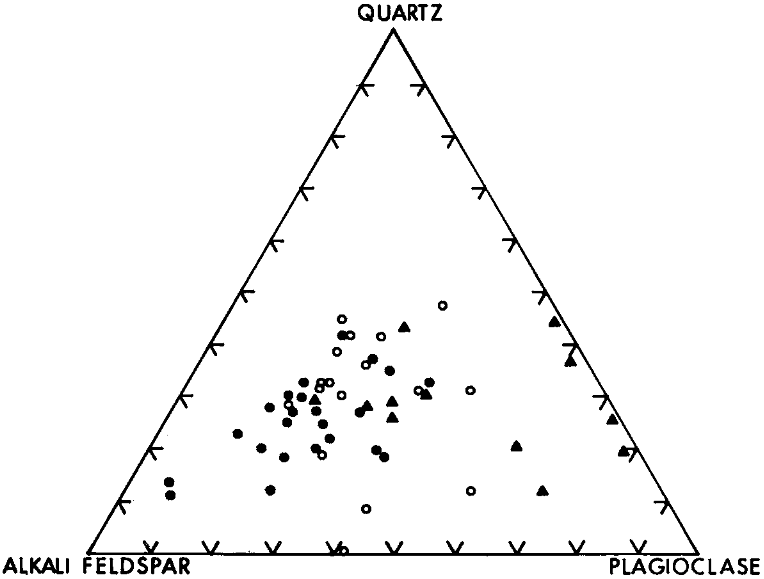


FIG. 15. Modal composition of Archean basement (○), late-tectonic (▲) and post-tectonic Nueltin Lake (●) granitoid plutons from the southwestern part of the Churchill Province (after Eade & Flint 1973, Money *et al.* 1970).

size (Davidson 1970a).

Reworked Archean granitoid rocks appear to be the dominant component of the gneiss subprovinces (Queen Maud Block, Armit Lake Block, Western Craton, Ennadai Fold Belt, and other unnamed areas), and a major and, in places, dominant component of three of the intracratonic mobile belts (Foxe Fold Belt, Dorset Fold Belt, Cree Lake Zone) (Eade 1978, Fraser 1978, Godfrey & Langenberg 1978, Jackson & Morgan 1978, Lecheminant *et al.* 1981, Lewry & Sibbald 1980). The reworking is generally assumed to be the result of Early Proterozoic Hudsonian deformation, but in some of the gneiss subprovinces, such as the Western Craton (11 on Fig. 14), where Early Proterozoic supracrustal sequences are rare, the deformation may be largely Archean (Lewry & Sibbald 1980). Based on the work of Henderson *et al.* (1982), a similar conclusion may apply to parts of the Queen Maud Block (1 on Fig. 14). The reworked Archean granitoid plutons vary in structure from massive to gneissic (Lewry & Sibbald 1980), but also include cataclastic, augen and metasomatic phases (Eade 1973, Lewry & Sibbald 1977, Money *et al.* 1970) and local anatectic pegmatite (Jackson & Morgan 1978, Tippett 1979). Lewry & Sibbald (1980) have speculated that the structural differences may be due either to age differences between the plutons (syntectonic Kenoran *versus* late-tectonic Kenoran; see also Ray & Wanless 1980) or to differences in the intensity of the Proterozoic Hudsonian deformation. The reworked plutons range from homogeneous to inhomogeneous on a large scale (Lewry & Sibbald 1980), and range in composition from gabbro to granite, but are dominantly tonalite – granodiorite – granite – quartz monzonite (Fig. 15; Davidson 1972a, Lewry & Sibbald 1980). In places, the plutons are hypersthene-bearing (charnockitic) because of superimposed granulite-facies metamorphism; these have been locally retrograded to the amphibolite facies (Godfrey & Langenberg 1978, Lewry & Sibbald 1977, 1980, Schledewitz 1978, Weber *et al.* 1975a). The charnockitic units have a more potassic bulk-composition than amphibolite-facies plutons and represent mesozonal to catazonal plutons (Davidson 1972a). In the Cree Lake Zone (12 on Fig. 14), the charnockitic rocks are intruded by hypersthene-free, foliated granite plutons (Weber *et al.* 1975b). In the intracratonic or ensialic mobile belts of the Foxe Fold Belt, Dorset Fold Belt and Cree Lake Zone subprovinces (4, 6 and 12 on Fig. 14), remobilized, metamorphosed plutons of the Archean basement form intrusions, gneiss domes and nappe-like migmatite lobes within deformed, Early Proterozoic supracrustal sequences (Godfrey & Langenberg 1978, Lewry & Sibbald 1977, 1980, Lewry *et al.* 1978, Tippett 1979).

Proterozoic granitoid plutons are present in all subprovinces but, in many areas, they have not yet been distinguished from the Archean plutons (Fig. 14); in the various subprovinces the Proterozoic plutons range in abundance from a minor to the dominant component. In the Early Proterozoic strata of the East Arm Fold Belt (10 on Fig. 14), granitoid rocks are restricted to quartz monzodiorite phases of calc-alkaline diorite to quartz monzodiorite laccoliths up to 25 km long (Badham 1978, Hoffman *et al.* 1977).

Proterozoic syntectonic to post-tectonic granitoid plutons are present in both the intracratonic and the gneiss subprovinces. The syntectonic plutons are highly variable, with their habits and compositions in part reflecting their depth of emplacement. On Baffin Island, 1.9-Ga dykes, sheets, mushroom-shaped plutons and irregular plutons of massive granite, both hypersthene-bearing (charnockitic) and hypersthene-free, are present in granulite-facies country rocks (Jackson & Morgan 1978, Pidgeon & Howie 1975). High initial $^{87}Sr/^{86}Sr$ ratios indicate that the plutons were probably derived by partial melting of Archean basement (Jackson & Morgan 1978). In the Cree Lake Zone of Saskatchewan (12 on Fig. 14), *in situ* anatexis produced extensive migmatites in the central Mudjatik domain, but in the eastern Wollaston domain, where deformation style was different, the anatectic melts were segregated and mobilized to form several generations of massive to weakly foliated, semiautochthonous to allochthonous granodiorite – quartz monzonite – granite plutons (Lewry & Sibbald 1980, Lewry *et al.* 1981). The junctions between major crustal elements of the Cree Lake Zone, which are marked by major shear zones, were the loci for emplacement of late syntectonic plutons (Lewry & Sibbald 1980, Ray & Wanless 1980); these plutons are generally characterized by the presence of coarse-grained K-feldspar megacrysts. In the Queen Maud Block (1 on Fig. 14), a megacrystic granite characterized by mesoperthite and minor hypersthene was emplaced into Archean gneisses as a large diapir; the mineral assemblage and structures suggest emplacement at relatively high crustal levels under hot, dry conditions (Bostock 1981).

Elsewhere in the Churchill Province, syntectonic plutons comprise variably deformed stocks and batholiths that range in age from 1.77 to 1.94 Ga (Wanless & Eade 1975, Weber *et al.* 1975a). They range from massive to gneissic rocks, in part augen gneiss, and include medium- to coarse-grained granodiorite and granite. Some plutons are composite and zoned (Wanless & Eade 1975). In the Armit Lake Block (5 on Fig. 14), deformed Proterozoic plutons that were intruded into Archean tonalite – granodiorite orthogneisses can be distinguished from the Archean plutons by their more potassic composition and lower degree of deformation (Lecheminant *et al.* 1981).

Late-tectonic plutons include widespread granodiorite – granite – pegmatite sills and dykes on Baffin Island (Jackson *et al.* 1975, Jackson & Morgan 1978), and massive, medium- to coarse-grained, equigranular to porphyritic, quartz diorite – tonalite – granodiorite – granite stocks and batholiths in the western Churchill Province (Fig. 15; Money *et al.* 1970, Weber *et al.* 1975a). As stressed by many authors (*e.g.*, Davidson 1972a, Eade 1978, Jackson & Morgan 1978), the timing of deformation varied from place to place, and syntectonic plutons in one part of the Churchill Province may be the same age as late-tectonic or post-tectonic plutons elsewhere.

Post-tectonic granitoid plutons include the 1.7-Ga Nueltin Lake plutons in the western part of the province (Wanless & Eade 1975) and the granitoid phases of the 1.4–1.5-Ga anorthosite – quartz monzonite – granite batholiths, some of which have rapakivi texture, in the southeast corner of the province (Fig. 14; Emslie 1978a, Emslie *et al.* 1980). The Nueltin Lake plutons were originally defined in the northern part of the Cree Lake Zone (12 on Fig. 14; Wright 1967), but similar plutons have been found in the Armit Lake Block, Ennadai Fold Belt and Western Craton subprovinces (5, 9, and 11 on Fig. 14; Lecheminant *et al.* 1979a, b, 1980, 1981, Tella *et al.* 1981, Wright 1967). These plutons form a distinctive suite of medium- to coarse-grained, generally porphyritic, massive, fluorite-bearing leucocratic granite, quartz syenite, and alkali-feldspar granite and syenite stocks and batholiths (Eade & Flint 1973). Near the common boundary of the Armit Lake Block, Ennadai Fold Belt and Western Craton (Fig. 14), many of the plutons are hypabyssal with miarolitic cavities, a well-developed chilled margin, and a granophyric to fine-grained groundmass (Lecheminant *et al.* 1979a, b, 1980, 1981, Tella *et al.* 1981); the rapakivi texture is present in several plutons (Lecheminant *et al.* 1980, 1981). These hypabyssal plutons are apparently the intrusive equivalent of rhyolites of the Pitz Formation at the top of the post-orogenic Dubawnt Group (Lecheminant *et al.* 1980, 1981). The Nueltin Lake and similar plutons are the most potassic plutons in the Churchill Province (Fig. 15).

The possible craton-margin mobile belts (Southeastern Zone, Fox River Belt, Circum-Ungava Geosyncline; 14, 15 and 7 on Fig. 14) have sedimentary and volcanic facies suggestive of craton-margin deposition (Baragar & Scoates 1981), but are bounded on both sides by Archean sialic terrane. These belts have been interpreted to represent either deposition and deformation on the margin of an Archean craton, with subsequent juxtaposition of Archean terrane on the opposite side of the belt (Lewry & Sibbald 1980, Ray & Wanless 1980), or fracturing and rifting of a larger Archean craton producing narrow seaways (Baragar & Scoates 1981). Granitoid plutons are rare in the Circum-Ungava Geosyncline (Dimroth *et al.* 1970), except in the eastward extension of the geosynclinal units, where metamorphic grade is high (Taylor 1979), and in the Fox River Subprovince, but are common in the Southeastern Zone Subprovince (Fig. 14). The Southeastern Zone consists of two east-trending Early Proterozoic greenstone belts that are separated by the Kisseynew sedimentary basin. As in the Superior Province, the greenstone belts appear to represent deformed chains of volcanic islands that provided clastic detritus to the intervening basin (Bailes & McRitchie 1978). Archean basement has been reported only rarely (Coleman 1970, Lewry *et al.* 1981), but includes both greenstone and granitoid components.

In the greenstone belts, where metamorphic grade is generally greenschist facies, granitoid plutons, which are the major if not the dominant component, include 1) texturally variable subvolcanic dykes, sills, sill complexes and stocks of tonalite – granodiorite – granite; textures range from aphanitic to medium-grained, and porphyritic to equigranular; some of the plutons are simple or zoned, whereas others are composite (*e.g.*, Baldwin 1980, Černý *et al.* 1981, Chute & Ayres 1977), and 2) pre- to post-tectonic, composite, epizonal to mesozonal tonalite – granodiorite – granite stocks and batholiths, many of which were diapirically emplaced (Bailes 1971, Lewry *et al.* 1978). The pre- to post-tectonic plutons comprise two distinct groups: 2a) pretectonic to early syntectonic plutons (in part gneissic), in which the emplacement sequence is generally early quartz diorite – tonalite followed by granodiorite, and leucogranodiorite – aplite, and 2b) late syntectonic to post-tectonic, massive to foliated, equigranular to locally porphyritic quartz monzonite – granodiorite – granite (Bailes 1971, Lewry *et al.* 1978, 1981). Late pegmatitic granite and pegmatite plutons are locally abundant (Černý *et al.* 1981). In the amphibolite-facies sedimentary basin, granitoid plutons are less abundant and are mainly tonalite – granodiorite sills and sheeted sill and dyke complexes that were formed by anatexis of the greywacke–shale metasedimentary sequence (Bailes & McRitchie 1978). The products of anatexis range from thin, *in situ* concordant segregations to large remobilized gneissic plutons (Bailes & McRitchie 1978, Lewry *et al.* 1978).

The Rottenstone–Chipewyan Subprovince (13 on Fig. 14) is a granitoid batholithic complex ranging in composition from diorite to granite. It comprises syntectonic gneissic diorite – tonalite – granodiorite and associated migmatites, intruded by late- to post-tectonic quartz monzonite – granite plutons (Lewry *et al.* 1978, 1981, Schledewitz 1978). Some of the older plutons are the result of anatexis of supracrustal units, but most of the plutons had a deeper source (Lewry *et al.* 1981). Lewry *et al.* (1981) stressed that plutons in the subprovince and adjacent parts of the Cree Lake Zone to the west are dominantly granodiorite – quartz monzonite – granite, and are thus more potassic than plutons in the Southeastern Zone to the east, where tonalite is abundant.

A large part of the Rottenstone–Chipewyan Subprovince is a late syntectonic batholith, the Wathaman–Chipewyan batholith, that is at least 50 km wide and has a lateral extent of more than 800 km. The batholith has limited compositional variation (granodiorite – quartz monzonite – granite), an average composition of monzogranite, and 10-30% K-feldspar megacrysts up to 9 cm long (Lewry *et al.* 1981, Ray & Wanless 1980). Ray & Wanless (1980) suggested that the Wathaman–Chipewyan batholith is a composite pluton possibly emplaced over an extended time span. Lewry *et al.* (1981), on the other hand, concluded that the batholith was emplaced as a single pluton or a limited number of related plutons, and is the largest coherent pluton in the Canadian Shield.

Bear Province

This province forms the northwesternmost part of contiguously exposed shield and several inliers on the mainland and on Arctic islands; on the west it is covered by Paleozoic strata (Fig. 3). On the east it is in fault, sedimentary, and deformation-metamorphic contact with the Archean Slave Province (Fraser *et al.* 1972, Frith 1978, Frith *et al.* 1977a). The main tectonic element is the Wopmay Orogen, which consists of Archean and Early Proterozoic (Aphebian) units that were deformed during the Hudsonian Orogeny (Fraser *et al.* 1972, Hoffman 1973, 1980, Stockwell 1961) at about 1.8 Ga (Frith *et al.* 1977a). The Wopmay Orogen is overlain to the north by unmetamorphosed, ho-

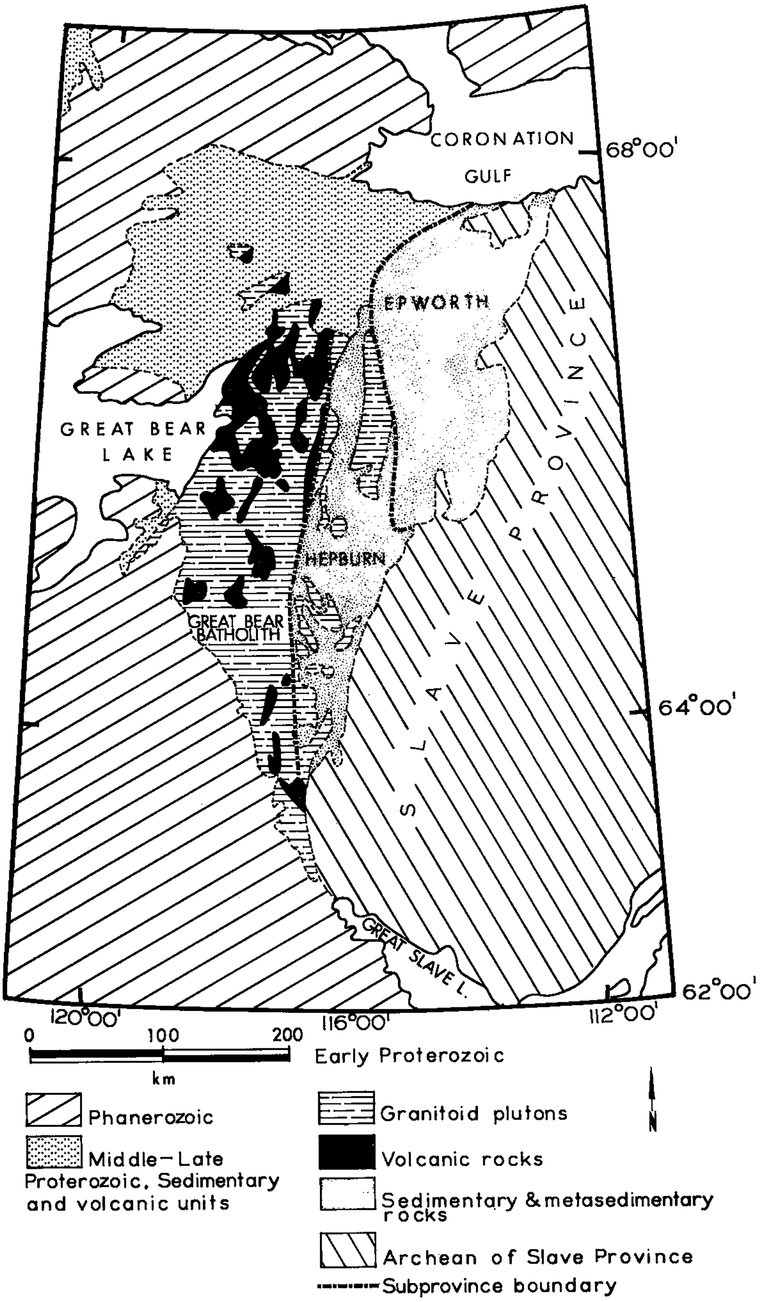


FIG. 16. Major lithological units and subprovinces of the southern part of the Bear Province. Modified after Fraser *et al.* (1972, 1978), Hoffman (1980) and Hoffman & McGlynn (1977).

moclinal, Middle to Late Proterozoic (Paleohelikian, Neohelikian and Hadrynian) sequences of clastic and carbonate sedimentary rocks and flood basalt flows that were intruded by extensive gabbroic dykes and sheets including the Muskox layered intrusion (Fraser *et al.* 1972); all of the inliers in the Paleozoic are part of the Middle to Late Proterozoic, post-Hudsonian sequence. Except for granophyric layers in the Muskox and some of the other gabbroic plutons, there are no post-Hudsonian granitic rocks in the Bear Province (Fraser *et al.* 1972).

The Wopmay Orogen comprises three subprovinces (Fig. 16). The Epworth Basin or Fold Belt on the northeast consists of unmetamorphosed to low-rank metamorphic, weakly deformed, Early Proterozoic (Late Aphebian) clastic and carbonate sedimentary strata of the shelf and platform facies (Fraser *et al.* 1972) that correlate with those in the Kilohigok Basin of the Slave Province and the East Arm Fold Belt of the Churchill Province to the east. The shelf and platform facies grade westward into more highly deformed and metamorphosed, continental-rise, sedimentary and volcanic rocks within the central Hepburn metamorphic–plutonic subprovince. On the west is the slightly younger volcanic–plutonic terrane of the Great Bear batholith (Hoffman & McGlynn 1977).

In the Hepburn Subprovince, Early Proterozoic sedimentary and volcanic rocks were deformed and intruded by various granitoid plutons prior to and during the Hudsonian Orogeny. The plutons appear to form less than 25% of the subprovince and comprise 1) large anastomosing, synvolcanic sills of porphyritic granite with fine-grained groundmass textures (Hoffman 1980), 2) sparse granodiorite – granite – pegmatite stocks that were emplaced during early stages of the orogeny at about 1.95 Ga; these extend eastward into bordering parts of the southern Slave Province (Frith *et al.* 1977a), 3) mesozonal to epizonal, porphyroblastic granodiorite stocks and batholiths of remobilized Archean basement plutons that were emplaced as diapirs and gneiss domes about 1.8 Ga (Frith *et al.* 1977a, Frith 1978), and 4) syntectonic to post-tectonic, in part funnel-shaped, composite batholiths of the Hepburn intrusive suite that range in composition from pyroxenite to granite but are dominantly granite (Hoffman 1980, Hoffman *et al.* 1978, 1980, St-Onge 1981). In contrast to many plutons in other provinces, granite, which is locally gneissic and in places contains orthoclase porphyroblasts, is the earliest phase of the syntectonic to post-tectonic plutons; successive phases become more mafic and more massive. This inverse sequence of emplacement and the local presence of garnet and sillimanite in the granite suggest that the granitic magma was derived by anatexis of upper crustal or sedimentary units (St-Onge 1981). Emplacement of the syntectonic plutons by magmatic stoping caused partial anatexis and migmatization of the immediately adjacent metasedimentary country rocks (Hoffman *et al.* 1980, St-Onge 1981). The remobilized Archean basement contains microcline porphyroblasts that are commonly deformed into augen, and a locally developed rapakivi texture (Fraser *et al.* 1972, Frith 1978). During remobilization, anatectic alaskitic pegmatite developed in both the granodiorite and adjacent metasedimentary rocks, producing migmatite (Frith *et al.* 1977a).

The Great Bear Batholith Subprovince consists of a thick unmetamorphosed to weakly metamorphosed, gently folded, subaerial basaltic to rhyolitic volcanic sequence intruded by comagmatic epizonal plutons (Badham 1973, Hoffman 1980, Hoffman & McGlynn 1977). The volcanic sequence is mainly calc-alkaline, rhyolitic and dacitic ash-flow tuff that was erupted in a volcano-tectonic depression at about 1.8–1.9 Ga. Plutons predominate over volcanic rocks (Fig. 16) and consist of concordant, subvolcanic tonalite – granodiorite – granite sills and stocks, and discordant, post-volcanic syenogranite dyke swarms, stocks and batholiths. The plutons are collectively termed the Great Bear batholith; granite is the dominant rock type. The plutons range in texture from porphyritic with aphanitic groundmass to coarse-grained and equigranular; the coarse-grained plutons are locally porphyritic. Some of the early plutons are layered owing to gravity settling. The granitic magma was derived from deeper crustal or mantle sources than the granitic magmas of the Hepburn Subprovince (Badham 1973, Hoffman 1980).

Grenville Province

This province forms the southeastern margin of the Canadian Shield (Fig. 3) and records the youngest major tectonic event in the Shield, the Grenvillian Orogeny (Table 1, Fig. 2; Stockwell *et al.* 1970). Rock units range in age from Archean to Middle Proterozoic, with the Archean and Early Proterozoic units having been subjected to several deformational events prior to the Grenvillian Orogeny at about 1.0–1.2 Ga (Table 1). The result is a polydeformed, generally intermediate- to high-rank metamorphic terrane that is still poorly documented (Davidson *et al.* 1979).

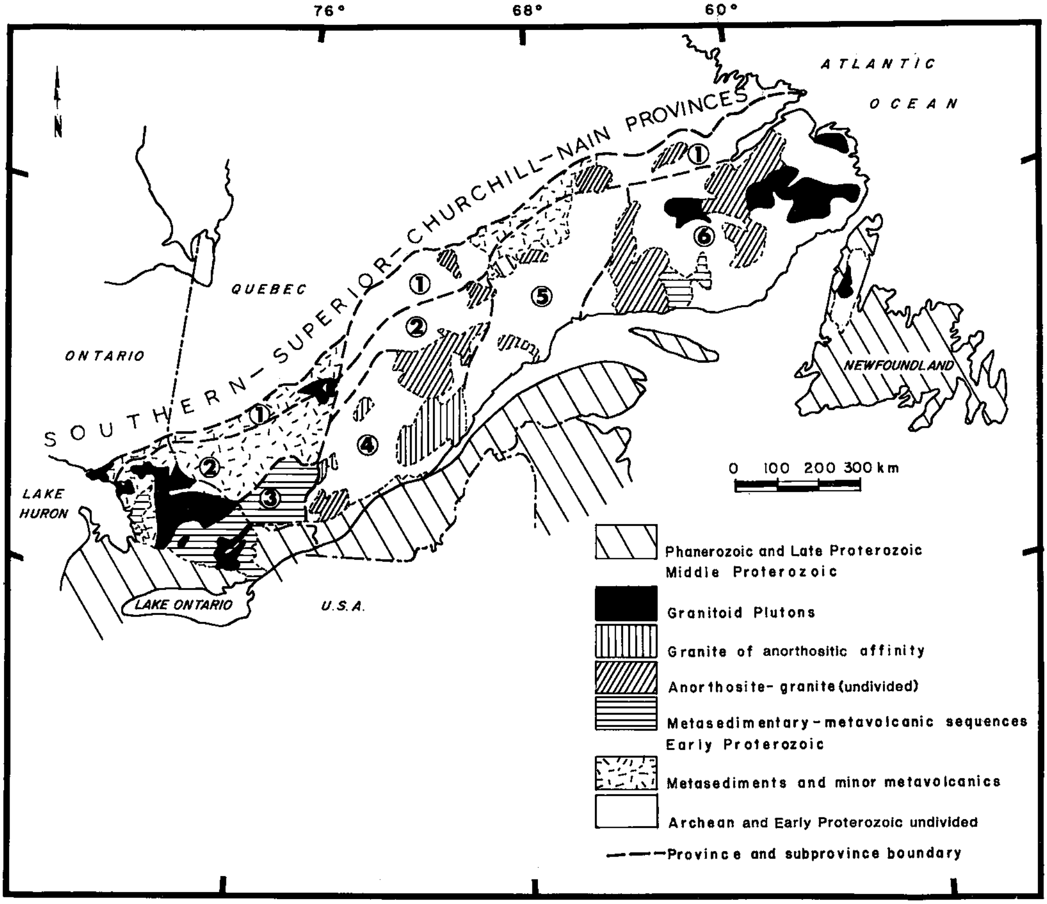


FIG. 17. Major lithological units and subprovinces of the Grenville Province. Modified after Ayres *et al.* (1971) Baer (1976), Davidson *et al.* (1982), Douglas (1969), Fraser *et al.* (1978), Schwerdtner & Lumbers (1980) and Wynne-Edwards (1972). Numbered subprovinces (Wynne-Edwards 1972) are: 1. Grenville Front Tectonic Zone, 2. Central Gneiss Belt, 3. Central Metasedimentary Belt, 4. Central Granulite Terrain, 5. Baie Comeau Segment, and 6. Eastern Grenville.

The boundary between the Grenville and the adjacent Southern, Superior, Churchill and Nain provinces (Fig. 3) is the Grenville Front Tectonic Zone (2 on Fig. 17; Davidson *et al.* 1979, Gower *et al.* 1980, Lumbers 1978, 1979, Wynne-Edwards 1972). In this zone, which is up to 80 km wide, rocks of the older provinces were intensely deformed, metamorphosed and uplifted during the Grenvillian Orogeny. In places, a major fault occurs near the northern margin of the tectonic zone and separates cataclastic rocks on the northwest from gneissic rocks on the southeast. In the south, the Grenville Province is covered by Phanerozoic strata (Fig. 17).

The Grenville Province has been divided into six subprovinces on the basis of differing metamorphic intensity, age of rock units and styles of deformation (Fig. 17; Wynne-Edwards 1972). Boundaries between subprovinces are, at least in part, major tectonic zones, and similar tectonite zones separate various domains within the Central Gneiss Segment Subprovince (2 on Fig. 17; Davidson *et al.* 1982). The tectonite zones apparently formed as a result of northwesterly directed deep-seated thrusting (Davidson *et al.* 1982). Except for the Central Metasedimentary Belt Subprovince (3 on Fig. 17), rock units are generally much older than the Grenvillian Orogeny, and record older events.

However, the exact age of rock units within, and the relationships between the various subprovinces are controversial (Baer 1976, 1981, Davidson *et al.* 1982, Dewey & Burke 1973, Irving *et al.* 1972, Lumbers 1978, Wynne-Edwards 1972), in part reflecting the polyphase deformation, high metamorphic grade and lack of detailed geological mapping in many areas. The abundance and nature of granitoid plutons are variable from subprovince to subprovince (Fig. 17); in most subprovinces, granitoid plutons do not seem to be abundant. However, recent work in the Ontario portion of the Central Gneiss Belt (2 on Fig. 14) has shown that deformed granitoid plutons are more abundant than previously believed (Davidson *et al.* 1982, Schwerdtner & Lumbers 1980). Thus the high abundance of plutons in Ontario (Fig. 14) may be representative of pluton abundance in the more poorly documented Quebec portion of the Grenville Province.

Quartzofeldspathic grey gneisses of probable Archean age, but derived from uncertain protoliths, underlie much of the Central Granulite, Baie Comeau and Eastern Grenville subprovinces (4, 5 and 6 on Fig. 17; Wynne-Edwards 1972). They apparently represent a continuation of the Archean terrane of the Superior and Nain provinces; by analogy with these provinces, granitoid orthogneiss of tonalite – granodiorite composition probably is a common constituent. Frith & Doig (1975) have documented the presence of tonalitic gneiss older than 3.0 Ga, but the exact age of most of the Archean gneisses is unknown. In places, these gneisses were remobilized during the Grenvillian Orogeny.

The Archean terrane was intruded by extensive anorthosite – quartz monzonite – granite batholiths prior to the culmination of the Grenvillian Orogeny. The plutons have been deformed and metamorphosed, and it is uncertain whether the reported age range of 1.1–1.5 Ga (Emslie 1978b, Martignole & Schrijver 1977, Wynne-Edwards 1972) represents a sequence of plutonic events or a single magmatic pulse, partly modified isotopically by superimposed metamorphism and deformation. Emslie (1978b) proposed that most of the anorthosite – granite complexes were emplaced at about 1.4–1.5 Ga. In conjunction with those in the Churchill and Nain provinces (Figs. 11, 14) and elsewhere in North America and Europe, these complexes form a linear zone that may reflect a Middle Proterozoic rifting event several hundred million years prior to the Grenvillian Orogeny (Emslie 1978b). The younger ages may reflect tectonic remobilization during the Grenvillian Orogeny (Baer 1976, 1981). Martignole & Schrijver (1977), on the other hand, considered that the 1.1–1.2 Ga ages of anorthosite – granite batholiths in the Central Granulite Subprovince (4 on Fig. 17) represent early-tectonic diapiric emplacement of the plutons at catazonal depths during the Grenvillian Orogeny.

In the Central Gneiss Belt Subprovince, Early Proterozoic (Aphebian) metasedimentary rocks unconformably overlie the Archean basement (2 on Fig. 17). Deformed and metamorphosed anorthosite – quartz monzonite – granite batholiths also are present but, unlike those further east, granitoid rocks greatly predominate here over anorthosite (Lumbers 1975a, 1978, Schwerdtner & Lumbers 1980). The granitoid rocks were originally massive, but during the Grenvillian Orogeny (1.0–1.3 Ga) they were deformed to different degrees to produce gneisses, and the plutons were diapirically reactivated and moved to higher structural levels (Schwerdtner & Lumbers 1980). The batholiths range in age from 1.1 to 1.5 Ga; this range in ages is believed to represent igneous emplacement during a 400-Ma time-span (Lumbers 1975a, 1978). Modal compositions of the granitoid phases are presented in Figure 18.

Deformed and metamorphosed, 1.5–1.7-Ga calc-alkaline granitoid plutons are also present in the Central Gneiss Belt. They are mainly medium- to coarse-grained porphyritic granodiorite – quartz monzonite dyke swarms, sheets, stocks and batholiths (Lumbers 1975a, 1978); folded sheets are particularly common (Davidson *et al.* 1982). These plutons are now commonly gneissic and locally migmatitic.

Middle Proterozoic (Helikian) volcanism and sedimentation that culminated with the Grenvillian Orogeny are largely restricted to the Central Metasedimentary Belt Subprovince (3 on Fig. 17). Granitoid plutons associated with these events include 1) an early tectonic, in part subvolcanic, recrystallized tonalite – granodiorite suite of epizonal to mesozonal stocks and batholiths emplaced in metavolcanic sequences at about 1.25 Ga (Lumbers 1967); these plutons have a trondhjemitic trend, 2) syntectonic, catazonal granodiorite – granite stocks and batholiths that were emplaced in intermediate- to high-grade metasedimentary sequences at about 1.125 Ga (Lumbers 1967), and 3) late tectonic granite – alkali feldspar granite – monzonite – syenite dykes, sills and stocks emplaced at about 1.0–1.1 Ga (Davidson *et al.* 1979, Lumbers 1967). Pegmatite is locally abundant and is confined largely to terranes in the amphibolite facies and at higher grades. In the locally developed greenschist-facies terrane, fluorite-bear-

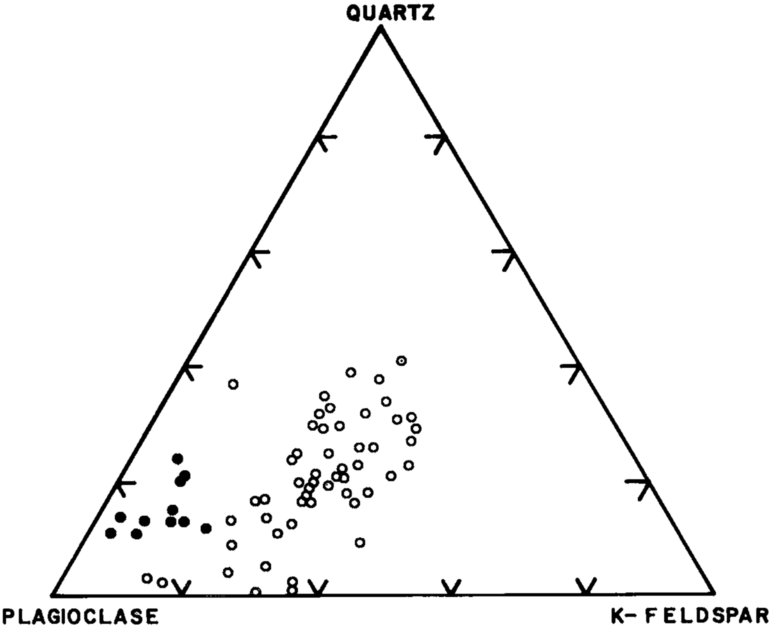


FIG. 18. Modal composition of granitoid rocks of anorthosite – granite complexes in the Central Gneiss Belt of Ontario (after Lumbers 1975a); diorite and tonalite (●), quartz monzonite and granite (○).

ing, in part granophyric, epizonal stocks of peralkaline granite are present (Davidson *et al.* 1979, Saha 1959). During the Grenvillian deformation, Early Proterozoic tonalite – granodiorite basement gneiss was locally remobilized to form mantled gneiss domes (Bright 1977).

Elsewhere in the Grenville Province, syntectonic and late-tectonic granitoid plutons appear to be rare (Baer 1976, Wynne-Edwards 1972), except in the Eastern Grenville Subprovince where they are poorly documented (6 on Fig. 17; Bourne 1978). The late tectonic plutons are characteristically potassic and include ubiquitous pegmatite dykes and sills and granite – alkali feldspar granite stocks and batholiths emplaced 1.0–1.2 Ga ago (Davidson *et al.* 1979, Lumbers 1978). During the Grenvillian Orogeny, *in situ* anatexis in intermediate- to high-grade metamorphic areas produced migmatitic units in both paragneiss and orthogneiss (Lumbers 1975a).

Post-tectonic plutons are rare but small Late Proterozoic to Early Paleozoic alkali plutons that locally have granitoid phases were intruded along and adjacent to the St. Lawrence Rift System (Doig & Barton 1968). These plutons are best documented along the Ottawa–Bonnechère Graben, an arm of the rift system that extends northwesterly across the Grenville Province along the Quebec–Ontario border. Plutons with granitoid phases are among the youngest of this group; they were emplaced at about 450 Ma (Doig & Barton 1968).

Summary of granitoid plutonism in the Canadian Shield

As shown in Table 1, tonalitic to locally granodioritic and, rarely, granitic orthogneiss, 2.8 Ga and older, occurs in most structural provinces. The nature and extent of the old plutons are unknown, but the presence of the plutons implies still older supracrustal sequences into which the plutons were emplaced. As yet, these supracrustal sequences have been identified only in the Nain and Superior provinces (Table 1; Collerson & Bridgwater 1979, Nunes & Thurston 1980). The older plutons also imply the development of a widespread, although possibly segmented 3.0-Ga cratonic terrane (Clark *et al.* 1981, Goodwin, 1977, Walker 1978) that could have been both a potential source-area for younger sediments and an anatectic source for younger granitoid plutons (Hargraves 1976). The 3.0-Ga and older plutons are characteristically deficient in potassium and have trondhjemitic chemical trends (Figs. 5, 12).

At the close of the Archean, extensive granitoid plutonism associated with the Kenoran Orogeny (2.55–2.65 Ga) produced a sialic cratonic terrane throughout the Canadian Shield. Although the Archean structural provinces were not necessarily in their present positions, the areal extent of the post-Kenoran sialic terrane was approximately equal to the present Canadian Shield. Subsequent Proterozoic events modified the sialic terrane but did not greatly change its size, at least in the presently exposed part of the Shield. In the Slave and Superior provinces, the cratonic terrane remained relatively stable throughout the Proterozoic, except for epeirogenic and tensional tectonics. The Bear, Southern and southwestern Grenville provinces represent Early and Middle Proterozoic sedimentation, volcanism and subsequent deformation on the margins of, or within, the Archean craton. Middle Proterozoic events are restricted to the Grenville Province. In the Churchill, Nain and northeastern Grenville provinces, the Archean basement was extensively reworked by Proterozoic orogenic events of variable intensity and age. Two major orogenic events have been recognized: the Hudsonian (1.6–2.2 Ga), which appears to comprise a series of possibly unrelated events within this general time-interval, and the areally restricted Grenvillian (1.0–1.2 Ga). There are no Late Proterozoic orogenic events.

The Archean craton was apparently segmented in the Early Proterozoic. The present shield represents either 1) several diverse cratonic blocks that collided during the Hudsonian Orogeny, or 2) an original large craton in which Proterozoic rift zones, that are in part ensimatic, produced major crustal extension and ocean development followed by later convergence and re-establishment of a single craton. The latter model is supported by paleomagnetic data (Irving & McGlynn 1976), but in either model, sedimentation and volcanism of the Circum-Ungava Geosyncline, Southeastern Zone and Fox River Belt subprovinces of the Churchill Province (Fig. 14), which are now bounded on both sides by Archean terrane, apparently took place on craton margins. These craton-margin sequences were deformed and welded onto or into the Archean craton during the Hudsonian Orogeny. Other rift and suture zones have also been proposed (*e.g.*, Gibb & Thomas 1977), although some of these are controversial (*e.g.*, Lewry & Sibbald 1980).

Elsewhere in the Churchill and parts of the Nain and northeastern Grenville provinces, the Archean craton was variably downwarped, overlain by thick sedimentary and volcanic sequences, deformed and metamorphosed. In places, the Archean basement was remobilized during this deformation.

Granitoid plutonism was an integral component of the three major orogenic events (Fig. 2), but the abundance of granitoid plutons appears to decrease with decreasing age (Table 1); the Grenville Province may be an exception to this trend, but many of the plutons in the Grenville Province are preorogenic. There is also a positive correlation between the abundances of metavolcanic rocks and of granitoid plutons. For example, in the Superior Province, Archean granitoid plutons are most abundant in the greenstone-belt subprovinces (Fig. 4); in the Slave Province, where the ratio of metasedimentary to metavolcanic components is considerably higher than in the Superior Province, granitoid plutons are less abundant. In other provinces, Proterozoic granitoid plutons associated with the Hudsonian and Grenvillian orogenies are most abundant in association with volcanic and metavolcanic sequences of the Southeastern Zone and Rottenstone–Chipewyan subprovinces of the Churchill Province (Fig. 14), the Central Metasedimentary Belt Subprovince of the Grenville Province (Fig. 17), and the Great Bear batholith of the Bear Province (Fig. 16). All of the Proterozoic volcanic – granitoid terranes are characterized by relatively low metamorphic grade and the probable absence of earlier sialic crust. Proterozoic granitoid plutons are generally less abundant in the deformed Archean basement and the higher-grade deformed metamorphic sequences that overlie the basement, although again the Early Proterozoic sequence of the Central Gneiss Belt of the Grenville Province (Fig. 17) is an exception. Remobilization of the basement resulted in emplacement of gneiss domes in some provinces.

The plutons span the complete spectrum of granitoid compositions and range in depth of emplacement from subvolcanic to catazonal, and in tectonic position from pretectonic to post-tectonic. However, some general conclusions can be drawn:

1) All volcanic sequences that include a calc-alkaline component contain subvolcanic granitoid plutons similar in composition to the volcanic sequence.

2) Syntectonic plutons are commonly composite and include early gneissic to foliated tonalite – granodiorite phases, and later foliated to massive, more leucocratic granodiorite – granite phases, but the actual sequence of emplacement in any one pluton is complex. Major ex-

ceptions to this generalization are the composite batholiths of the Hepburn Subprovince of the Bear Province, in which early granite was succeeded by later more mafic phases, and the immense Wathaman–Chipewyan batholith of the Rottenstone–Chipewyan Subprovince of the Churchill Province, which is apparently a single-phase pluton.

3) Most tonalitic plutons are associated with low-grade metamorphosed metavolcanic sequences; plutons intruded into intermediate- to high-grade paragneiss and reworked basement terranes are generally more potassic than those in greenstone-belt terranes.

4) In general, plutons associated with younger deformational events appear to be more potassic than those associated with older events, although plutons associated with metavolcanic sequences invariably have early tonalitic phases; the temporal increase in potassium correlates with decreasing abundance of metavolcanic rocks and increasing abundance of metasedimentary rocks.

5) The apparent temporal increase in potassium content of granitoid plutons may indicate that older paragneiss and granitoid crustal rocks through which the magmas moved to their present position contributed to the higher potassium content by contamination or anatexis.

6) Both trondhjemitic and calc-alkaline chemical trends are represented in the plutons, but trondhjemitic trends are most common in early syntectonic plutons associated with greenstone belts.

7) As regional metamorphic grade of the country rocks increases, the style of pluton emplacement changes, with catazonal plutons in higher-grade terranes and mesozonal and epizonal plutons in lower-grade terranes.

8) Many syntectonic, epizonal to mesozonal plutons were originally emplaced as a series of discrete magmatic pulses at some depth below their present level of exposure and were subsequently diapirically emplaced at their present structural level.

9) Plutons metamorphosed during superimposed intermediate- to high-grade metamorphism are commonly gneissic and recrystallized, and in places show evidence of cataclasis, metasomatism, isotopic re-equilibration and partial remelting. This deformation commonly resulted in remobilization of the plutons to form diapirs, gneiss domes and nappes; these structures have been best documented in the Churchill Province.

10) Post-tectonic plutons are rare except adjacent to younger structural provinces or tectonic zones or associated with post-orogenic volcanism. These plutons are potassic and, in places, peralkaline.

11) Emplacement of large granitoid batholiths is probably the major factor in crustal thickening, leading to the production of large, stable cratonic terranes. In the Canadian Shield, this was primarily a late Archean event. Thus the late Archean (2.55–2.75 Ga) was the major magma-producing epoch in the geological evolution of North America. The magma produced is represented by both extensive tholeiitic basaltic metavolcanic rocks of the greenstone belts and calc-alkaline granitoid plutons and was thus essentially bimodal (*cf.* Barker *et al.* 1981).

The origin of the granitoid plutons is controversial; several different mechanisms have been proposed including: 1) derivation of magma from the mantle by either fractionation of basaltic magma (Wilson *et al.* 1974) or by partial melting (single or multiple stage, wet or dry) processes with only minor subsequent fractionation (Birk 1979, Collerson & Bridgwater 1979, Drury 1979, Wooden 1978), 2) anatexis of sialic basement or paragneiss and intrusion at higher crustal levels (Clark *et al.* 1981, Drury 1979, Emslie 1978b, Jackson & Morgan 1978, Lewry & Sibbald 1980, St-Onge 1981), 3) anatexis of granulite-facies lower crust (Collerson & Fryer 1978), 4) *in situ* anatexis of paragneiss with only local remobilization (Bailes & McRitchie 1978), 5) diapiric remobilization of earlier granitoid units without extensive anatexis (Frith *et al.* 1977a, Lewry *et al.* 1978, Schwerdtner *et al.* 1979, Verpaelst *et al.* 1980), and 6) contamination of mantle-derived magmas by older crust (Wooden 1978). All of these processes appear to have operated at different places and different times, reflecting differences in lithologic, tectonic and thermal settings.

In areas of low metamorphic grade, such as in greenstone belts, Sr- and O-isotope and REE data suggest that most of the magma was probably derived from the mantle (*e.g.*, Birk 1979, Birk *et al.* 1979, Drury 1979, Green & Baadsgaard 1971, Longstaffe & Birk 1981), although late-tectonic potassic plutons may have been derived by anatexis of sedimentary rocks that had a short period of crustal residence (Drury 1979). In some plutons, such as the Preissac–Lacorne batholith (Abitibi Subprovince of the Superior Province), magmas from several sources are spatially associated (Card 1981): early tonalite – granodiorite was apparently derived from the mantle but late granite was derived from anatexis of metasedimentary rocks. Similar complexties can be expected in other Archean batholiths as well (*e.g.*, the Lac-du-Bonnet batholith in the English River Subprovince of southeastern Manitoba: Černý *et al.* 1981, Černý 1982a). In areas of higher metamorphic grade, crustal anatexis and remobilization are common processes. However, as pointed out by Collerson & Fryer (1978) and Birk *et al.* (1979), present isotope ratios and REE patterns may represent a combination of various magmatic and post-magmatic events. The problems are compounded in areas of more intense deformation and metamorphism. Consequently, interpretation of isotope and REE data must be done with caution, particularly if only limited data are available.

METALLOGENY

To date, only sparse mineral deposits have been documented in granitoid plutons of the Canadian Shield. These comprise porphyry copper and molybdenum deposits, non-porphyry copper and molybdenum occurrences, gold and silver deposits that are spatially (although not necessarily genetically) related to granitoid plutons, uranium- and thorium-bearing pegmatites and related granitoid rocks, lithium-, cesium-, beryllium-, tantalum- and rare-earth-element-bearing pegmatites, and rare deposits of other elements or types. Tin and tungsten mineralization are conspicuously absent, except subeconomic but widespread tin concentrations in rare-element pegmatites. Many pegmatites and granitoid plutons have been mined for feldspar and mica, or quarried for building stone, but we have excluded these and other industrial products from this discussion.

In this compilation we have attempted to include most published descriptions of mineral deposits in or associated with granitoid rocks where the description is sufficiently detailed to document a spatial or genetic relationship. The sources used to compile the distribution maps (Figs. 19, 22, 23, 28, 36 and 40) are too numerous to document individually, but many important deposits are discussed in the text.

COPPER–MOLYBDENUM–GOLD

Copper ± molybdenum ± gold mineralization occurs within or adjacent to many relatively small granitoid and syenitoid plutons in greenstone belts of the Canadian Shield (Fig. 19), but has been reported only rarely from large batholithic complexes and from small plutons emplaced in metasedimentary sequences or reworked basement. Consequently, this type of mineralization appears to be restricted largely to small Archean plutons of the Superior Province; a few mineralized plutons of Archean age occur also in the Slave Province and a few of Early Proterozoic age in the Southeastern Zone Subprovince of the Churchill Province (Fig. 19). Although high-grade zones have been mined from several deposits, most occurrences are subeconomic and poorly documented, particularly in remote areas. The paucity of reported occurrences from the Slave Province may reflect inaccessibility and the reconnaissance nature of the geological investigations rather than a low abundance. Similarly, although the lack of reported occurrences in metasedimentary sequences, large batholithic complexes and reworked basement probably reflects a true low abundance, these terranes have not been extensively prospected for this type of mineralization.

The apparent concentration of occurrences in the southern part of the Superior Province (Fig. 19) may reflect a number of factors including relative inaccessibility elsewhere and uneven prospecting activity, but is probably largely a function of the size of the greenstone belts. In the Slave and northern Superior provinces, the greenstone belts are commonly narrower and contain fewer internal plutons than those in the southern Superior Province.

Most of the mineralized plutons are subvolcanic to epizonal tonalite (including trondhjemite) and granodiorite, and include simple to composite dykes and dyke swarms, sill complexes, stocks and small batholiths. Texturally they range from medium-grained equigranular to porphyritic with aphanitic to medium-grained groundmasses; phenocrysts are medium- to coarse-grained and comprise one or more of quartz, plagioclase, K-feldspar, biotite and hornblende. Pegmatitic and primary potassic phases are rare. Mineralized plutons are most common in the larger greenstone belts associated with, or stratigraphically below, calc-alkaline, felsic to intermediate metavolcanic sequences. Many syngenetic Cu–Zn–Ag deposits are spatially associated with mineralized or unmineralized, commonly sill-like granitoid plutons that occur near the base of the volcanic cycle that hosts the deposits (Franklin & Thorpe 1982). Many plutons have been metamorphosed to the same grade as adjacent units, but the intensity of penetrative deformation is generally somewhat lower, reflecting the originally more massive nature of many plutons.

Some of the mineralized plutons have attributes of porphyry deposits (Table 3) but most

TABLE 3. CHARACTERISTICS OF THE BETTER-DOCUMENTED PORPHYRY COPPER AND MOLYBDENUM OCCURRENCES IN THE CANADIAN SHIELD

							Nature of Deposit				
Number on Figure 19	Name	Age	Nature of pluton	Granitoid rock type(s)	Mineralization	Habit of mineralization	Size	Grade	Alteration	Reference	Remarks
SUPERIOR PROVINCE											
7	Jogran	1070±30 Ma	plug 200x120 m	gnd-gr; (fg-mg porphyry)	cp,bn, mo, py	diss; in qtz-chl-bi veins; in qtz-cc veins	surface dimensions 200x120 m	0.19% Cu 0.05% MoS_2	upper zone - qtz-ser-alb; lower zone - ep-cc-chl (propylitic); qtz-Kspar adjacent to some fractures	Blecha (1974), Armbrust (1980)	small size but typical porphyry mineralization and low intensity alteration; plug intruded Archean metavolcanic rocks but related to adjacent Southern Province
8	Tribag breccias	1055±35 Ma	3 breccia pipes with underlying massive plugs	felsite and porphyry with aphanitic gm (composition not specified)	cp,py, sp, gn	in qtz-cc-dol matrix of breccia; dissem cp in wallrock; mo in qtz veins in wallrock	surface area ranges from $3.7x10^4$-$17.5x10^4$ m^2. Depth > 750 m	0.1-0.2% Cu; 0.03-0.05% MoS_2, 1.35 ppm Ag; > $150x10^6$ tonnes	chl-cc-dol-ser-qtz-clay	Blecha (1974), Franklin & Thorpe (1982)	breccia consists of varied amounts of angular fragments of country rocks, felsite, and porphyry with <5-15% qtz-cc-dol matrix; altered porphyry plug found at depth below one breccia; mineralization occurs in 3 of 5 known breccia pipes in Archean granitoid batholiths and metavolcanic rocks; high grade sections previously mined; related to adjacent Southern Province
3	Oxford Lake	Archean	marginal phase of batholith	ton (plag & qtz phenos in fg gm)	py,cp, mo	in chl filled fractures	?	0.15-0.25% Cu; minor Mo	ep-chl-py	Elbers (1976), Haskins & Stephenson (1974)	several occurrences; cp mineralization also occurs in qtz-dol veins, breccia zones, and diss in nearby felsic metavolcanic units
4	Setting Net Lake	2643 Ma	stock; 5.7 km^2 late tectonic	single phase gnd-gr (Kspar phenos in fg-mg gm)	mo,cp, py	in qtz veins and locally diss	1 km^2	0.06% MoS_2 minor Cu	alb-chl-ser-ep-py-cc; alteration intensity decreases away from mineralized zone; mainly propylitic with incipient phyllic and rare potassic in mineralized zone	Ayres et al. (1982)	one major and several minor vein sets controlled by fractures
5	Lang Lake	Archean	sill complex 100^+ m thick	ton (plag, qtz, & mafic phenos in fg gm)	cp,py, mo,po	in qtz-cc-ser-ep-chl veins & locally diss	850 m x 100 m	0.4% Cu, minor Mo, Ag	ep-ser-py-cc-alb-qtz-Kspar-bi; metamorphosed alteration assemblage	Findlay & Ayres (1977), Findlay (1980)	minealization occurs both in sill complex (unit of sheeted sills produced by gradual expansion of magma chamber) and in overlying metavolcanic-metasedimentary sequence; distribution of mineralization in part controlled by discordant fracture zone
6	Beidelman Bay	$2733.8^{+1.4}_{-1.3}$ Ma	sill-like lens, 2.4 km thick & 19 km long	ton with more mafic rim; rare gnd (mainly mg and equigranular; local porph phase with fg gm)	cp,po, sp	in qtz veins and microfractures	0.3km^2 (higher grade areas)	0.06% Cu (0.15% Cu in 3000 m^2 areas); 0.03% MoS_2	ser-chl with bi-qtz adjacent to cp veinlets	Franklin (1978a), Friske et al. (1979), Poulsen & Franklin (1981), Davis & Trowell (1982)	three zones of cp mineralization occur within a 2.7x0.6 km zone of anomalous Cu surrounded by a broad zone of anomalous Zn (75ppm). Au occurs elsewhere in pluton, both diss and in qtz-tour-ank-py veins
9	McIntyre	Archean	concordant, somewhat irregular lens 1.8 km long	gnd-gr (qtz & alb megacrysts in fg matrix	cp,py bn,mo, tet,Au	diss and in fractures	$9x10^6$ t $70x10^6$ t	0.8% Cu, 0.05% Mo, 1 ppm Au >0.1% Cu	zoned alteration superimposed (?) on greenschist facies alteration: inner grey alb-qtz (ser-carb-py); intermediate pink alb-qtz (anh-hem); outer qtz-ser-alb-ank	Griffis (1962, 1979), Pyke & Middleton (1970), Davis & Luhta (1978, 1979)	controversial genesis; host rock interpreted variously as subvolcanic pluton (Griffis, Pyke & Middleton) or as an altered felsic metavolcanic unit (Davies & Luhta); Au-qtz-carb veins occur in mafic metavolcanics immediately north of felsic unit

TABLE 3. (Continued)

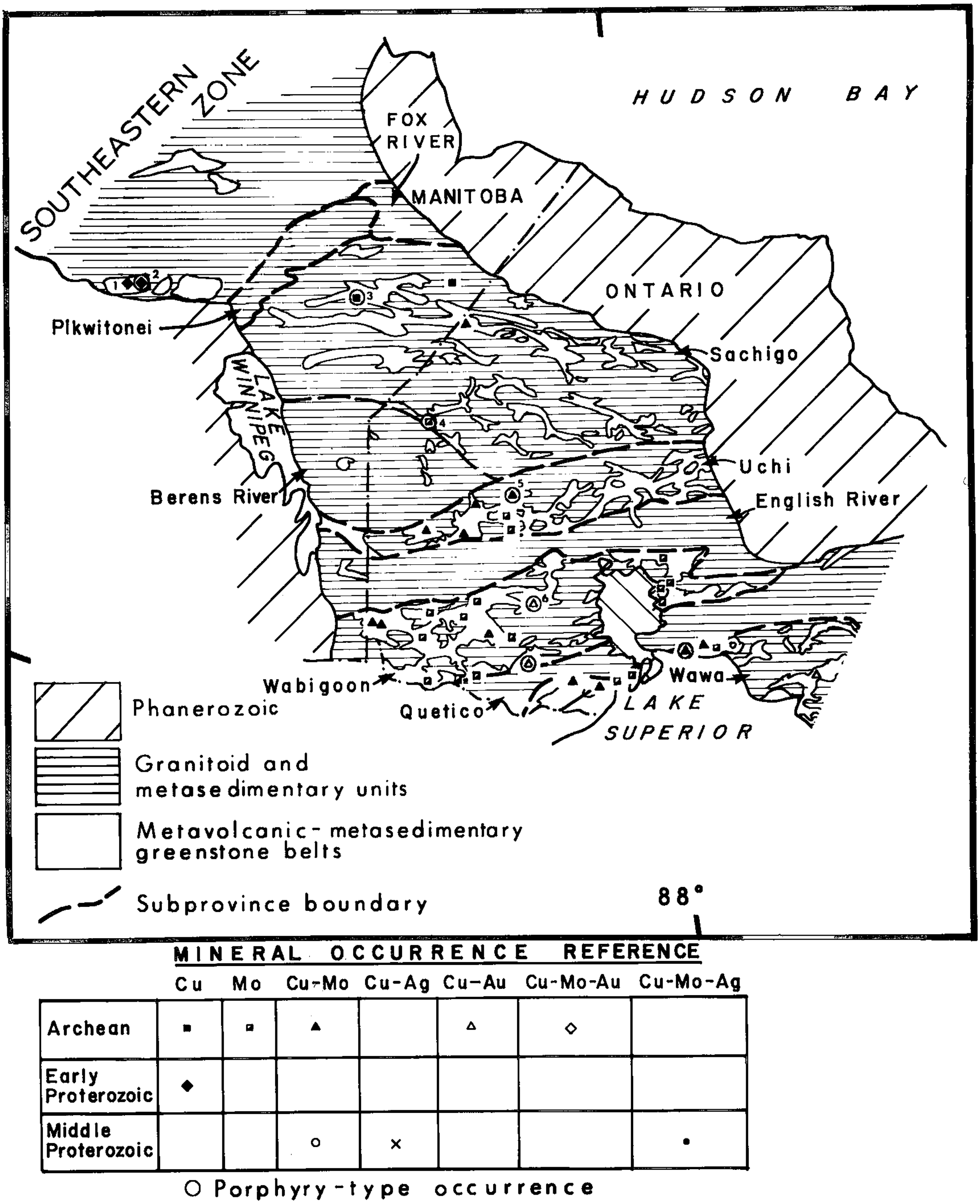
10	Matachewan	Archean	zoned stock (8 km diameter) & associated plugs & dikes	sy & qtz sy	cp,mo, py,bn	diss; in qtz vein stockworks of several ages; and in fractures	varied; up to 1 km^2 area	0.1-0.5% Cu, 0.17-0.34 ppm Au, 0.69-1.72 ppm Ag; Mo generally minor, but locally dominant metal	qtz-chl-hem (propylitic); Kspar-hem-bi-mag (potassic) adjacent to veins	Sinclair (1979, 1982)	non-granitoid host but included for comparison; at least 6 areas of mineralization are present in plutons and adjacent country rocks; Au-Ag-py deposits occur nearby and some have been classified as porphyry Au deposits; high grade zones have been mined
11	Don Rouyn	2.7 Ga	stock 9 km x 3 km	ton and minor gnd (mg & equi); late porph dikes with fg gm	py,cp, bn,mo	diss; in fractures, & in qtz-ank-cc veins	zoned; inner bn-cp-py zone 20 m diameter; middle cp-py zone 70 m diameter; outer py zone	inner zone >0.25% Cu middle zone 0.1-0.25% Cu rare Mo	except for hem in outer zone, no alteration observed; possibly masked by superimposed metamorphism	Goldie <u>et al.</u> (1979)	mined at rate of 1.45 x 10^{5}t as a source of siliceous flux for copper smelter; most mineralization predates late felsite phases, but veins may represent remobilization during subsequent deformation & greenschist facies metamorphism
12	Chibougamau	Archean	Chibougamau batholith (450 km^2) and associated stocks and dikes	ton-diorite-gnd-gr composite, zoned pluton; most mineralization is associated with porph dikes (fg gm) of several ages and breccia zones; some dikes are intermineral	py,cp, mag, hem, mo	diss in qtz-rich breccia matrix; in open stockwork of ep-cc-qtz veins cutting breccia; & in later qtz-ep-chl-cc filled fractures	variable size but up to several km^2	0.05-0.1% Cu; high grade zones contain up to 9x10^5 t of 2.45% Cu; minor Mo	Kspar replacing plag; ser-ep-bi in fractures; tour in matrix; hem in feldspar; chl-carb-ep-ser-mag replacing mafic minerals; secondary qtz decreases in abundance outwards	Kirkham (1972a), Gobeil & Cimon (1979), Kavanaugh (1979), Bureau <u>et al.</u> (1979), Cimon (1979b)	several occurrences in batholith, satellitic plutons, & locally in country rocks.
CHURCHILL PROVINCE											
1	Missi Island	Early Proterozoic	several sill complexes up to 500 m thick	ton-gnd-gr (porph with fg gm)	py,cp, mo	diss & in fractures	Cu occurs in 3 distinct zones over large areas	unknown	qtz-ser-carb-ep-chl-hem	Chute & Ayres (1977), Chute, (in prep)	mineralization occurs in sill complex composed of 100%, 1 cm-20 m thick sills and dikes that were emplaced during alteration; younger intrusions are less altered than older intrusions
2	Whitefish Lake	Early Proterozoic	stock 2900 m x 600 m	qtz md (plag & hblde phenos in fg gm)	py,cp, mo	in fractures & in Kspar-qtz-chl veins	3 zones up to 750 m long & 200 m wide	0.01-0.05% Cu, minor Mo	ep-chl-ser-carb-qtz-Kspar; propylitic & local potassic alteration	Baldwin (1980)	

<u>Abbreviations</u>. Rock Types: gnd granodiorite, gr granite, md monzodiorite, sy syenite, ton tonalite; Textures: fg fine-grained, mg medium-grained, porph porphyritic, phenos phenocrysts, gm groundmass, diss disseminated; Minerals: bn bornite, cp chalcopyrite, gn galena, hem hematite, mag magnetite, mo molybdenite, po pyrrhotite, py pyrite, sp sphalerite, tet tetrahedrite, alb albite, anh anhydrite, ank ankerite, bi biotite, carb carbonate minerals, cc calcite, chl chlorite, dol dolomite, ep epidote, hblde hornblende, Kspar potassic feldspar, plag plagioclase, qtz quartz, ser sericite, tour tourmaline; Others: ppm parts per million (= grams/tonne), t tonne.

plutons simply contain localized chalcopyrite–pyrite–gold–molybdenite occurrences in fault-, fracture- or breccia-controlled veins, stockworks or disseminations. For example, in the central Superior Province of Ontario, about 100 mineralized plutons were examined by Colvine & Sutherland (1979a). Of these, 60% have some attributes of Phanerozoic porphyry deposits, 20% resemble porphyry deposits in several aspects, but only one deposit closely resembles Phanerozoic deposits (Colvine & Marmont 1981).

Porphyry-type deposits

In spite of uncertainties in classification and the fact that some workers do not recognize the existence of porphyry-type mineral deposits in the Canadian Shield, many Precambrian deposits with porphyry affinities are now known or postulated. Many of these are still poorly documented, particularly as to the nature and distribution of the mineralization and alteration. Since these are essential parameters for most definitions of porphyry deposits, many Precambrian occurrences cannot be readily classified. Accordingly we have used the less precise definition of Kirkham (1972b), which emphasizes large size, low- to medium-grade, structurally controlled hypogene sulfide mineralization, and a spatial and genetic association with felsic to



MINERAL OCCURRENCE REFERENCE

	Cu	Mo	Cu-Mo	Cu-Ag	Cu-Au	Cu-Mo-Au	Cu-Mo-Ag
Archean	■	▫	▲		△	◇	
Early Proterozoic	◆						
Middle Proterozoic			○	×			•

○ Porphyry-type occurrence

intermediate porphyritic plutons, rather than zonal distribution of sulfide minerals and alteration (Lowell & Guilbert 1970). Using these definitions, we have tabulated the major characteristics of the better documented Precambrian copper and molybdenum occurrences with porphyry affinities (Table 3). A somewhat similar tabulation is given by Franklin & Thorpe (1982, Table 6).

Even in the best-documented occurrences, al-

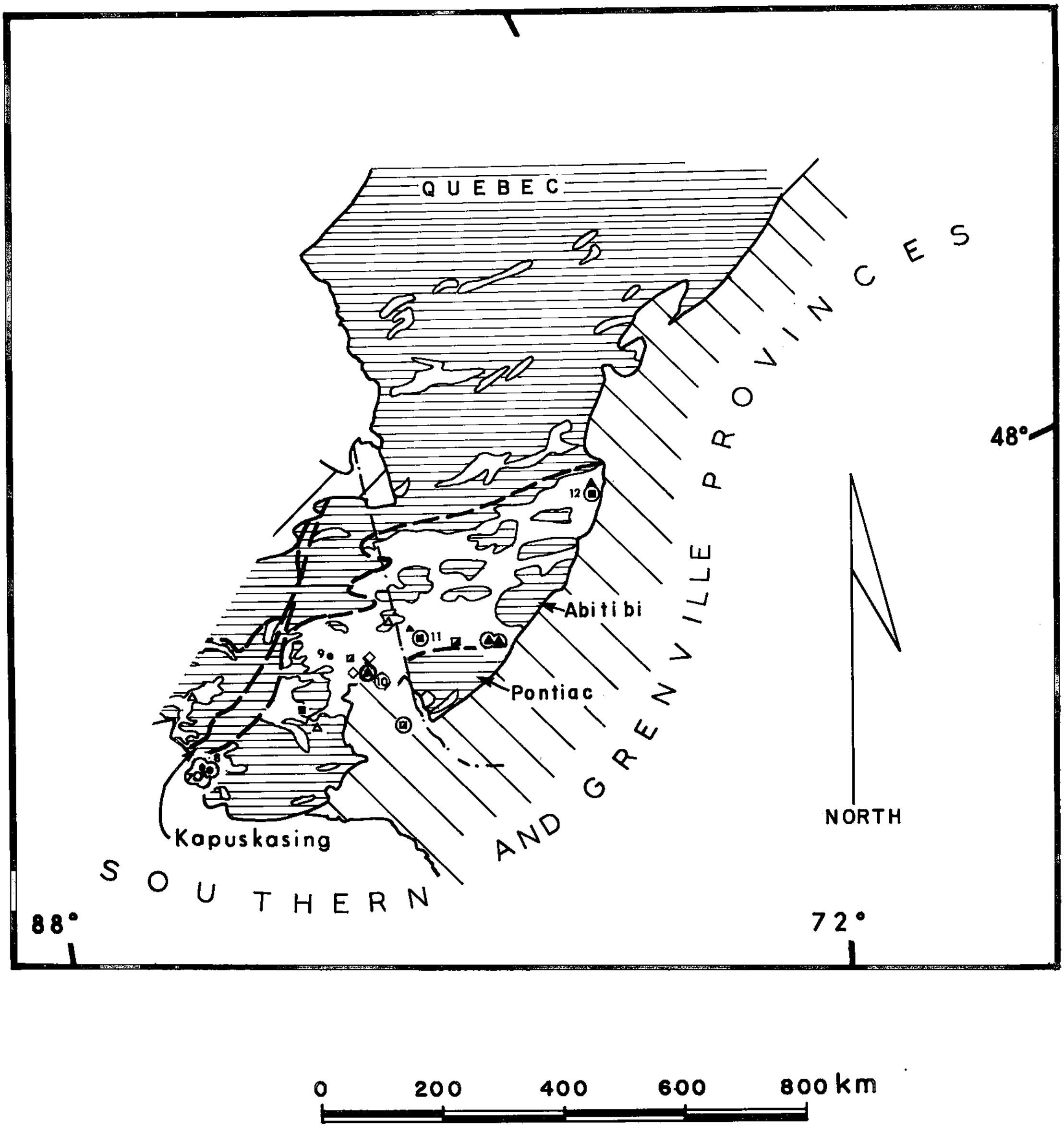


FIG. 19. Distribution of granitoid plutons that contain copper, molybdenum and gold mineralization within the Superior and part of the Churchill provinces. Numbered occurrences refer to Table 3.

teration and sulfide mineral zoning are difficult to evaluate. In part this reflects the superimposed metamorphism and deformation that have affected many occurrences (Kirkham 1972a). Metamorphism has commonly converted the original alteration-mineral assemblages to metamorphic assemblages. Alteration can still be recognized by increasing abundances of metamorphic minerals, but 1) the alteration cannot be compared directly to that in younger, unmetamorphosed deposits, and 2) any original zonal variations defined by relative abundances of specific species of minerals, such as kaolinite or sericite, will have been converted into a simple abundance zoning of metamorphic minerals, in this case sericite. Deformation may have caused regional tilting of the pluton and its contained mineralization and alteration. In many greenstone belts, isoclinal folding produced subvertically dipping stratigraphic sequences, and if the pluton was emplaced prior to deformation it would have been tilted along with the country rocks (*e.g.*, Elbers 1976). Thus the present outcrop surface would represent a near-vertical cross-section through the deposit, and any present pattern of horizontal zoning would represent an original vertical zoning. In places, penetrative deformation has destroyed original textures or caused remobilization of sulfide and gangue minerals.

With the possible exception of the McIntyre mine (now Schumacher Division of Pamour Porcupine Mines Limited; No. 9 on Fig. 19, Table 3), the porphyry-type deposits identified to date are all subeconomic, and many are of relatively small size compared to commercial Phanerozoic deposits. In the McIntyre deposit, copper is currently being mined from steeply plunging ore-shoots within a concordant, fine-grained, strongly altered, schistose felsic unit that contains quartz and albite megacrysts (Davies & Luhta 1978). In addition to the ore shoots, which contain more than 0.8% copper plus minor molybdenum and gold, disseminated copper occurs throughout a large volume of the felsic unit. The origin of the felsic unit is controversial. Griffis (1962, 1979) and most other geologists (*e.g.*, Ferguson *et al.* 1968, Pyke & Middleton 1970) consider that the felsic unit is a deformed, subvolcanic porphyritic pluton. Pyke & Middleton (1970) have further interpreted the McIntyre to be a porphyry copper deposit; the zone being mined is a high-grade section within a large low-grade deposit. On the other hand, Davies & Luhta (1978, 1979), on the basis of detailed study, have proposed that the host rock is a felsic metavolcanic unit in which quartz and albite porphyroblasts developed during late-stage metasomatism. According to them, zoned alteration-assemblages and the megacrysts postdate penetrative deformation. Davies & Luhta (1978) concluded that, although alteration and mineralization are somewhat analogous to those in porphyry deposits, the lack of intrusive rocks and the late-stage development of alteration preclude the possibility that the McIntyre is a porphyry deposit. Identical problems of host-rock identification have been encountered in other occurrences (Sutherland & Colvine 1979). This controversy illustrates the problems involved in dealing with metamorphosed and deformed deposits, particularly those in host rocks that have a fine-grained groundmass or matrix and poorly exposed or nebulous contact-relations.

In the Canadian Shield, there are two basic types of porphyry-type occurrences: 1) Middle Proterozoic, unmetamorphosed plutons that are genetically and temporally unrelated to Archean country rocks in which they occur, and 2) Archean and Early Proterozoic metamorphosed to unmetamorphosed plutons, many of which are genetically related to the host volcanic rocks. Middle Proterozoic porphyry-type occurrences have been reported only from the south-central Superior Province (No. 7, 8, Table 3, Fig. 19). These occurrences are close to exposures of Keweenawan volcanic rocks (Southern Province) of similar age, and the host plutons appear to be genetically related to Southern Province volcanism. One of these Middle Proterozoic occurrences, the Tribag deposits, from which high-grade sections were previously mined, appears to be the best example of breccia-pipe, porphyry deposits yet reported from the Canadian Shield (No. 7, Table 3; Blecha 1974). The Tribag breccias were emplaced at about 1.055 Ga into Archean granitoid and greenstone units. Middle Proterozoic deposits appear to have higher silver contents and to be in or associated with more potassic plutons than Archean and Early Proterozoic occurrences (Table 3). Although all known Middle Proterozoic deposits are restricted to a relatively small area (Fig. 19), small copper occurrences and breccia pipes have been found elsewhere in the Superior Province close to the Keweenawan volcanic sequence of the Southern Province.

Archean and Early Proterozoic plutons that host porphyry-type occurrences differ greatly in composition, texture, habit, size, and mode and depth of emplacement (Table 3). Most are tonalite or granodiorite (Table 3, 4) but granite occurs in more than 40% of the occurrences shown in Table 3; the granite varies from a minor to a widespread phase. The Matachewan occurrences (No. 10, Table 3, Fig. 19; Sinclair 1979, 1982) are associated with a zoned syenite – quartz syenite stock and small satellitic plutons. They are included here for comparison with occurrences in granitoid plutons and to indicate the wide range in composition of host plutons.

Most plutons are either single-phase but compositionally varied and locally zoned, or single-phase with relatively minor late dyke-phases and both cognate and country-rock xenoliths. Multiphase composite plutons are relatively rare; the best examples are the sill complexes (No. 1, 5, Table 3). These are sill-like plutons up to 500 m thick that are composed of 100% sheeted sills; individual sills range in thickness from 1 cm to 30 m (Chute & Ayres 1977,

TABLE 4. SELECTED CHEMICAL ANALYSES OF ARCHEAN GRANITOID PLUTONS HOSTING PORPHYRY COPPER-MOLYBDENUM OCCURRENCES IN THE SUPERIOR PROVINCE OF THE CANADIAN SHIELD

	1	2	3	4	5	6	7	8	9
SiO_2	72.25	74.10	73.40	75.20	75.73	74.6	69.30	67.40	70.10
Al_2O_3	15.49	14.76	14.35	13.48	12.40	12.4	14.70	14.60	14.00
TiO_2	0.28	0.14	0.20	0.09	0.29	0.25	0.21	0.11	0.13
Fe_2O_3	1.96^1	0.98^1	1.39^1	0.80^1	0.71			1.51	
FeO					1.93	3.83^2	1.90^2	1.18	2.35^2
MnO					0.05	0.06	0.07	0.07	
MgO	0.62	0.38	0.52	0.35	0.25	0.70	1.14	0.97	0.80
CaO	1.62	1.26	1.56	0.86	1.05	1.10	1.90	2.42	0.31
Na_2O	4.06	3.80	3.98	3.38	5.15	4.30	5.58	4.53	3.16
K_2O	3.38	4.25	3.23	4.67	1.25	0.56	1.87	2.66	5.12
P_2O_5	0.18	0.19	0.17	0.10	0.03	0.02		0.46	
CO_2	0.00	0.29	0.37	0.47	0.84	0.58		3.14	
H_2O	0.85	0.95	0.72	0.55	0.44	1.49	1.45	1.20	1.34
Cu (ppm)							7	24	72

[1] Total iron as Fe_2O_3

[2] Total iron as FeO

1-4 Setting Net Lake stock (No. 4, Table 3; after S.A. Averill, unpubl.). 1,2 Unmineralized part of pluton, No. 2 is from alteration in south part of stock (Fig. 20B). 3,4 Country rock between mineralized veins. Both samples have intense alteration of plagioclase. Some K metasomatism possibly occurred in Sample 4.

5-Beidelman Bay stock (No. 6, Table 3; after Franklin 1978a). Trace elements include Rb - 25 ppm, Sr - 110 ppm, Y- 53 ppm, Zr - 340 ppm, Nb - 23 ppm, Ba - 350 ppm.

6-Powell stock hosting Don Rouyn deposit (No. 11, Table 3; after Goldie et al. 1979). Mean of 3 samples collected within 1 km of mineralized zone.

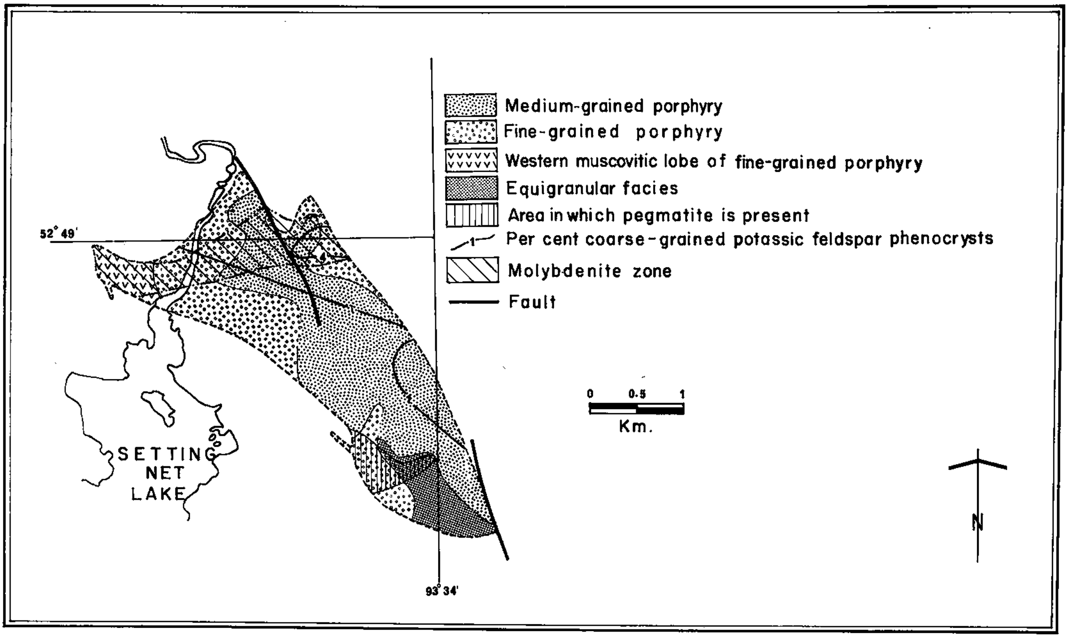
7-9 Chibougamau batholith (No. 12, Table 3; after Cimon 1976). 7-Tonalite away from mineralization. 8-Tonalite in mineralized zone; carbonate-sericite-epidote alteration. Trace elements include Zn - 15 ppm, Pb - 10 ppm, Ag - 0.6 ppm, S - 0.03%. 9-Tonalite in mineralized zone; potassic alteration.

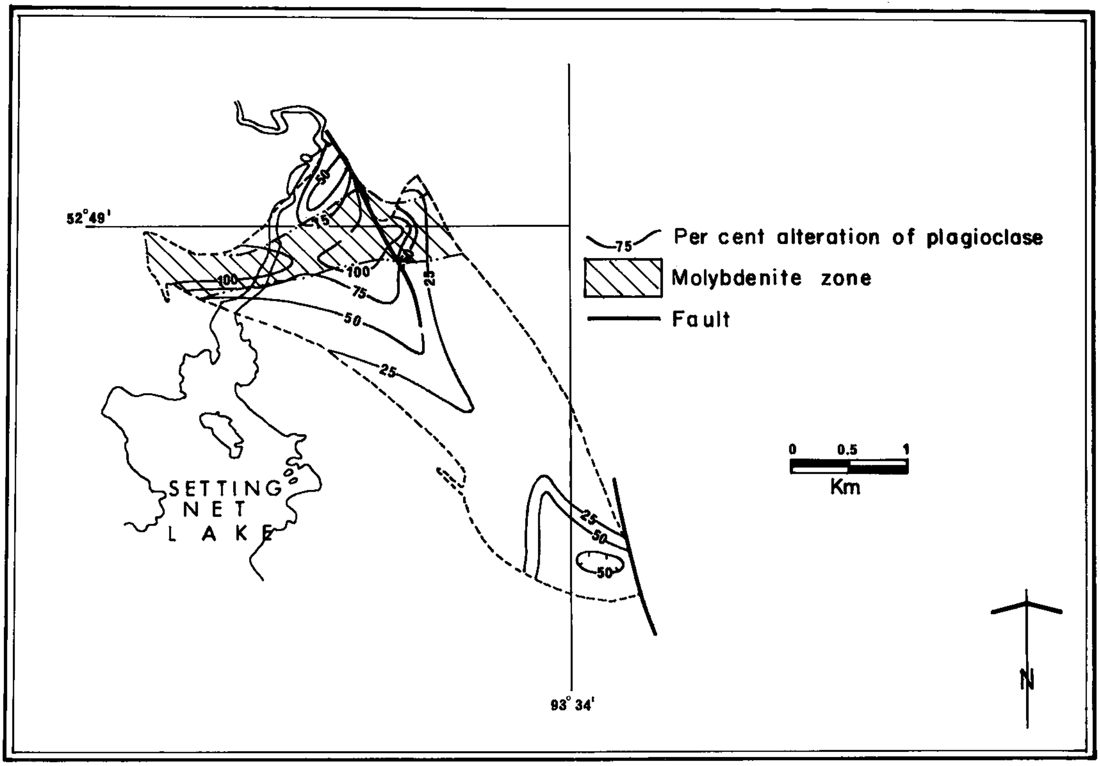
Findlay & Ayres 1977).

Plutons are generally subvolcanic or epizonal. Subvolcanic plutons form plugs, small stocks and sill complexes that have a ubiquitous porphyritic texture with an aphanitic to fine-grained groundmass. Epizonal plutons form larger stocks and small batholiths, many of which are crudely concordant, that range in age from synvolcanic to locally late-tectonic. Many of the epizonal plutons are more sparsely porphyritic than the subvolcanic plutons and have a fine- to medium-grained groundmass; some are equigranular (No. 6, 11, 12 and part of No. 4, Table 3; Fig. 20A). At Beidelman Bay, deformation of medium-grained equigranular trondhjemite locally has produced a pseudoporphyritic unit with quartz augen in a fine-grained cataclastic matrix (Franklin 1978a). The equigranular plutons do not rigorously fit the definition of porphyry deposits used herein (Kirkham 1972b), but late porphyritic dyke phases are present in all equigranular plutons. In the Chibougamau occurrences (No. 12, Table 3), the late porphyritic dykes are spatially associated with mineralization and some are intermineral, *i.e.*, they were intruded after early stages of mineralization but before the late stages (Cimon 1979b, Kirkham 1972a). In the late-tectonic Setting Net Lake pluton (No. 4, Table 3; Fig. 20A), marked textural zoning reflects uneven cooling of the pluton.

Although most mineralized plutons are small and within greenstone belts, several occurrences are found in or adjacent to the margins of large batholithic complexes (Elbers 1976, Wilkinson 1979). In some of these occurrences, such as those at Oxford Lake (No. 3, Table 3), the fine-grained groundmass of the granitoid host indicates that these are epizonal plutons rather than the more normal mesozonal batholithic complexes. Elbers (1976) has proposed that at Oxford Lake, the occurrence of an outward transition from subvolcanic porphyritic dykes in the greenstone belt through epizonal margins of the batholith to mesozonal interiors represents a tilted crustal section through a comagmatic volcanic-tectonic system.

Mineralization is simple and consists mainly of pyrite, chalcopyrite, bornite, molybdenite and, locally, gold. It is generally fracture-controlled, with sulfide minerals occurring either in one or more sets of relatively planar, dilational fractures or in more irregular and diversely oriented fractures, producing stockworks. In many occurrences, the sulfides are associated with quartz and carbonate veinlets that are generally less than 1 cm thick and that locally contain tungsten minerals and fluorite; some fractures have coatings of alteration minerals such as epidote, chlorite or sericite. Disseminated sulfides are present also in most occurrences. Zoning of sulfide minerals has been reported only rarely (Goldie *et al.* 1979). Although small breccia-zones are present at


52° 49'
93° 34'
Medium-grained porphyry
Fine-grained porphyry
Western muscovitic lobe of fine-grained porphyry
Equigranular facies
Area in which pegmatite is present
Per cent coarse-grained potassic feldspar phenocrysts
Molybdenite zone
Fault
0 0.5 1
Km.
N
SETTING NET LAKE


52° 49'
93° 34'
Per cent alteration of plagioclase
Molybdenite zone
Fault
0 0.5 1
Km
N
SETTING NET LAKE
50
75
100
100
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25
25
25
50
50

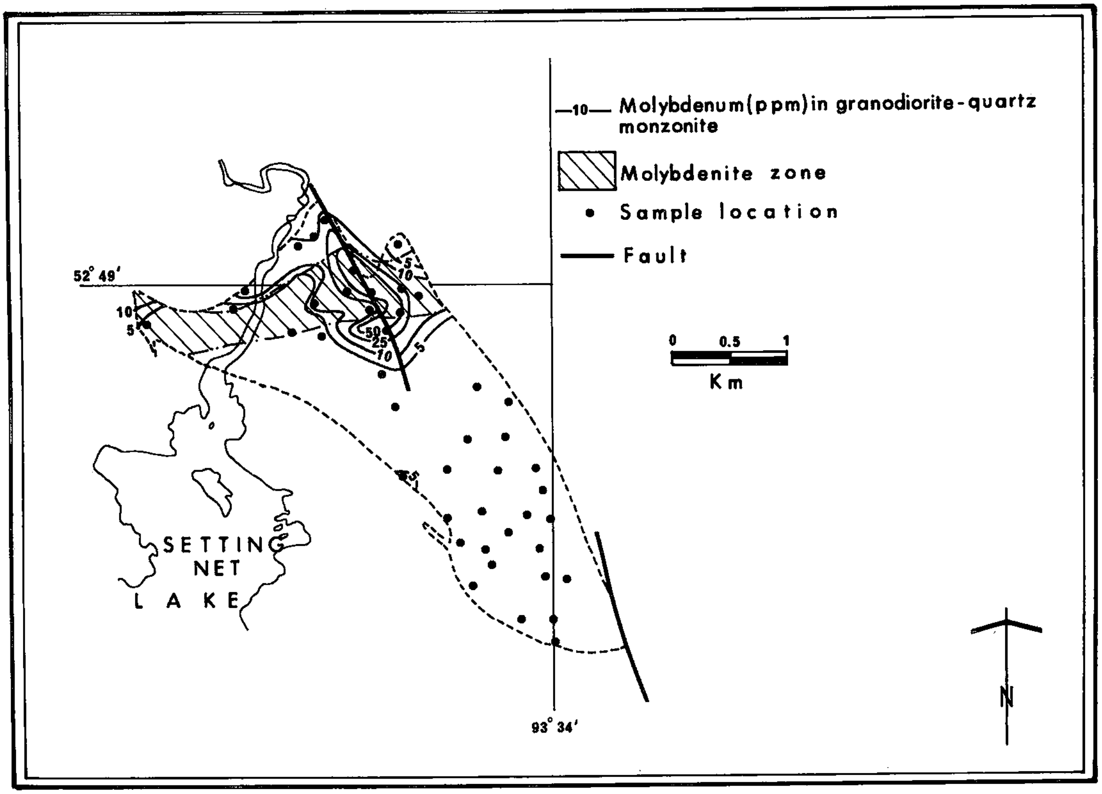


FIG. 20. Some attributes of the Archean Setting Net Lake porphyry-molybdenum occurrence (No. 4, Table 3). A. Textural variations (after Ayres *et al.* 1982). Fine-grained porphyry is distinguished by the presence of sparse, coarse-grained K-feldspar phenocrysts and abundant medium-grained quartz, plagioclase, K-feldspar and biotite phenocrysts in an aphanitic to fine-grained groundmass. With increase in grain size of the groundmass, this grades gradually into medium-grained porphyry. This phase still contains the coarse-grained K-feldspar phenocrysts, but the groundmass has the same grain-size as, and is composed largely of, the medium-grained phenocrysts of the margin. B. Distribution of alteration as measured by intensity of alteration of plagioclase (after Ayres *et al.* 1982). The original oligoclase has been replaced by albite and sericite plus minor carbonate and epidote. There is no change in alteration assemblages across the alteration zone; the only change is in intensity of alteration. Comparable trends are found for replacement of biotite by chlorite and muscovite, replacement of sphene by ilmenite, and increase in abundance of pyrite. C. Distribution of molybdenum (after Wolfe 1974). Samples from the mineralized zone were selected to avoid contamination by sulfide-bearing veinlets.

many occurrences, large breccia-zones have been described only from the Chibougamau occurrences (No. 12, Table 3). Only minor mineralization occurs in the breccia matrix; most mineralization is present in several generations of fractures that cut the breccia (Cimon 1979b). At Beidelman Bay (No. 6, Table 3), mineralization is best developed in areas of abundant metavolcanic xenoliths (Poulsen & Franklin 1981); irregular breccia zones occur locally in the xenolith-rich areas; in contrast to breccia zones in the Chibougamau occurrences, mineralization is confined to the breccia matrix.

Most occurrences contain both copper and molybdenum, but, of the occurrences listed in Table 3, copper is the dominant metal in all except that at Setting Net Lake (No. 4, Table 3). However, molybdenum predominates in some of the more poorly documented occurrences (Fig. 19; Colvine & Marmont 1981, Colvine & Sutherland 1979b). Colvine & Sutherland (1979b) have postulated that molybdenum is more abundant in deeper-seated plutons than in high-level plutons. Gold is present in variable amounts but analyses for gold are not available for all occurrences. In many porphyry occurrences, the zone of dispersed mineralization in Cu or Mo (or both) grades outward into a zone containing discrete gold-bearing veins (Franklin & Thorpe 1982, Kirkham & Thorpe 1973). Considering the current high price of gold, mineralized plutons should be re-examined for low-grade porphyry-gold potential (Friske *et al.* 1979). At Matachewan (No. 10, Fig. 19), both porphyry copper–molybdenum–gold and copper-poor porphyry-gold deposits are present in a single plutonic complex (Sinclair 1982).

Most mineralized zones described to date are relatively small, but many have not been completely delineated. All are currently subeconomic as porphyry deposits, although high-grade zones have been mined or are currently being explored (Table 3).

As exemplified by the Setting Net Lake pluton (Fig. 20B), all occurrences have widespread alteration that decreases in intensity away from the mineralized zone. In most occurrences, alteration is poorly documented and cannot always be distinguished from normal metamorphic effects. Furthermore, some unmineralized metamorphosed plutons show alteration patterns similar to those associated with mineralization (Baldwin 1980). Alteration comprises uniform replacement of primary minerals, more intense replacement adjacent to fractures and deposition of minerals in fractures that are both sulfide-bearing and sulfide-free. The common alteration minerals are sericite, albite, epidote, pyrite, carbonate minerals, chlorite and quartz (Table 3). Hematite is locally developed, particularly in wall rock adjacent to fractures. Secondary biotite, potassium feldspar and muscovite have been reported from only a few Precambrian occurrences (Table 3). Thus potassium metasomatism, a characteristic feature of many Phanerozoic, ore-grade porphyry deposits, appears to be absent or poorly developed in most Precambrian occurrences. It is best documented in the Chibougamau batholith (Table 4, columns 7–9) and Matachewan deposits (Sinclair 1982).

Trace-metal contents of the host granitoid plutons have been examined at several of the porphyry occurrences. Copper and molybdenum are anomalous only in areas of observed sulfide mineralization (Table 5, Figs. 20C, 21; Friske *et al.* 1979, Sinclair 1982, Wolfe 1974). Elsewhere in the plutons, copper and molybdenum contents are identical to those in unmineralized plutons. Zinc content of the Setting Net Lake pluton (No. 4, Table 3) is identical (30 ppm) in both unmineralized and mineralized parts of the pluton (Wolfe 1974), but at Beidelman Bay (No. 6, Table 3), there is a wide zinc-rich halo (75 ppm) surrounding the copper-rich zones (Friske *et al.* 1979). Thus, although extensive studies have not yet been made, plutons that contain mineralization do not seem to be geochemically anomalous except in the vicinity of the mineralization (Table 4); in the absence of visible mineralization, there is as yet no geochemical parameter that can be used to distinguish unmineralized from potentially mineralized plutons.

The genesis of mineralization and alteration in porphyry-type deposits is controversial. The lack of geochemical anomalies has led some authors (*e.g.*, Friske *et al.* 1979) to suggest that the source of the copper, molybdenum and hydrothermal fluids was the country rocks rather than the pluton. The pluton is simply an ap-

TABLE 5. COPPER AND MOLYBDENUM CONTENTS OF THREE GRANITIC AND ONE SYENITIC PLUTONS THAT CONTAIN PORPHYRY OCCURRENCES

Deposit	Rock type	Copper (ppm)		Molybdenum (ppm)		Reference
		Mineralized zone	Away from mineralized zone	Mineralized zone	Away from mineralized zone	
Setting Net Lake (No. 4) (Fig. 20C)	granodiorite and granite	61^1	8^2	26^1	1.7^2	Wolfe (1974)
Beidelman Bay (No. 6)	tonalite	600^3	12			Friske et al. (1979)
Whitefish Lake (No. 2) (Fig. 21)	quartz monzodiorite	234^4	17	8	3	Baldwin (1980)
Matachewan (No. 10)	syenite	835	47			Sinclair (1982)

[1] Mean of 25 samples collected in and adjacent to the mineralized zone in the north part of the stock (Fig. 20C). Samples selected to avoid contamination by mineralized veinlets.

[2] Mean of 25 samples collected from the unmineralized south half of the stock.

[3] Samples from main mineralized areas.

[4] Boundary between mineralized and non-mineralized areas arbitrarily placed at 50 ppm Cu.

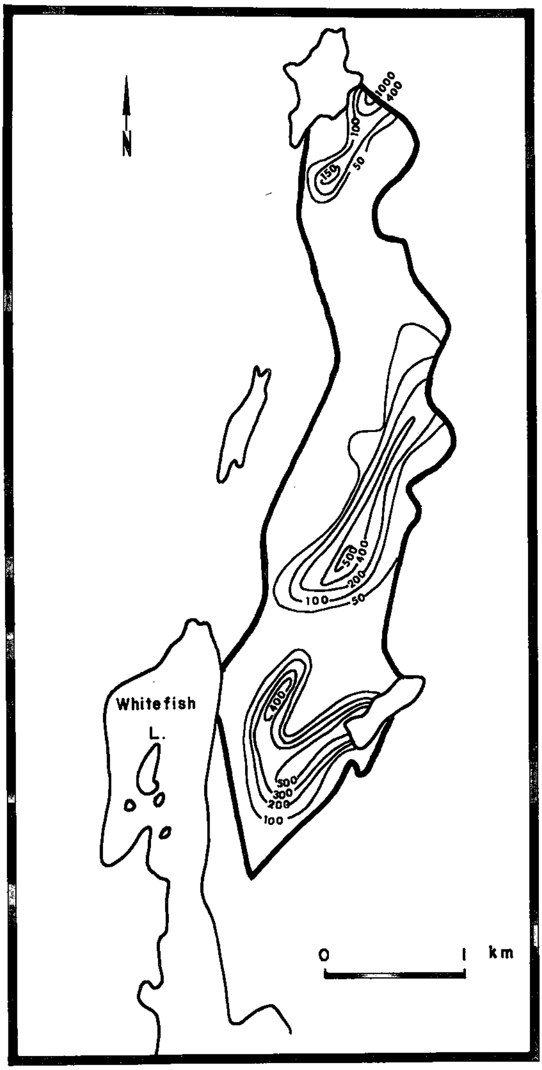


FIG. 21. Distribution of copper (ppm) in the Whitefish Lake pluton (No. 2, Table 3; after Baldwin 1980). Observed copper and molydenite mineralization occurs in areas of anomalous copper contents.

propriate structural host, a permeable pathway for fluids and a heat source to facilitate migration of fluids. In this regard, it should be noted that some mineralized sill-like porphyry plutons, such as that at Beidelman Bay (No. 6, Table 3), are stratigraphically below, but apparently genetically related to stratiform massive Cu–Zn–Ag ore deposits. The plutons were the heat engines generating ore-forming solutions that vented on the sea floor (Franklin & Thorpe 1982).

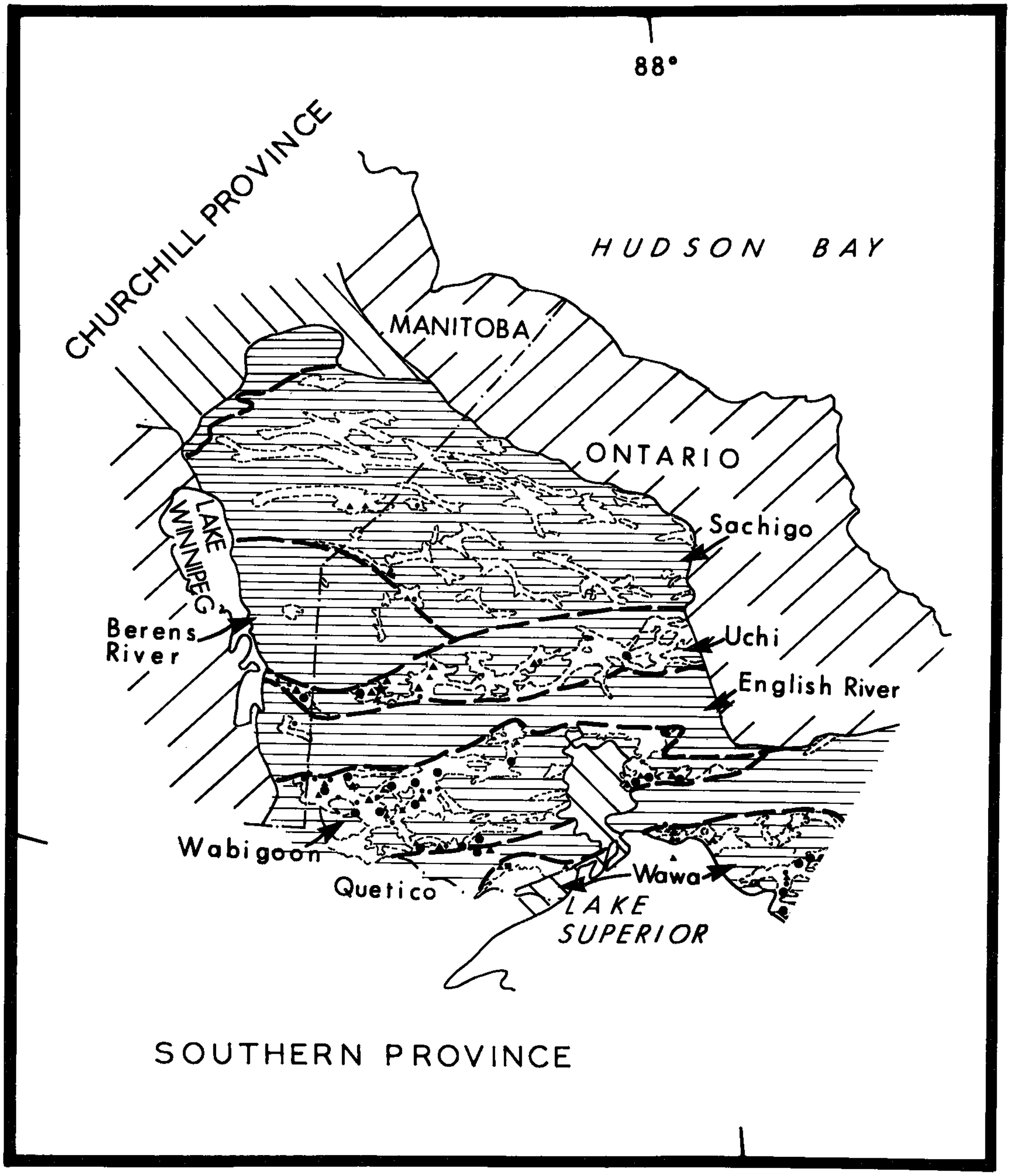
On the other hand, in many Phanerozoic porphyry deposits whose host plutons also lack anomalous Cu and Mo, except in and adjacent to mineralization (Olade & Fletcher 1976), the metals and much of the hydrothermal system appear to have been derived from the magma during crystallization (McMillan & Panteleyev 1980). The mineralization may have been later modified and possibly augmented by convective circulation of country-rock fluids driven by the heat of the pluton, but the major source of metals was the pluton. It has also been proposed that the hydrothermal fluids and metals originated in the same source-area as the magma, but moved to higher crustal levels independently of, and somewhat later than the magma (McMillan & Panteleyev 1980).

Other mineralized plutons

These plutons are distinguished from plutons hosting porphyry-type occurrences by the smaller size or more restricted nature of the mineralization, the less intense and more restricted alteration and, in places, the greater thickness of individual veins within vein systems. There are no apparent differences in composition, texture, habit, depth of emplacement or relationship to volcanism. Some of these mineral occurrences may represent insufficiently explored porphyry-type occurrences (Fig. 19).

Sulfide mineralization in these plutons occurs in several habits (Colvine & Sutherland 1979a, b, Colvine & McCarter 1977, Studemeister & Colvine 1978, Sutherland 1978, Sutherland & Colvine 1979). 1) Single or multiple quartz and, locally, quartz – carbonate veins, lenses, pods and irregular masses. Individual veins and pods are generally much wider (up to several metres) than veinlets in porphyry-type occurrences, and more restricted in extent. Many of the veins occur in faults or follow lithologic contacts rather than occupy simple dilational fractures as in porphyry occurrences. Vein boundaries range from sharp to diffuse. 2) Planar to irregular fractures, in part associated with narrow veinlets of quartz, or along the margins of pegmatite dykelets. These resemble porphyry-type occurrences but are of much more localized extent. 3) Disseminations. 4) Pegmatite dykes. This type of habit is restricted to molybdenum mineralization and will be mentioned under pegmatites (Table 8).

Mineralization in most plutons appears to have the same rather nebulous origin as porphyry-type occurrences. In other plutons, however, the mineralization can be related to re-



mobilization or assimilation of pre-pluton sulfide occurrences in country rocks (Studemeister & Colvine 1978, Sutherland & Colvine 1979).

Summary

Copper, molybdenum and gold mineralization of both porphyry and non-porphyry types is confined largely to small pretectonic or early-tectonic granitoid plutons that are genetically related to volcanism and that occur within greenstone belts, particularly those in the southern Superior Province; late-tectonic plutons that are unrelated to the host volcanic sequences appear to be mineralized only rarely. Mineralized plutons are generally tonalite – granodiorite, but they are apparently indistinguishable from unmineralized plutons of similar composition, texture, habit and tectonic position.

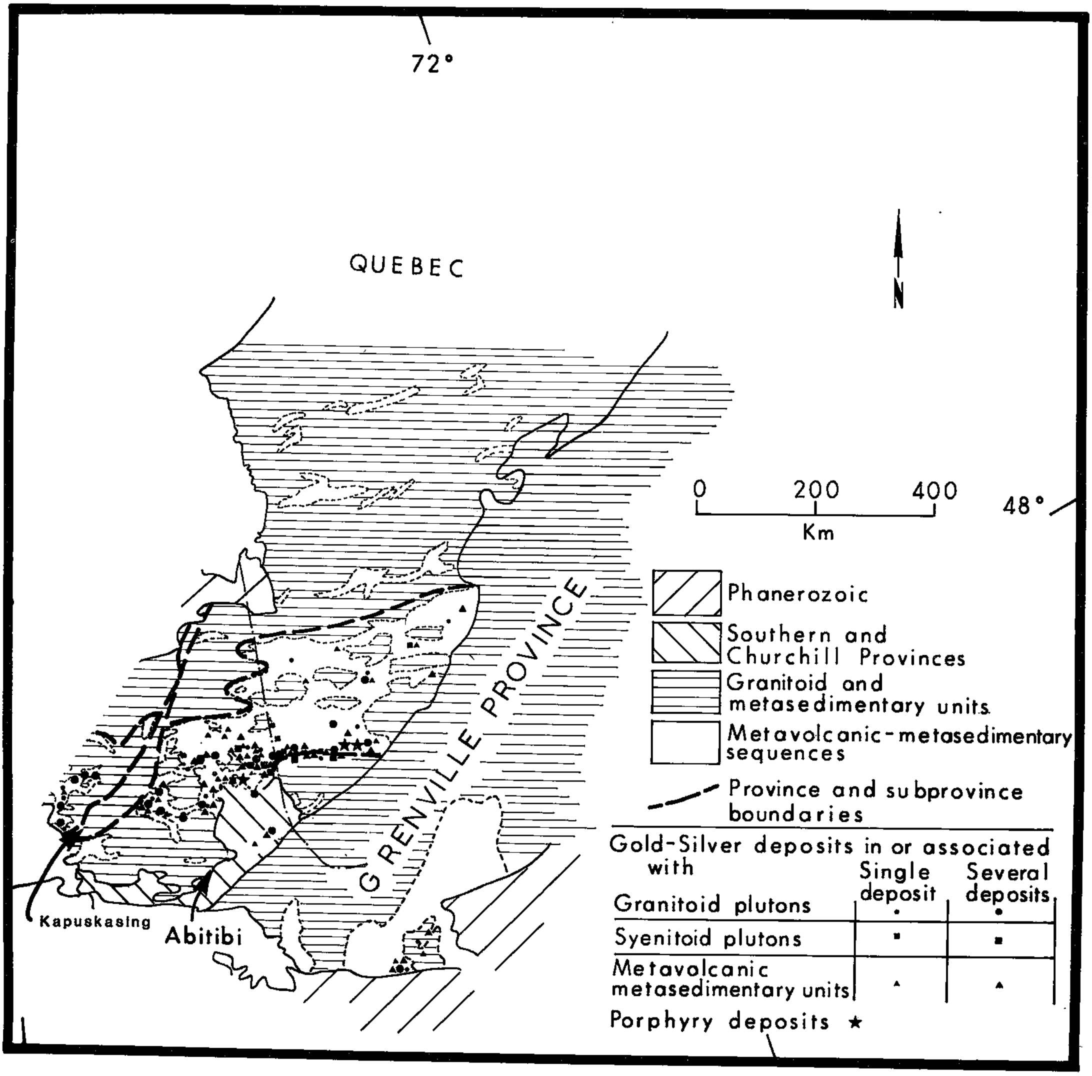


FIG. 22. Locations of major gold–silver deposits in the Superior and Grenville provinces of the Canadian Shield. These include producing mines, former producers and major prospects. Deposits in which the mineralization is completely or partly within granitoid and syenitoid plutons are distinguished from deposits in which it occurs in the metavolcanic–metasedimentary sequence. Possible porphyry-gold deposits after Franklin & Thorpe (1982).

Mineralization also occurs in late, post-tectonic granitoid plutons, but these are spatially and genetically related to nearby younger volcanism of overlapping structural provinces. Mineralization is apparently rare in the subvolcanic plutons of the Bear Province, although these plutons have not been extensively explored. Hoffman & Cecile (1974) considered that plutons in the Bear Province are unlikely hosts for porphyry deposits, although Badham & Morton (1976) have reported minor porphyry-copper-type mineralization.

The spatial and apparent temporal and genetic association of many mineralized plutons with volcanism suggests that 1) greenstone belts and older crustal terranes adjacent to younger volcanic sequences are the prime prospecting targets for additional discoveries, and 2) metals

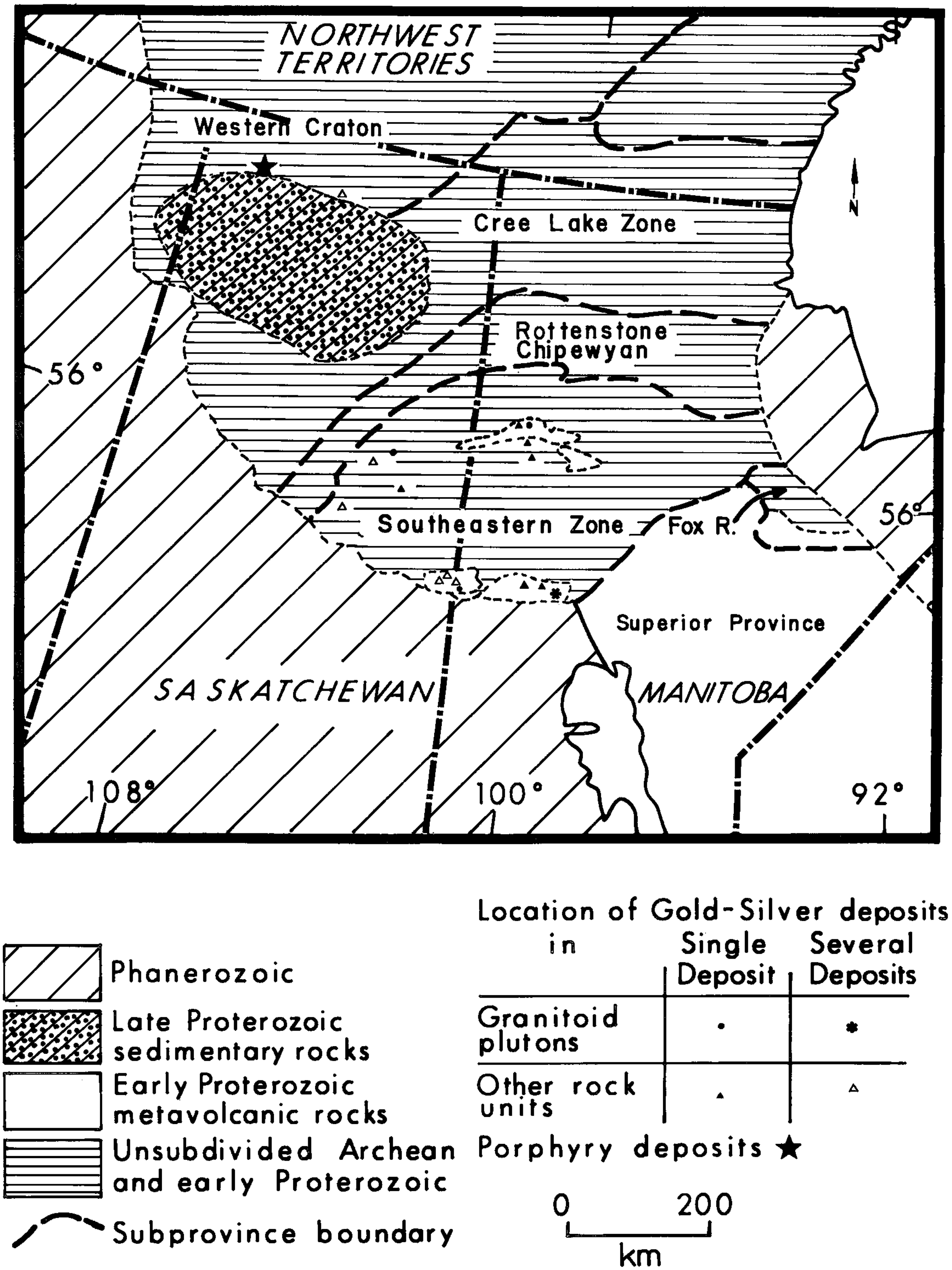


FIG. 23. Locations of major gold–silver deposits in the western Churchill Province of the Canadian Shield. Possible porphyry-gold deposits after Franklin & Thorpe (1982).

concentrated in the plutons may have been scavenged from the volcanic sequence rather than being concentrated by magmatic crystallization.

GOLD–SILVER

In addition to the copper–molybdenum–gold association just described, granitoid rocks also host gold–silver occurrences that lack (or contain only minor) copper; some have been classified as porphyry-gold deposits (Franklin & Thorpe 1982, Sinclair 1982). Gold-bearing plutons are relatively small, subvolcanic and epizonal dykes, sills, stocks or small batholiths of both granitoid and syenitoid compositions. Pluton-hosted gold occurrences are restricted almost entirely to greenstone-belt terranes in the Superior Province (Fig. 22). A few occurrences have been reported from the Southeastern Zone Subprovince of the Churchill Province (Fig. 23) and the Central Metasedimentary Zone Subprovince of the Grenville Province (Fig. 22), but these plutons are also associated with greenstone belts. Gold-bearing plutons are rare in the large granitoid batholithic complexes, paragneiss terranes, reworked basement, and sedimentary cover sequences. Numerous gold–silver deposits occur in the Slave Province, but except for a large deposit in a tonalite dyke near Indin Lake (Annis *et al.* 1976, p. 75), all of the major deposits are in metavolcanic–metasedimentary sequences and not directly associated with granitoid plutons. Scarce gold–silver deposits in the Southern and Bear provinces are also not associated with granitoid plutons. No gold deposits of any type have been reported from the Nain Province. Unlike the copper–molybdenum occurrences, many of the gold–silver deposits have been mined; only the mines and larger prospects are shown in Figures 22 and 23.

Both granitoid and syenitoid plutons host gold deposits (Fig. 22). Gold-bearing granitoid plutons are mainly tonalite (some of which is trondhjemite) and granodiorite with minor granite (Table 6; Boyle 1979, Riley *et al.* 1971, Whitmore 1970) and range from simple single-phase bodies to composite, locally zoned plutons, some of which have dioritic phases. Gold-bearing syenitoid plutons include diorite, monzodiorite, monzonite, syenite and quartz syenite and form either discrete plutons or phases of granitoid plutons. Syenitoid plutons associated with gold–silver mineralization are restricted largely to the Abitibi Subprovince of the Superior Province (Fig. 22), with the best examples being the various mines of the Kirkland Lake area (Ridler 1970, Thomson *et al.* 1950), the Matachewan area (Sinclair 1982), and some mines in the Val d'Or area (Latulippe & Germain 1979). Published chemical data on gold-bearing granitoid plutons, particularly trace-element data, are sparse. Consequently, only a few data have been given in Table 6 to show the compositional range and alteration effects. Plutons hosting gold deposits are slightly enriched in gold compared to plutons that lack gold deposits (Table 7, Kerrich *et al.* 1980, Wolfe 1975).

TABLE 6. SELECTED CHEMICAL ANALYSES OF ARCHEAN GRANITOID PLUTONS THAT ARE SPATIALLY ASSOCIATED WITH GOLD-SILVER DEPOSITS IN THE SUPERIOR PROVINCE OF THE CANADIAN SHIELD

	1	2	3	4	5	6	7	8
SiO_2	61.70	65.05	66.00	68.95	57.37	57.00	67.09	66.09
Al_2O_3	18.52	16.88	16.60	14.21	14.48	16.44	15.73	15.12
TiO_2	0.40	0.12	0.30	0.18			0.44	0.43
Fe_2O_3	1.36	1.58	0.80	0.60	1.58	0.86	4.08	4.93
FeO	2.40	2.20	1.88	1.08	8.98	6.33		
MnO	0.02	0.02		0.02			0.04	0.07
MgO	1.63	2.06	1.80	1.17	1.96	1.73	1.46	1.46
CaO	2.19	4.63	2.40	2.50	3.49	5.36	3.02	2.08
Na_2O	4.10	4.35	3.80	3.88	7.13	6.40	5.31	4.51
K_2O	3.36	1.19	4.72	2.06	0.32	0.90	0.63	1.29
P_2O_5	0.14	0.12		0.08	0.03	0.08	0.06	0.06
CO_2	1.47	0.21	0.00	4.21	4.52	4.76	2.32	3.91
H_2O	2.31	1.34	0.72	0.80				
S	0.44	0.00			0.14	0.23	0.04	0.14
Ni	50	59						
Cu	49	32						
Co	26	32					33	28
Zn	280	68					26	37
Pb	150	101					9	9
Rb	125	37					14	28

1,2-Tonalite stock, Rice Lake-Beresford Lake greenstone belt, Manitoba (Uchi subprovince), containing gold-quartz veins (analyses 269-2 and 269-17 of Stephenson 1971). Sample 1 occurs adjacent to vein and is strongly altered; sample 2 is 50 m away from vein and is unaltered. Unaltered tonalite elsewhere in stock contains 1.1±0.6 ppb Au (Stephenson & Ehmann 1971).

3-Granite core of zoned gabbro-granite stock, western Lake of the Woods greenstone belt, Manitoba (Wabigoon subprovince). Gold-quartz veins occur in core (Analysis 14, Gibbins 1971).

4-Fine-grained porphyritic granodiorite, Pickle Lake area, Ontario (Uchi subprovince), adjacent to gold-quartz vein (Fig. 26; analysis 3 of Ferguson 1966).

5,6-Tonalite batholith, Val d'Or area, Quebec (Abitibi subprovince) that contains numerous gold-silver deposits. Samples collected from mine dumps (compiled by Gussow 1937).

7,8-Trondhjemite stock, Michipicoten greenstone belt, Ontario (Wawa subprovince). Sample 7 is the mean of 20 relatively unaltered samples from the core of the stock. Sample 8 is the mean of 20 altered samples from the margin of the stock. Gold mineralization occurs in the margin of the stock or adjacent country rocks. Data from Studemeister et al. (1981, Table 1a); total iron is given as Fe_2O_3.

Texturally, there are two main types of plutons: 1) porphyritic subvolcanic dykes, sills, irregular plugs and small stocks that contain medium-grained phenocrysts of quartz or plagioclase (or both, more rarely with orthoclase) in an aphanitic to fine-grained groundmass. Lithologically, these are commonly referred to as quartz porphyry, feldspar porphyry or quartz feldspar porphyry (Figs. 24, 25, 26). 2) Porphyritic to equigranular medium-grained epizonal

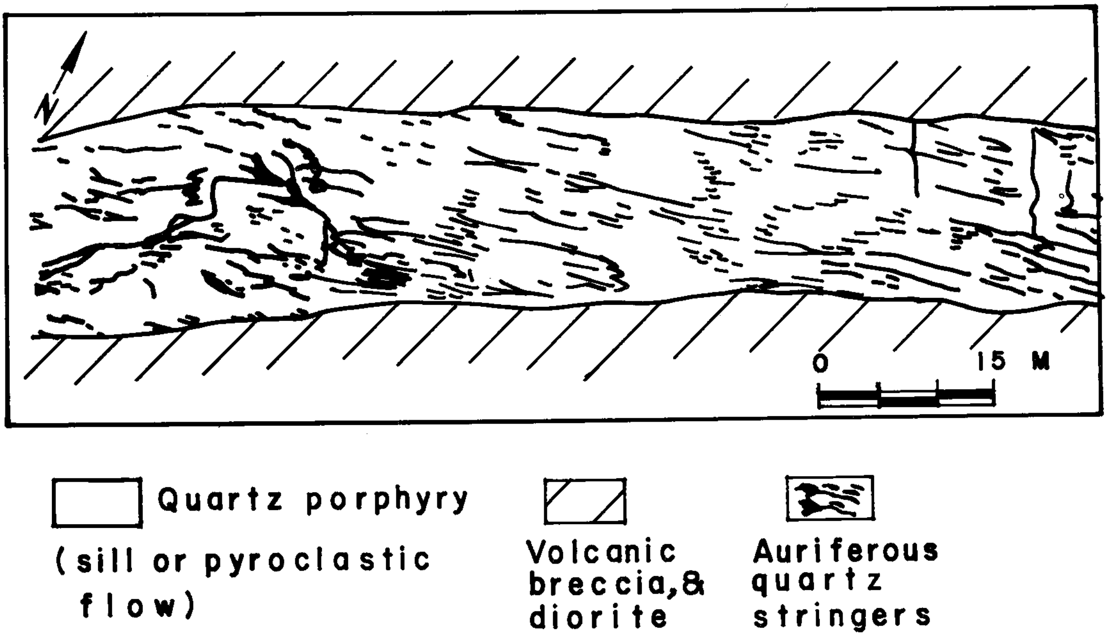


FIG. 24. Distribution of gold–quartz veinlets in the former Howey mine of the Red Lake district, Ontario. Veinlets are largely restricted to a tonalitic quartz porphyry unit that was interpreted by Horwood (1948) and Pirie (1981) to be an intrusive dyke, and by Ferguson (1968) to be a pyroclastic flow unit. The country rocks that in part were mapped as diorite by Horwood (1948) and Pirie (1981), have been interpreted by Ferguson (1968) to be more mafic pyroclastic flows. Franklin & Thorpe (1982) consider that this may be a porphyry-gold deposit.

plutons that form stocks (Fig. 27) and small batholiths, some of which are also subvolcanic (Latulippe & Germain 1979). Most plutons appear to be pre-tectonic or early-tectonic and are an integral part of the volcanism, particularly the upper calc-alkaline parts of the metavolcanic sequences. For example, in the Malartic – Val d'Or area and other parts of the Abitibi Subprovince of the Superior Province, gold deposits in both plutons and metavolcanic–metasedimentary rocks are most abundant in the upper felsic-to-intermediate, commonly calc-alkaline part of volcanic cycles (Latulippe & Germain 1979). Although most gold-bearing plutons of both granitoid and syenitoid composition are inferred to be approximately coeval and, in part, comagmatic with volcanism (*e.g.*, Latulippe & Germain 1979, Ridler 1970, Sinclair 1982), precise age-data are not available for many plutons, and there is some controversy about the age of the plutons and mineralization relative to tectonic events. For example, the pluton associated with the Camflo deposit in the Abitibi Subprovince of the Superior Province is described as subvolcanic by Latulippe & Germain (1979) and late-tectonic by Meikle & Scherkus (1979). Mineralization in other nearby plutons is also considered to be late-tectonic (Audet 1979, J. M. Franklin, pers. comm. 1981). Late-tectonic epizonal granite plutons associated with gold deposits are well documented in the Central Metasedimentary Zone Subprovince of the Grenville Province (*e.g.*, Davidson *et al.* 1979, Lumbers 1964).

The early plutons have been metamorphosed and deformed, with metamorphic grade ranging from zeolite to amphibolite facies locally. Adjacent to the mineralization, the plutons are also altered in a zone of variable width. The most common secondary minerals are sericite, albite, quartz, carbonate minerals, epidote, pyrite and tourmaline (Boyle 1979). K-feldspar and hematite are common immediately adjacent to veins (Issigonis 1980, Kerrich & Fryer 1981, Sinclair 1982).

Kerrich *et al.* (1980) and Gorman *et al.* (1981) have found that, as a result of alteration, subvolcanic granitoid plutons hosting gold occurrences in the Timmins–Kirkland Lake area of the Abitibi Subprovince of the Superior Prov-

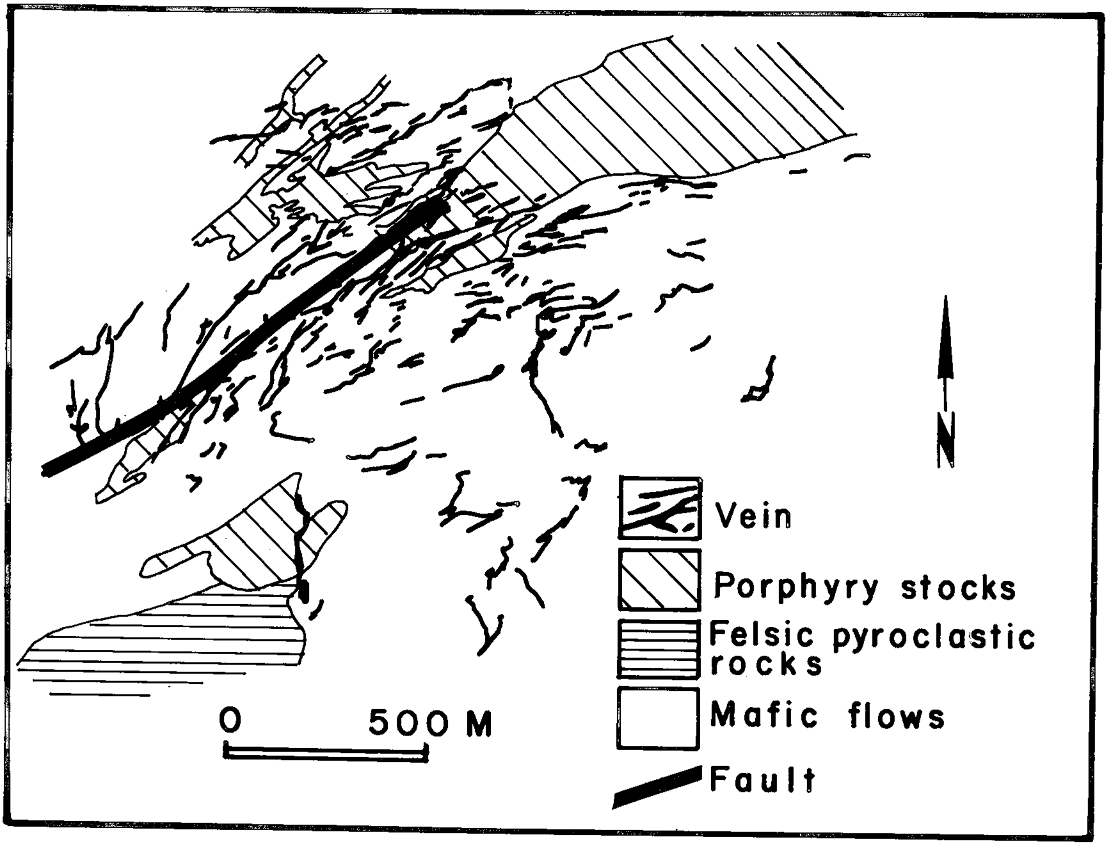


FIG. 25. Distribution of gold–quartz veins at the Hollinger mine, Timmins area, Ontario (after Jones 1948). Most veins are in mafic metavolcanic flows, but some veins occur in the porphyry bodies. These porphyry bodies have been mapped as intrusions by most authors (*e.g.*, Ferguson *et al.* 1968, Griffis 1962, 1979) but detailed work by Davies & Luhta (1978) suggests that the largest porphyry body (Pearl Lake porphyry) may be a strongly altered felsic metavolcanic unit. Karvinen (1981) has interpreted the Pearl Lake porphyry to be a volcanic vent.

ince are anomalously enriched in Na, volatiles, Au and ^{18}O (Table 7) compared to plutons that lack gold mineralization. The alteration is most intense near gold concentrations, but the entire pluton is somewhat anomalous (Table 7). In other plutons, however, Na and Ca have been strongly depleted, with K and, in places, Mg enriched adjacent to gold-bearing veins (Poulsen & Franklin 1981, Studemeister *et al.* 1981).

As a result of the combined deformation, metamorphism and alteration, primary textures in the groundmass are poorly preserved in many subvolcanic plutons. This has led to some controversy about the origin of the porphyry units (*e.g.*, Hopwood 1976) and the distinction between plutons and texturally similar flows and pyroclastic units. The data are not always unequivocal, but in most areas, plutons can be distinguished by their more massive character and by their contact relations. Although some bodies originally mapped as plutons have been suggested, on more detailed examination, to be altered pyroclastic units (Figs. 24, 25; Davies & Luhta 1978, 1979, Ferguson 1968, Karvinen 1981, Sutherland & Colvine 1979), other workers have questioned this interpretation (*e.g.*, Griffis 1979, Pirie 1981). The presence of many subvolcanic plutons is well documented but, in spite of these data, some authors (*e.g.*, Boyle 1976) have suggested that all porphyry plutons are metasomatic replacement zones.

The deposits are mainly hypogene, epigenetic, single- to multi-stage quartz and quartz–carbonate veins, lodes, lenses, stockworks, silicified zones and disseminations within or marginal to

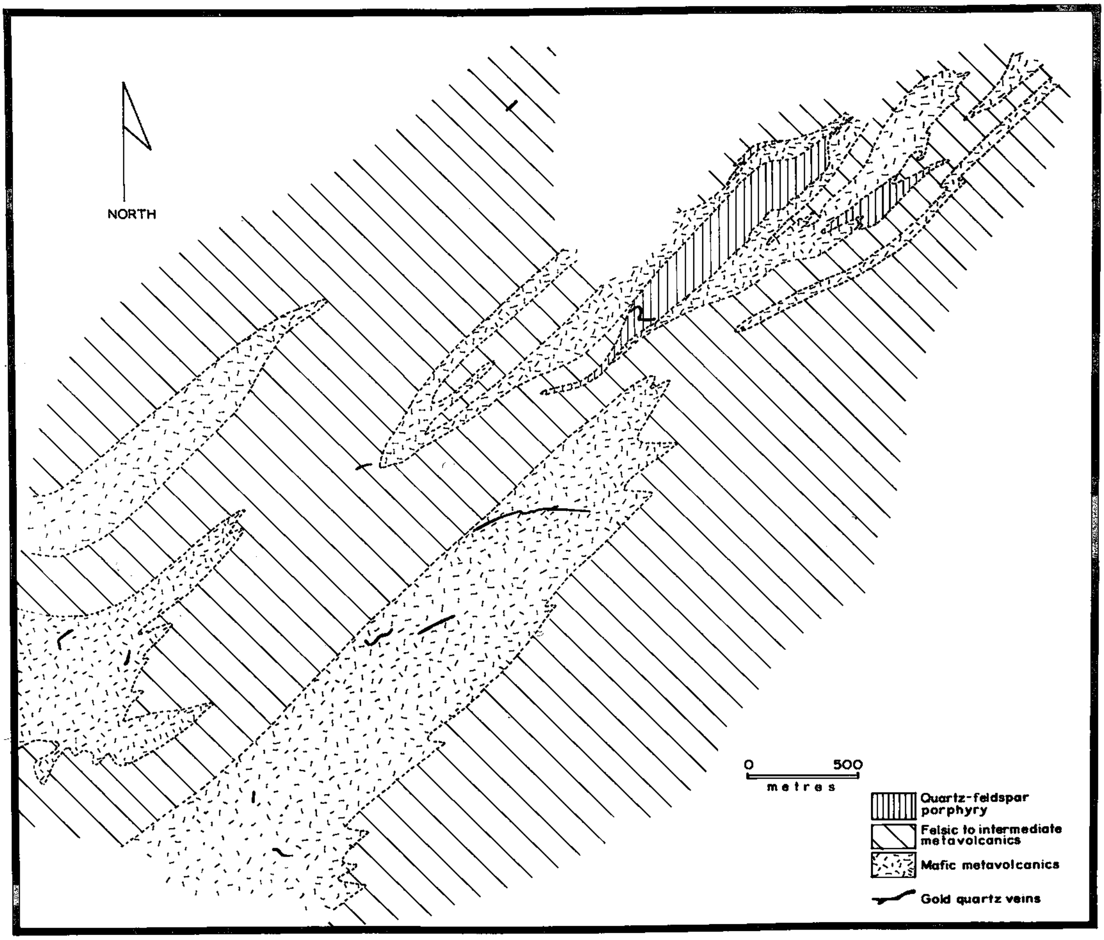


FIG. 26. Distribution of gold–quartz veins at the former Pickle Crow gold mine, Ontario (after Ferguson 1966). Veins occur throughout the volcanic sequence and seem to occur only accidentally in the pluton of quartz–feldspar porphyry.

faults and fracture zones (Boyle 1979, Whitmore 1970), some of which are ductile shear zones developed prior to or during metamorphism (Poulsen & Franklin 1981). In some gold-bearing plutons, the gold mineralization is apparently preferentially concentrated near country-rock xenoliths and hybrid zones (Mackasey *et al.* 1974), or in the marginal zone and adjacent country rocks (Studemeister *et al.* 1981). Most deposits are confined to planar, curviplanar or irregular zones within which there may be one or more vein systems; vein boundaries range from sharp to gradational. Many veins contain several generations of quartz. not all of which are auriferous. The carbonate, where present, comprises ankerite, dolomite and calcite. Scheelite, tourmaline, pyrite, arsenopyrite, chalcopyrite and other sulfide and telluride minerals are present in varying amounts in gold-bearing quartz and quartz–carbonate veins at many deposits, although at some deposits the quartz and quartz–carbonate veins contain only native gold and silver. Most of the gold is native and is commonly associated with pyrite and arsenopyrite and alloyed with native silver; the gold commonly fills brittle fractures in both quartz and sulfide minerals (Goman *et al.* 1981). Gold is generally more abundant than silver by a factor of 3 to 5 (Boyle 1979); in some deposits, the ratio Au/Ag decreases with depth (Boyle 1979, Fitzgerald *et al.* 1967). Deposits in which silver predominates over gold are rare in granitoid plutons (Boyle 1968).

Some gold-bearing plutons have been clas-

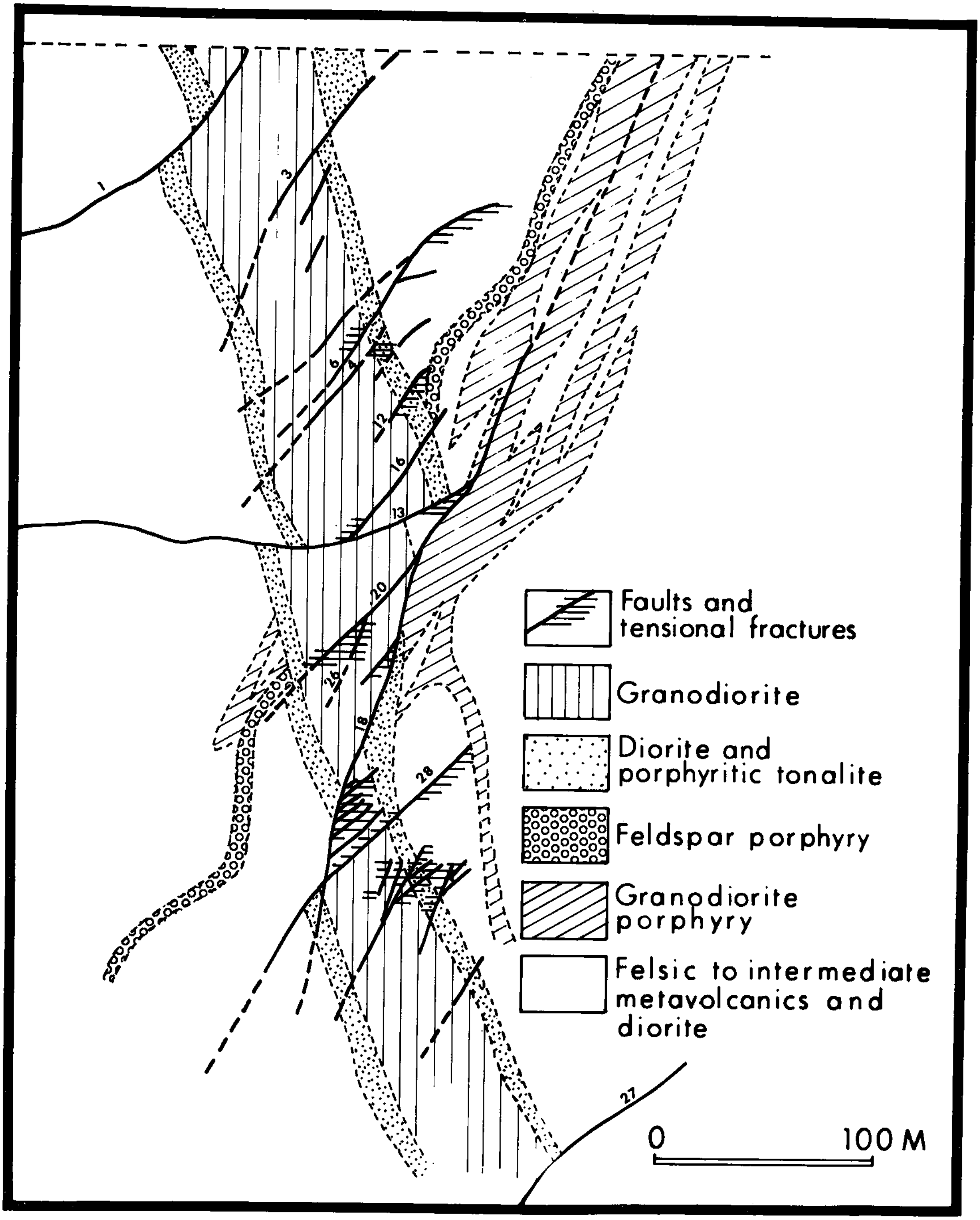


FIG. 27. Distribution of gold–quartz veins in a vertical section through the Lamaque mine, Quebec (after Wilson 1948). Veins occur along faults and are largely restricted to the zoned granodiorite–diorite plug.

TABLE 7. COMPARISON OF ARCHEAN SUBVOLCANIC GRANITOID PLUTONS FROM THE TIMMINS GOLD AREA, ABITIBI SUBPROVINCE, SUPERIOR PROVINCE.[1]

	Gold-bearing plutons[2]		Gold-free pluton (2 samples)
	low Au enrichment (6 samples)	unmineralized (8 samples)	
Na_2O (%)	5.70	4.23	3.75
L.O.I[3] (%)	5.21	2.69	1.69
Au (ppm)	0.15[4]		0.0015
^{18}O (°/∘∘)	14.04[4]		9.87

[1] Data from Kerrich et al. (1980)

[2] Preston and Paymaster porphyry plutons

[3] Loss on ignition at 1000°C (uncorrected for oxidation of iron)

[4] Four samples

sified as porphyry-gold deposits (Figs. 22, 23; Franklin & Thorpe 1982, Sinclair 1982). They differ from other pluton-hosted gold deposits in that areally extensive gold and associated pyrite are disseminated or present in minor fractures (Fig. 24) within the pluton rather than related to a major vein or shear-zone system. Alteration appears to be less extensive than in porphyry-copper and -molybdenum deposits (Franklin & Thorpe 1982), although Issigonis (1980) and Sinclair (1982) have described potassic alteration at several deposits. Franklin & Thorpe (1982) have identified 13 possible porphyry-gold deposits in the Slave, Churchill and Superior provinces (Figs. 22, 23). Grade ranges from 1 to 2.8 ppm, with reserves of 1–18 × 10^6 tonnes (Franklin & Thorpe 1982); some deposits in the Superior Province, such as Howie–Hasaga (Red Lake, Fig. 24) of the Uchi Subprovince and Camflo (Val d'Or), Sigma (Malartic) and Young–Davidson (Matachewan) of the Abitibi Subprovince have been or are currently being mined.

There is considerable controversy about the role of granitoid and syenitoid plutons in the genesis of gold deposits. In the greenstone belts, most gold–silver deposits are in metavolcanic and metasedimentary country-rocks rather than in felsic plutons, although plutons commonly occur nearby (Franklin & Thorpe 1982). However, statistical analysis of relationships between host rock and gold–silver deposit shows that gold deposits are preferentially concentrated in or near small plutons, at least in some areas. For example, in the west-central part of the Superior Province of northwestern Ontario, Riley *et al.* (1971) found that 30% of the 253 gold occurrences, including some producing mines, were, at least in part, in small felsic plutons, yet these plutons comprise less than 5% of the greenstone belts in the region examined (Riley 1973). Even in the case of deposits not in felsic plutons, plutons occur in the immediate vicinity of many of them. Where plutons are associated with gold–silver deposits, the vein system may be largely confined to the pluton and immediately adjacent country rocks, or it may occupy a fault or fracture system that crosses both pluton and country rocks, *i.e.*, it is not related obviously to pluton emplacement. However, in some of the latter deposits the gold content of the vein system is higher where the veins cross the pluton.

Riley *et al.* (1971) found also a spatial association between mafic and ultramafic plutons and gold–silver deposits, but not for any of the metavolcanic or metasedimentary rock units tested. On the other hand, in the Abitibi Subprovince, Ridler (1970, 1976) has shown that carbonate-rich units are greatly enriched in gold and host many gold occurrences. Ridler (1970) considered that the carbonate-rich units were chemically precipitated sedimentary rocks (exhalites), but chemical and textural data now indicate that these units are carbonatized, possibly volcanic ultramafic rocks (Tihor & Crocket 1977). Elsewhere in the Abitibi Subprovince, Pyke (1975) has shown that gold deposits are associated with ultramafic metavolcanic units.

Although there appears to be a spatial association in many areas between gold–silver deposits and felsic plutons, there is some controversy about whether the deposits are genetically related to the emplacement of the plutons (*e.g.*, Latulippe & Germain 1979, Riley *et al.* 1971) or whether the plutons are structurally and chemically favorable hosts for mineralization that is not genetically related to pluton emplacement (Boyle 1979, Franklin & Thorpe 1982, Gorman *et al.* 1981, Kerrich *et al.* 1980). Boyle (1979) based his conclusion favoring no genetic link on several factors: 1) some vein systems occupy regional structures that only accidentally cross plutons, 2) the gold–silver–quartz veins occur in structures that postdate pluton consolidation, and 3) felsic plutons have a low gold content, although Wolfe (1975) and Kerrich *et al.* (1980) found that Archean felsic plutons associated with gold deposits are slightly enriched in gold. These arguments, however, are equivocal; points 2 and 3, with appropriate substitution of copper and molybdenum for gold and silver, could be applied also to porphyry-copper and porphyry-molybdenum deposits, for which most authors agree that the host porphyritic plutons are genetically related. The uncertainties are the source of the metals and the concentrating mechanisms.

As in porphyry deposits, the heat introduced by rising magma, particularly in relatively long-lived volcanic conduits, could have caused convective movement of formational and introduced waters which, in turn, led to leaching and migration of gold and other elements toward the plutons (*e.g.*, Mackasey *et al.* 1974, Sutherland & Colvine 1979). In this model, the veins were deposited in fractures and faults, either in the plutons or in country rocks, that developed after consolidation but prior to final cooling. The actual depositional site would be a function of location and nature of favorable structures, temperature gradients, and chemistry, pressure and temperature of the fluids *vis-à-vis* those of the rock sequence. The plutons initiated gold migration but did not necessarily control the final site of deposition. Poulsen & Franklin (1981) have proposed that, in some deposits, widely dispersed gold within a porphyry deposit may have been concentrated and redeposited into shear zones during metamorphism, with consequent destruction of the original porphyry deposit.

Arguments presented by Kerrich & Fryer (1981), on the other hand, suggest that the above mechanism is an unlikely concentrating agent for gold deposits hosted by subvolcanic plutons, although it could possibly apply to deposits in deeper-seated plutons. These authors stressed that, although copper can be concentrated from country rocks by large volumes of circulating water, concentration of gold without copper requires low fluid-to-rock ratios. They suggested that the most likely fluids for gold concentration are those produced during the transition from low to moderate grades of metamorphism at some time after pluton emplacement. However, if, as suggested by Ayres (1978), granitoid batholiths are the major sources of heat for metamorphism of greenstone-belt sequences, then batholiths are a potential driving force for gold concentration. In this case, plutons are both the host and driving force, although the host and driving plutons would generally be different, particularly for deposits hosted by early subvolcanic plutons. Lower-epizonal gold-bearing plutons, however, could be both hosts and concentrating agents.

The enrichment of some gold-bearing plutons in sodium and volatiles (Table 7) has been attributed to early interaction between the plutons and large volumes of seawater at temperatures of <200–350°C, producing extensive albitization (Gorman *et al.* 1981, Kerrich *et al.* 1980). The gold is considered to have been introduced later by metamorphically produced fluids at higher temperatures (420–480°C), but the early albitization apparently was a prerequisite for gold deposition (Kerrich *et al.* 1980, Kerrich & Fryer 1981). According to Kerrich *et al.* (1980), plutons that lack early interaction with seawater will not contain gold deposits.

In summary, the spatial association between gold and subvolcanic to epizonal tonalite–granodiorite and syenite plutons cannot be ignored. Although many of these felsic plutons have no associated mineralization, and the plutons are not the sole, nor necessarily the most important host for gold deposits, they are spatially associated with some gold–silver deposits. The nature of the genetic association, if any, is more controversial, but irrespective of genetic models, such plutons in greenstone belts of the Canadian Shield are a favorable target for prospecting. They may host or be adjacent to major vein or other structurally controlled deposits. As stressed by a number of authors, with the rapid rise in the price of gold, felsic plutons should be examined also for the presence of large low-grade, porphyry-type gold deposits.

As with copper–molybdenum–gold occurrences, gold–silver deposits are concentrated in the southern part of the Superior Province (*cf.* Figs. 19, 22). This probably also reflects the greater width of the greenstone belts and greater abundance of internal plutons in this region (Goodwin 1970).

GRANITIC PEGMATITES

Introduction

The Canadian Shield is relatively rich in mineralized granitic pegmatites, and the number of recognized pegmatite fields and districts can be expected to increase with continued prospecting. However, the petrogenetic aspects of most pegmatite localities have not been studied in sufficient detail; the relationship of the pegmatites of granitic intrusions and anatectic events is poorly understood in many cases. Consequently, broad generalizations are not feasible for many provinces and subprovinces. Several case-histories of better-known fields and districts are emphasized instead, as examples that may be typical of pegmatites generated by granitic fractionation in different host-units. Pegmatites of metamorphic parentage are also briefly mentioned to complement the review and to provide contrast to magmatogenic pegmatites.

Rare-element pegmatites are not known from the Nain, Southern and Bear provinces, although late leucogranitic and pegmatite intrusions are typical of some segments of the latter two (Cannon 1970, Frith *et al.* 1977a, Hoffman & McGlynn 1977). These three provinces are thus excluded from the following discussion. A

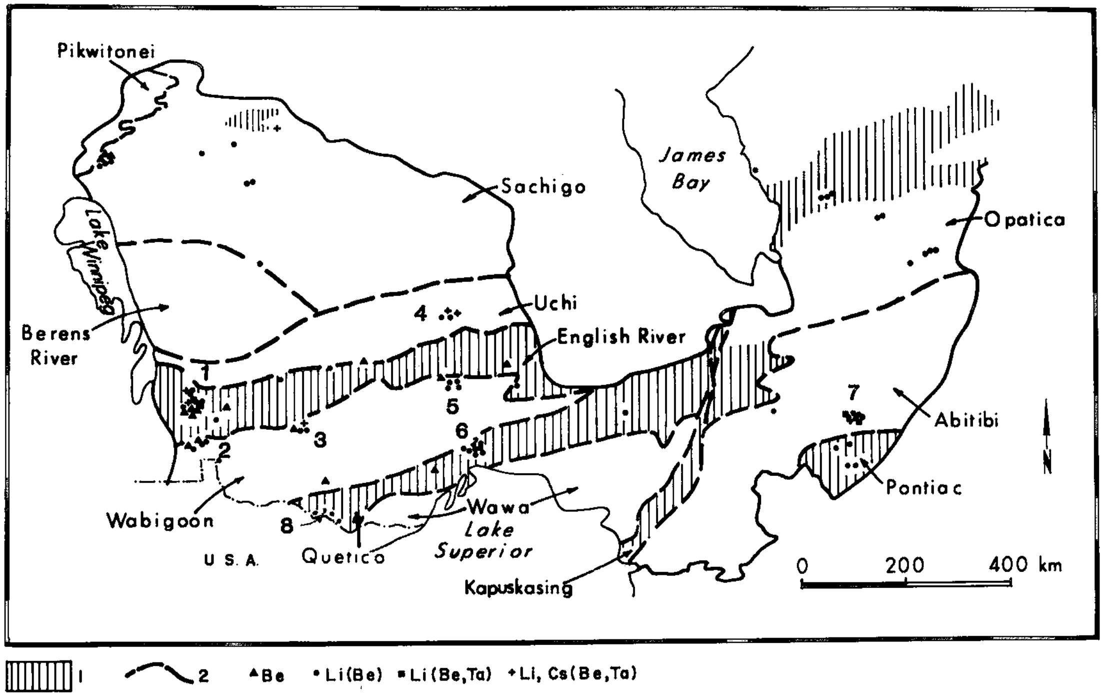


FIG. 28. Distribution of mineralized pegmatites in the Superior Province. Most individual symbols represent larger groups of pegmatites. Symbols: 1. subprovinces and terranes with predominant parageneiss; 2. subprovince boundaries. Localities of pegmatite fields and districts: 1. Cat Lake – Winnipeg River field, 2. Falcon Lake district, 3. Dryden district, 4. Fort Hope district, 5. Zigzag Lake field, 6. Georgia Lake field, 7. Preissac–Lacorne field, 8. Lac-La-Croix field. See Table 8 for characteristic features of some of these fields and districts.

separate section is devoted to each of the other four provinces because of gross differences among the pegmatite types populating them.

Detailed listings and brief characteristics of pegmatites with Li, Cs, Be, Nb–Ta, Sn, Mo, U and Th in the Canadian Shield are available in Mulligan (1961, 1965, 1968, 1975), Lang *et al.* (1962), Vokes (1963), Hewith (1967) and Dawson (1974). These references also contain production and reserve data; for lithium, this information has been recently updated by Flanagan (1978), Lasmanis (1978) and Williams & Trueman (1978).

Superior Province

In the complex structures and lithologies of the Superior Province, most occurrences of rare-element pegmatites are concentrated (1) within the paragneiss–granitoid subprovinces (English River, Quetico and Pontiac), (2) along and near the boundaries of these subprovinces with the greenstone–granodiorite subprovinces, and (3) along the boundaries of other subprovince types (Fig. 28). The remaining occurrences are scattered in the northern parts of the Sachigo and Opatica subprovinces, in part spatially related to their paragneissic segments. Their geological setting cannot be specified in more detail because the regional geology of these parts of the shield is still poorly understood.

In terms of age relationships, all rare-element pegmatites dated so far are related to the main 2.6 Ga (Kenoran) event (*e.g.*, Dawson 1966, Penner & Clark 1971). Within this event, better-known pegmatite occurrences have originated during its latest tectonic and intrusive stages (*e.g.*, the Winnipeg River pegmatite district: Černý *et al.* 1981).

Structurally, many pegmatite occurrences are spatially associated with large-scale systems of deep faults that separate (locally) the subprovinces (Pashkokogan Lake, Roadhouse Lake and other localities along the Lake St. Joseph fault bounding the English River and Uchi subprovinces) or slice their interiors, commonly in directions subparallel to the subprovince boundaries (Winnipeg River and Cat Lake–Maskwa Lake districts in the English River Subprovince; Red Cross Lake district in the Sachigo Subprovince) or along orthogonal greenstone-belt patterns (Fort Hope district in the Uchi Subprovince). These fault systems have had a long history of displacements, although their present expressions appear to be rather late, postdating most of the regional metamorphic fabric and plutonic structure (Jolly 1978, Schwerdtner *et al.* 1979). Pegmatite-generating granitoids and their pegmatite aureoles are mostly related to these final stages of faulting. In some areas, contacts of large batholiths represent the regional structural element controlling the emplacement of satellite granitoid and their pegmatite suites. However, emplacement of the batholiths was apparently structurally controlled (Breaks *et al.* 1978). Late intrusive activity along their contacts, possibly reflecting a reactivation of the old structures along the relatively weak margins of the batholith, may have healed the original structure.

Most of the rare-element pegmatites were intruded into greenstone-belt sequences or, to a lesser degree, into paragneiss. During late-tectonic disturbances along reactivated fault systems, and in regional compressional regimes (Fyson *et al.* 1978), the highly deformed and jointed supracrustal sequences evidently provided dilated structural traps much more readily than the relatively competent orthogneiss suites and younger plutons. However, some pegmatite groups are also hosted by these more competent lithologies (Černý *et al.* 1981). Mineralized pegmatites occur only exceptionally within their parent granitoid complexes (Dawson 1966); even in these complexes the pegmatites seem to be external in relation to their parent intrusive phases.

The metamorphic environment in which rare-element pegmatites and their parent granitoids have been intruded is characterized, in most cases, by (1) steep regional gradients, (2) upper greenschist- to lower-amphibolite grade of the host rocks, and (3) proximity (at least relative) to thermal highs marked by sillimanite occurrences or to local areas of low-pressure granulite-facies metamorphism. The steep metamorphic gradients have been documented in several pegmatite districts (*e.g.*, Pirie & Mackasey 1978, Thurston & Breaks 1978, Breaks *et al.* 1978, Trueman 1980). In the English River Subprovince, low-pressure granulite terranes were documented (*e.g.*, Trueman *et al.* 1976, Thurston & Breaks 1978) in close proximity to the low-grade pegmatite-bearing terranes. Sillimanite is generally rare but typical of greenstone belts near the boundaries of the English River, Quetico and Berens River subprovinces (Ayres 1978) close to but not within areas populated by mineralized pegmatites. Metapelite components of supracrustal sequences hosting mineralized pegmatites commonly contain muscovite along with andalusite, staurolite, cordierite, anthophyllite and garnet, individually or in different combinations (Breaks *et al.* 1978, Pirie & Mackasey 1978, Trueman 1980).

Granitoid complexes parental to the rare-element pegmatites have been unambiguously identified in relatively few areas. They generally (1) are emplaced at late-tectonic to post-tectonic stages, (2) consist of relatively small stocks and plugs that are, in some cases, satellitic to intrusions of batholithic proportions, but not necessarily related to them genetically, (3) are leucocratic with biotite, biotite + muscovite, muscovite, or muscovite (+ garnet) as mafic minerals, and (4) are silicic and Ca-poor in bulk composition, lack normative diopside and contain 0–5% normative (CIPW) corundum. Li, Rb, Cs, Be, Sn, Ga, Nb and Ta typically are enriched in the parent granites, whereas Ba, Sr, Ti, Zr, LREE and Eu are depleted. Although accurate data are too scarce for generalized quantitative characterization, some individual examples are given in the subsequent sections. Lack of data is even more conspicuous with respect to the genesis of pegmatite-generating melts. Anatexis of supracrustal sequences is suggested (Breaks *et al.* 1978, Černý *et al.* 1978, Breaks, pers. comm. 1980), but I-type magmas generated in the lower crust and contaminated during their ascent through supracrustal lithologies may also be represented (Černý *et al.* 1981, Goad & Černý 1981, Longstaffe *et al.* 1981).

Geochemical distinction of parental lithologies, however, appears to be difficult since the leucogranites and pegmatitic granites must have undergone a volatile-promoted fractionation in liquid state, beyond the levels attainable by simple crystal–melt fractionation (which is currently the only one amenable to quantitative modeling). Hildreth's (1979) thermogravitational convection–diffusion may have operated in the internal evolution of the "fertile" granites, compounded by the effects of vapor transfer in separating supercritical fluids (Černý 1982a, Černý & Brisbin 1982).

The rare-element pegmatites of the Superior Province are considerably diversified in their mineralogy and geochemistry, but most of them can be correlated with one or another of the six pegmatite types listed in Table 8. However, distinction of these categories on the basis of published descriptions commonly is difficult.

TABLE 8. CLASSIFICATION OF GRANITIC PEGMATITES IN THE SUPERIOR PROVINCE

Geochemical type	Morphology and internal structure	Parent process	Characteristic accessory and rare-element minerals	Typical example	No. in Fig. 28	Reference
1. U(Th)	fracture-filling to lenticular; unzoned	fractionation from plutonic potassic granitoids	biotite, uraninite, uranothorite, allanite	Kenora area	-	Pryslak (1976) Breaks et al. (1978)
2. Li(Be, Nb-Ta,±B)	fracture-filling; unzoned to poorly zoned; local albitization	fractionation from plutonic biotite (+ muscovite) granites (?)	primary spodumene, beryl, tourmaline (columbite-tantalite, triphylite, cassiterite)	Georgia Lake field Preissac-Lacorne field	6 7	Pye (1965) Rowe (1953) Mulligan (1965)
3A. Be,Nb-Ta	fracture-filling; poor to good zoning; extensive albitization	fractionation from muscovite + garnet pegmatitic granites	beryl, columbite-tantalite, cassiterite, niobian rutile, garnet, cordierite, gahnite (monazite, zircon)	Greer Lake group in the Cat Lake-Winnipeg River field	1	Černý et al. (1981)
3B. Be,Nb-Ta (Sn,REE,U, Th,Zr-Hf)	fracture-filling; poor to good zoning; extensive albitization	fractionation from biotite leucogranite stocks	granet, topaz, beryl, columbite-tantalite, allanite, monazite (euxenite, yttrotantalite, gadolinite, uraninite, thorite, zircon)	Shatford Lake group in the Cat Lake-Winnipeg River field	1	Černý et al. (1981)
4. Li,Rb,Cs, Ta-Nb, Sn, Be,F,B	fracture-filling; good zoning; very extensive albitization and other replacements	fractionation from muscovite + garnet + tourmaline pegmatitic granites	petalite, secondary spodumene, eucryptite, lepidolite, amblygonite, triphylite, pollucite, Ta/Nb-oxide minerals, cassiterite, beryl, tourmaline	Bernic Lake group in the Cat Lake-Winnipeg River field	1	Černý et al. (1981) Crouse et al. (1979)
5A. Mo(Be,Bi)	fracture-filling; moderate zoning; local quartz + muscovite replacement	fractionation from biotite-muscovite granitoids (?)	molybdenite (bismuth, beryl)	Falcon Lake area Preissac-Lacorne field	2 7	Černý & Turnock (1971b) Vokes (1963) Mulligan (1965)
5B. Mo(Fe)	leucosome in migmatites; unzoned	anatexis (?)	molybdenite (pyrrhotite, pyrite, chalcopyrite)	Cole Lake in the Cat Lake-Winnipeg River field	1	Černý & Turnock (1971b)
6. U,Th(Zr, Mo)	leucosome in migmatites; veins in paragneisses; unzoned	anatexis, or not established	uraninite, thorite, zircon, (allanite, uranothorite, molybdenite, pyrrhotite, pyrite); locally garnet, sillimanite, cordierite	Caddy Lake-Rennie area in the Falcon Lake district Grenville Lake Sydney Lake fault system	2 - -	Lang et al. (1962) Franklin (1978b) Breaks et al. (1978)

Thus, a modified classification of pegmatite types is used in Figure 28, which does not include, for sake of simplicity, the few localities of types 1, 5A, 5B and 6.

Pegmatites of most of the tabulated types may occur in isolation or as parts of more or less zoned regional sequences. Anatectic pegmatites (types 5B, 6) and radioactive pegmatites related to late potassic plutons (type 1) are the only exceptions. The absence of garnet, sillimanite and cordierite is the best criterion for distinguishing igneous U-Th-bearing pegmatites (type 1) from the products of partial melting (type 6; Breaks *et al.* 1978, Breaks 1980, Franklin 1978b, Pryslak 1976). Igneous U-Th-bearing pegmatites are also more fractionated than the anatectic U-Th-bearing pegmatites and have lower Th/U, K/Rb, Ba/Rb and higher K/Ba values (Breaks 1982).

Lithium pegmatites with primary Fe-enriched spodumene (type 2) are one of the most widespread types of rare-element pegmatite in the province. However, they are commonly difficult to assign to specific parental intrusions (Černý *et al.* 1981). Their structural position and internal structure frequently reflect the high-P regime of their crystallization, as indicated experimentally (Stewart 1963, 1978, London 1981, London & Burt 1982). In contrast, the geochemically more diversified type (4), enriched in Li, Rb, Cs, Ta-Nb, Sn, Be, B and F, commonly carries the low-pressure phase petalite as the primary Li-aluminosilicate (see the references above) and, locally, pollucite, which also crystallizes in low-pressure environments (Černý & Simpson 1978, Černý 1979, 1982b).

The Mo-bearing pegmatites of igneous descent (type 5) are commonly transitional into feldspar-bearing quartz veins with more diversified mineralization (Dawson 1966, Vokes 1963). Anatectic leucosome with molybdenite is, however, characterized by very simple assemblages of minerals (Černý & Turnock 1971b).

In the following sections, two examples of pegmatite districts and fields are demonstrated that encompass all of the geochemical pegmatite types of igneous derivation.

The Winnipeg River pegmatite district. This district is located predominantly in the Bird River greenstone belt, along the boundary separating the southern Winnipeg River batholithic belt from the northern Manigotagan – Ear Falls gneiss belt of the English River Subprovince in southeastern Manitoba (Fig. 28, No. 1, Fig. 29; Beakhouse 1977, Trueman 1980). An upper greenschist metamorphic grade predominates in most of the metasedimentary and metavolcanic rocks of the greenstone belt, but the grade in-

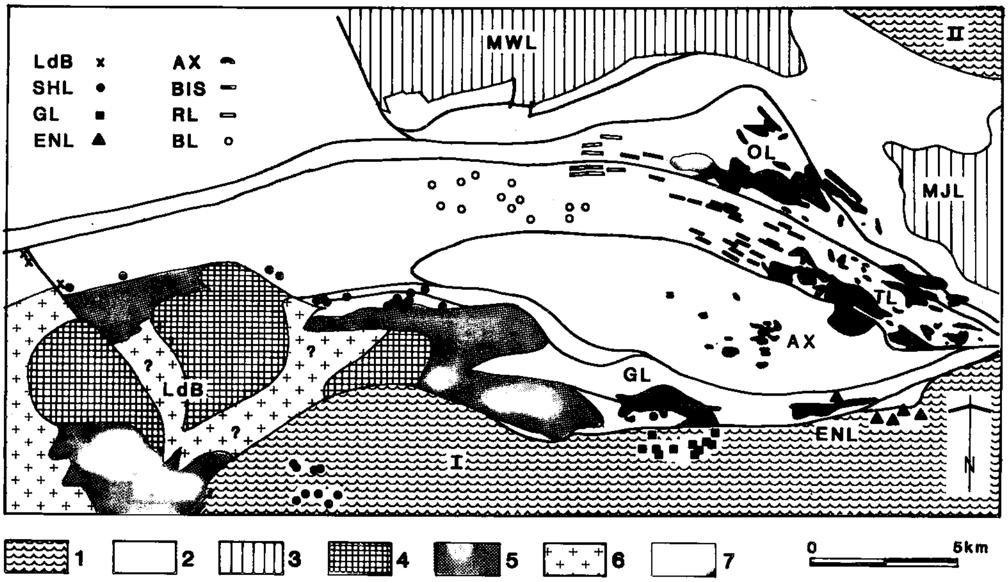


FIG. 29. The Winnipeg River pegmatite district. 1. gneissic "schollen"-zone of the Winnipeg River batholithic belt (I) and paragneiss of the Manigotagan–Ear Falls belt (II); 2. Bird River greenstone belt; 3. Maskwa Lake (MWL) and Marijane Lake (MJL) composite batholiths; Lac-du-Bonnet (LdB) batholith; 4. early hornblende–biotite granodiorite, 5. leucogranite parental to the SHL pegmatite group; 6. biotite granite; 7. pegmatitic granites (GL Greer Lake, ENL Eaglenest Lake, AX Axial, TL Tin Lake and OL Osis Lake bodies). Pegmatite groups (see inset for symbols): LdB Lac-du-Bonnet, SHL Shatford Lake, GL Greer Lake, BIS Birse Lake, RL Rush Lake, ENL Eaglenest Lake, AX Axial, BL Bernic Lake. From Černý (1982a)

creases to the upper amphibolite facies in the northwestern part of the area shown in Figure 29. Several periods of folding and metamorphism, partly contemporaneous with diapiric emplacement of the Maskwa Lake and Marijane Lake tonalites, shaped the belt into a broad synclinorium that was subsequently segmented by regional east-trending subvertical faults (Černý *et al.* 1981, Trueman 1980). The volcanic, metamorphic and plutonic evolution of the area spanned the period from 2.7 to 2.5 Ga (Farquharson & Clark 1971, Farquharson 1975, Penner & Clark 1971).

Three sequences of granitoid intrusions can be distinguished in the district, mostly separated in time but partly overlapping, and apparently of independent origin: (1) syntectonic diapiric tonalite batholiths, (2) late-tectonic potassic biotite granites, and (3) late- to post-tectonic leucogranites and pegmatitic granites (Fig. 29; Černý *et al.* 1981).

Diapiric tonalite – trondhjemite batholiths, emplaced during the main episode of dynamic metamorphism of the greenstone belt, display a foliation due to a range of processes, from igneous flow to metamorphic recrystallization. Plagioclase (An$_{26-34}$), hornblende, quartz, biotite and minor K-feldspar constitute these rocks, with accessory zircon and apatite, and secondary epidote, chlorite and sericite. Rare barren pegmatite stringers are associated with the tonalites. In chemical composition, as shown in Table 9 and in Figures 30 to 32, they are typical of Arth's (1979) class of continental tonalites derived from lower crust or upper mantle by partial melting of amphibolite.

Biotite granites, which dissect and mantle the tonalite diapirs, are massive and mostly nonfoliated, with weak recrystallization effects. Plagioclase (An$_{10-20}$), K-feldspar and quartz predominate over biotite; apatite, zircon and allanite are the main accessory constituents, along with epidote, sericite, carbonate and other alteration products. Minor potassic pegmatites with U–Th mineralization and allanite (type 1) crosscut the margins of the biotite granites as well as the adjacent host-rocks. By their chemical composition represented in Table 9 and in Figures 30 to 32, these granites are classified as granodioritic to granitic calc-alkalic to alkali-

TABLE 9. CHEMICAL COMPOSITION OF PLUTONIC GRANITOID ROCKS OF THE WINNIPEG RIVER PEGMATITE DISTRICT*

	1	2	3	4	5	6	7	8	9	10
SiO_2	67.95	72.10	64.65	68.30	72.10	76.90	73.90	74.90	72.65	73.40
Al_2O_3	14.44	14.14	15.36	15.14	13.45	12.14	14.07	13.44	14.46	13.62
TiO_2	0.45	0.34	0.66	0.42	0.23	0.10	0.14	0.19	0.17	0.11
Fe_2O_3	2.26	1.10	1.90	1.50	1.37	0.71	0.45	0.82	0.76	0.97
FeO	2.44	1.64	3.04	2.32	1.30	0.72	0.52	0.76	0.76	0.72
MnO	0.09	0.04	0.06	0.09	0.04	0.04	0.01	0.02	0.03	0.03
MgO	1.69	1.04	2.54	1.84	0.98	0.14	0.20	0.38	0.40	0.45
CaO	3.92	1.96	3.23	2.84	2.14	0.61	0.79	0.94	1.01	1.06
Na_2O	4.06	4.22	3.92	4.85	3.45	3.62	3.18	3.04	3.65	3.56
K_2O	1.62	1.65	2.32	1.66	3.81	4.28	5.63	4.89	5.02	5.63
P_2O_5	0.13	0.09	0.29	0.20	0.06	0.02	0.08	0.08	0.09	0.08
CO_2	0.10	0.09	0.29	0.12	0.03	0.03	0.04	0.09	0.09	0.04
H_2O	0.73	0.86	0.92	0.68	0.78	0.47	0.38	0.42	0.51	0.35
	99.88	99.29	99.18	99.96	99.74	99.78	99.39	99.97	99.60	100.02
Li	54	22	28	148	29	32	24	20	49	57
Rb	101	34	92	179	144	168	156	146	224	231
Cs	2.1	3.5	1.7	4.2	2.7	2.3	3.8	2.8	2.6	4.9
Be	3	2	4	5.0	1	3	2	1	2.5	2
Sr	190	130	973	208	138	46	135	140	150	225
Ba	353	549	960	94	658	652	523	741	675	926
Pb	9	6	9	5	8	21	37	33	26	22
Ga				38					33	28
U	4	1	nd**	2	nd	5	12	12	26	2
Th	nd	nd	nd	6	nd	13	nd	13	24	16
Zr	179	151	200	134	140	148	111	197	217	212
Hf	4.7	4.1	6.2	3.65	4.3	4.6	2.65	5.25	6.15	6.0
Sn	2	3	4	10	2	4	5	4	4	5
K/Rb	133	403	209	77	219	211	299	278	186	202
K/(Csx100)	63	39	112	32	117	154	122	145	160	95
K/Ba	38	24.9	20	147	48	54.4	89.3	54.8	61.8	50
Ba/Rb	3.5	16.1	10.4	0.52	4.6	3.9	3.4	5.07	3.0	4.
Ba/Sr	1.86	4.2	0.99	0.45	4.8	14.2	3.9	5.3	4.5	4.12
Rb/Sr	0.53	0.26	0.09	0.86	1.04	3.65	1.1	1.04	1.5	1.03
Mg/Li	189	286	546	75	203	25	50	115	49	47.4
Zr/Sn	89.5	50.3	50	13.4	70	37	22.2	49.2	54.2	42.4
Zr/Hf	38	36.8	32.2	36.7	32.6	32.2	41.9	37.5		35.3
Al/Ga				2108					2318	2574
La	15.05	31.3	95.5	55.2	28.85	30.8	16.1	34.35	41.4	87.1
Ce	39	63.5	191	105	58.5	72	34.5	77	87.5	153
Nd	19.5	24	66.5	39.5	20	29.5	13	29.5	33.5	78
Sm	4.14	3.03	6.05	5.60	2.77	3.83	3.12	5.29	5.48	5.94
Eu	0.81	0.66	1.5	0.76	0.51	0.38	0.45	0.53	0.51	0.69
Dy	4.8	2.7	2.05	2.95	1.95	2.95	0.95	2.2	2.2	1.2
Yb	4.8	6.35	0.7	1.7	1.45	2.05	0.45	0.85	1.25	1.25
Lu	0.62	0.24	0.06	0.16	0.18	0.28	0.06	0.14	0.20	0.13
Y	28	nd	nd	21	nd	7	nd	27	9	nd

* from Černý et al. (1981); ** not detected. 1. Maskwa Lake tonalite (anal. PG-50); 2. Maskwa Lake trondhjemite (anal. PG-47); 3. Marijane Lake tonalite (anal. PG-84); 4. Lac-du-Bonnet tonalite (anal. AEC-43); 5. Maskwa Lake biotite granite (anal. PG-150); 6. Maskwa Lake biotite granite (anal. PG-82); 7. Marijane Lake biotite granite (anal. PG-73); 8. Marijane Lake biotite granite (anal. PG-31); 9. Lac-du-Bonnet biotite granite (anal. AEC-21); 10. Lac-du-Bonnet biotite granite (anal. PG-133).

calcic intrusions, genetically independent of the tonalites, and generated probably by partial melting of mafic sources below the sialic crust (Černý *et al.* 1981, Longstaffe *et al.* 1981). However, a close similarity exists, in some respects, between them and the biotite granites of northeastern Minnesota, for which Arth & Hanson (1975) developed a convincing model based on partial melting of short-lived greywacke at crustal depth.

Leucogranites and pegmatitic granites partly predate biotite granites and, in these cases, are extensively sheared and recrystallized. However, most of them postdate the emplacement of the biotite granites and show negligible strain, if any. They were intruded as small stocks and plugs along the east-trending subvertical faults segmenting and bounding the greenstone belt during a regional dilation. The granites show a complex fingering-out of contacts in schistose host-rocks, and simple straight boundaries plus angular xenoliths in massive hosts, suggestive of stoping. They consist of a wide diversity of phases, including equigranular fine-grained leucogranites, megacrystic pegmatitic leucogranites, sodic aplites, and potassic pegmatite layers and pods. They are composed of plagioclase (An_{2-6}), K-feldspar and quartz, subordinate but highly varied proportions of biotite, garnet and muscovite, and accessory zircon, gahnite, monazite, columbite–tantalite and other phases. This is the type of granitoid rock that is parental to most of the groups of mineralized pegmatite in the district.

Their chemical composition, as shown in Table 10 and in Figures 30 to 32, indicates their alkali-calcic affinity; they are highly silicic and Ca-poor, K-rich in bulk composition, and extremely fractionated in terms of K/Rb, K/Cs, Mg/Li, Al/Ga, K/Ba, Ca/Sr, Ca/Y and Rb/Sr

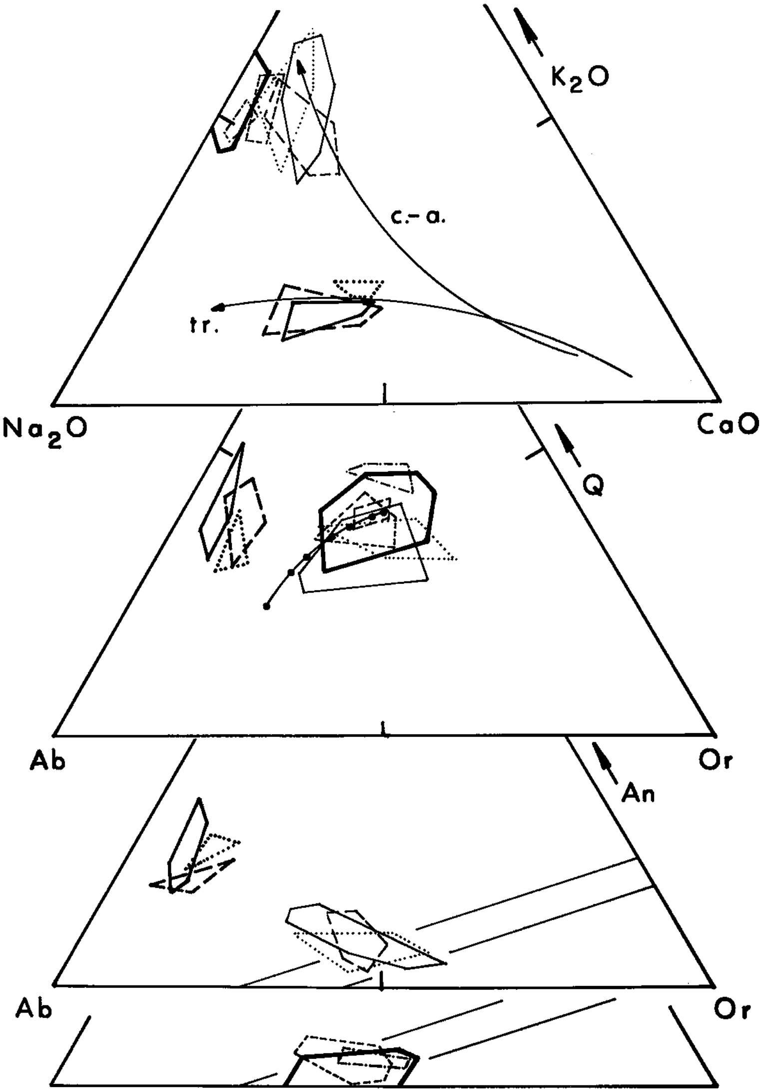


FIG. 30. Na_2O–K_2O–CaO, Ab–Or–Q and Ab–Or–An (mesonorm) diagrams for granitoid rocks of the Winnipeg River pegmatite district. Maskwa Lake batholith (long dash), Marijane Lake batholith (dots) and Lac-du-Bonnet batholith (solid line): tonalites (heavy) and biotite granites (light); Lac-du-Bonnet leucogranite (short dash), metarhyolites of the Peterson Creek Formation (dash–dot) and fine-grained leucogranite phases of the pegmatitic granites (extra heavy outline); tr. trondhjemitic trend, c.-a., calc-alkaline trend (after Barker & Arth 1976). In the Ab–Or–Q mesonorm diagram, thin line connecting solid dots marks granitic minima and eutectics from 1 to 10 kbar (after Tuttle & Bowen 1958, Luth *et al.* 1964). In the Ab–Or–An mesonorm diagram, the low-temperature trough covers the range of 1 to 10 kbar (after Kleeman 1965). After Černý *et al.* (1981).

ratios. The compositional data exclude any genetic relationship with either the tonalites or biotite granites discussed above. A separate line of descent is apparent from trace-element, stable-isotope and REE data, but the available evidence is not sufficient for unequivocal def-

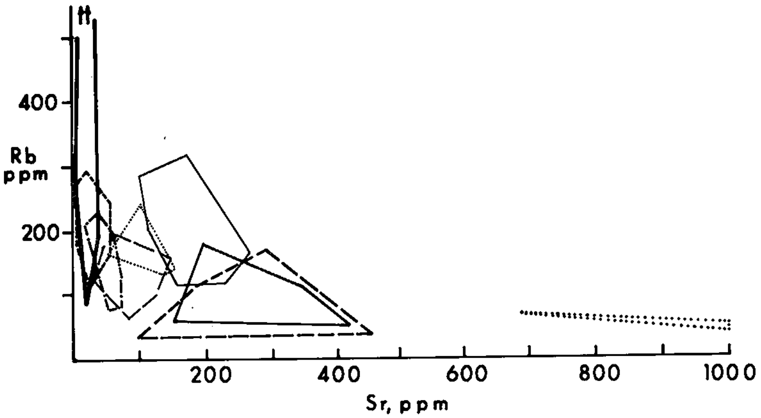


FIG. 31. Rb *versus* Sr diagram for the granitic rocks of the Winnipeg River pegmatite district. Symbols as in Figure 30. After Černý *et al.* (1981).

inition of their origin (Černý *et al.* 1981, Goad & Černý 1981, Longstaffe *et al.* 1981). Fractionation from a juvenile I-type granitoid source modified by reaction with supracrustal sequences, is one possibility. It may include a relationship to one of the rhyolite formations of the greenstone belt (Table 10, Figs. 30 to 32). Shallow anatexis of greenstone-belt lithologies, particularly metapelite and metarhyolite, followed by crystal–melt and liquid fractionation is another possible mechanism.

Table 11 summarizes the geochemical and mineralogical characteristics of the individual leucogranites and pegmatitic granites, and of the pegmatite groups in the district. In conjunction with Figure 29, these data indicate a good correlation between the major intrusions and their spatially associated pegmatite aureoles. Further geochemical documentation is given by Černý *et al* (1981). Current research conducted in the western part of the Superior Province indicates that the petrogenetic relationships of mineralized pegmatites established in the Winnipeg River district are characteristic of numerous other districts and fields (Breaks 1982, Ucakuwun 1981, Černý, unpubl. data).

At present market conditions, some pegmatites in this district are marginally economic for Ta and Be, and several pegmatites can produce refractory-grade spodumene. The only deposit currently productive is the Tanco pegmatite, a member of the Bernic Lake group, with major reserves of Li, Ta, Be and Cs (Crouse *et al.* 1979).

The Preissac–Lacorne pegmatite district. This pegmatite district is located in the Abitibi Subprovince, just north of its faulted boundary with the Pontiac Subprovince in Quebec (Fig. 28, No. 7; Fig. 33). Most of the information on this district comes from Tremblay (1950), Rowe (1953), Ingham & Latulippe (1957), Siroonian *et al.* (1959), Dawson (1966), Goodwin & Ridler (1970) and Jolly (1978).

The pegmatite district is centred around the Preissac–Lacorne batholith, which upwarped an anticlinal dome in the greenstone sequence. The batholith is surrounded by synformal troughs with coincident regional faults. The regionally developed greenschist grade of the metavolcanic rocks is elevated to amphibolite facies in a contact-metamorphic aureole mantling the batholith. Dawson (1966) considered 2.63 Ga to be the most probable age of the Preissac–Lacorne batholith.

The batholith outcrops in three massifs, Preissac, Lamotte and Lacorne, separated by synclinal schist bands on the surface but continuous at depth (Fig. 33). The batholith consists mainly of hornblende monzonite, granodiorite and leucogranite, with minor hornblende diorite and monzodiorite.

Bulk chemical compositions and Li contents of whole rocks and their micas are given in Table 12 for the three major rock-types. A partial overlap of the hornblende monzonite and granodiorite categories of Siroonian *et al.* (1959) and Dawson (1966) is not detrimental to the present survey but should be kept in mind. According to Dawson, granodiorite represents the parent-melt composition, which yielded the leucogranite by fractionation; all other lithologies, which are quartz-poor and mafic, originated by contamination of the granodiorite *via* digestion of metavolcanic rocks,

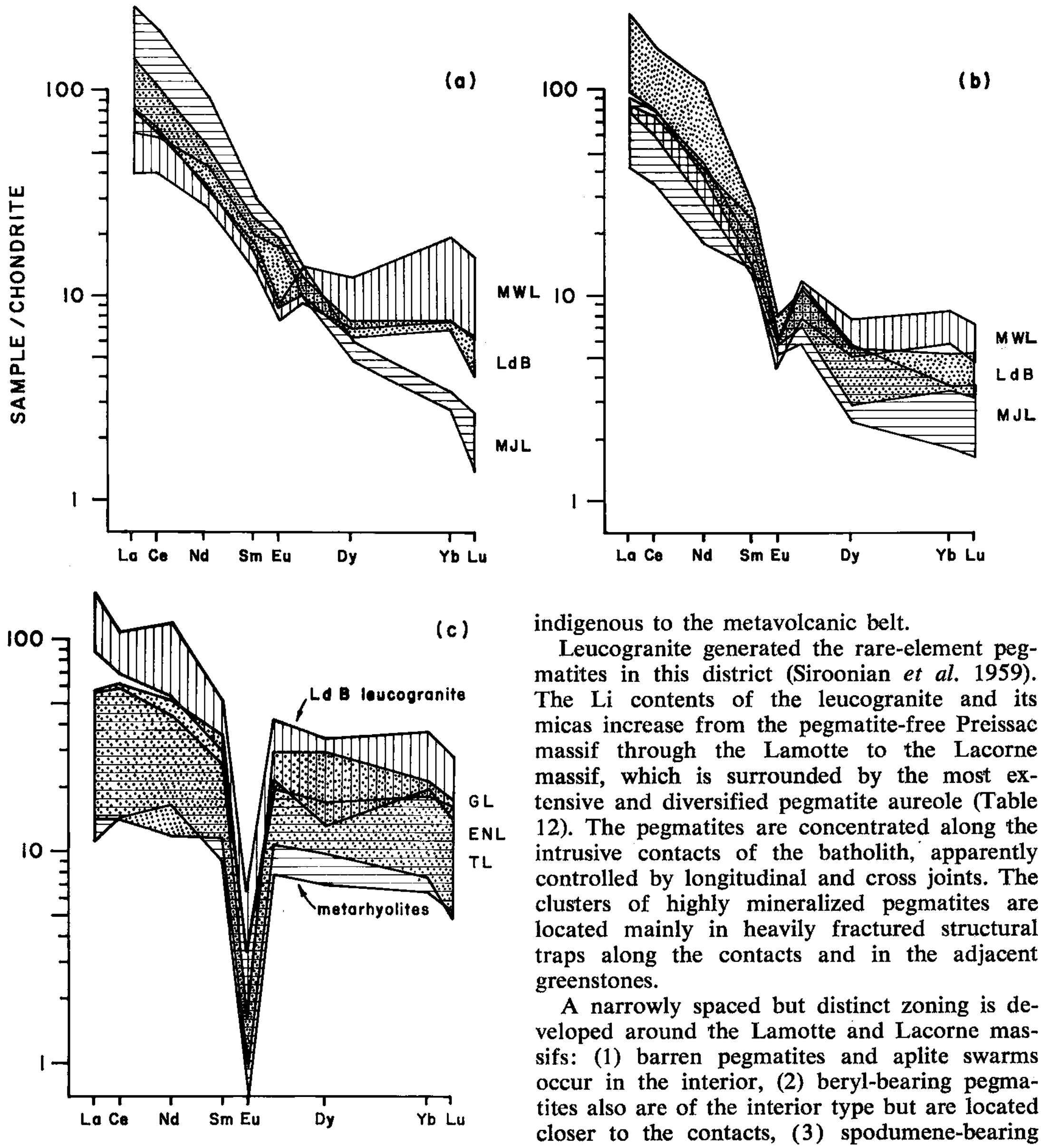


FIG. 32. REE abundances in the granitic rocks of the Winnipeg River pegmatite district: (a) tonalites, (b) biotite granites, (c) silicic types. After Černý *et al.* (1981). For abbreviations of unit names, see Fig. 29.

whose abundant xenoliths are dispersed throughout these rock types. However, Card (1981) suggested that the leucogranite formed by anatexis of metasediments (possibly Pontiac gneisses underlying the Abitibi belt), and it happened to intrude the early granodiorites to tonalites indigenous to the metavolcanic belt.

Leucogranite generated the rare-element pegmatites in this district (Siroonian *et al.* 1959). The Li contents of the leucogranite and its micas increase from the pegmatite-free Preissac massif through the Lamotte to the Lacorne massif, which is surrounded by the most extensive and diversified pegmatite aureole (Table 12). The pegmatites are concentrated along the intrusive contacts of the batholith, apparently controlled by longitudinal and cross joints. The clusters of highly mineralized pegmatites are located mainly in heavily fractured structural traps along the contacts and in the adjacent greenstones.

A narrowly spaced but distinct zoning is developed around the Lamotte and Lacorne massifs: (1) barren pegmatites and aplite swarms occur in the interior, (2) beryl-bearing pegmatites also are of the interior type but are located closer to the contacts, (3) spodumene-bearing pegmatites are typically marginal, on both sides of the contacts, and (4) molybdenite-bearing pegmatites transitional into Mo-, Bi-, Fe-bearing quartz veins are external, followed by a zone of hydrothermal Au mineralization.

Pegmatites of geochemical types 3A, 2 and 5A are thus represented in the district, with a single pollucite-bearing pegmatite approaching type 4. Features typical of the different types of pegmatite are given in Table 13. Molybdenum, beryllium and lithium reserves are quoted by Vokes (1963), Mulligan (1968) and Flanagan (1978), respectively.

TABLE 10. CHEMICAL COMPOSITION OF SILICIC GRANITOID ROCKS OF THE WINNIPEG RIVER PEGMATITE DISTRICT*

	1	2	3	4	5	6	7	8
SiO_2	77.15	79.55	76.30	77.75	77.10	75.90	73.50	75.30
Al_2O_3	12.88	11.26	12.10	11.53	12.28	13.48	14.40	14.30
TiO_2	0.02	0.08	0.10	0.06	0.03	0.01	0.03	0.04
Fe_2O_3	0.48	0.28	0.96	0.92	0.31	0.35	0.47	0.86
FeO	0.40	0.12	0.76	0.52	0.68	0.26	0.88	0.92
MnO	0.02		0.049	0.01	0.01	0.01	0.03	0.08
MgO	0.32	0.03	0.035	0.05	0.20	0.03	0.09	0.03
CaO	0.22	0.13	0.32	0.34	0.42	0.31	0.36	0.21
Na_2O	2.95	1.99	3.48	3.66	3.23	3.68	3.98	5.20
K_2O	4.89	5.54	5.17	4.94	5.24	5.41	5.63	2.19
P_2O_5	0.01		0.030	0.02	0.06	0.98	0.05	0.06
CO_2	0.13	0.03	0.076	0.03	0.02	0.03	0.09	0.08
H_2O	0.65	0.39	0.24	0.21	0.52	0.34	0.23	0.55
	100.11	99.40	99.62	100.04	100.10	99.89	99.74	99.82
Li	19	25	72	10	42	57	28	76
Rb	243	264	370	154	168	340	275	442
Cs	2.9	1.2	2.7	2	4	13.7	3.2	2.3
Be	1.9	2.2	2.2	2	1	3	0.5	1.7
Sr	13	27	2	28	3	20	43	31
Ba	nd**	21	52	145	244	142	50	1
Pb	17	18	15	12	30	33	20	11
Ga	32	5	34	30	27	45	62	64
U	nd	13	14	6	36	9	3	8
Th	30	40	40	15	15	25	nd	5
Zr	121	103	142	217	130	58	5	16
Hf	6.05	4.7	7.75	6.75	4.35	1.2	0.45	1.25
Sn	9	2	11	12	3	8	13	23
K/Rb	167	174	116	266	259	132	170	41.2
K/(Csx100)	140	383	158	205	108	32	145	79
K/Ba		219	825	289	178	316	934	18200
Ba/Rb		0.08	0.14	0.94	1.45	0.42	0.18	0.002
Ba/Sr		0.8	26	5.2	81.3	7.10	1.16	0.03
Rb/Sr	18.7	9.8	185	5.5	56	17	6.4	14.3
Mg/Li	100	11.2	2.9	30	28.7	3.2	20	2.7
Zr/Sn	13.4	51.5	12.9	18.1	43.3	7.2	0.4	0.7
Zr/Hf	20	21.9		32.1	29.9	48.3	11.1	12.8
Al/Ga	2128	11920	1882	2033	2407	1584	1229	1183
La	14.2	6.2	35.85	39.9	19.7	5.5	2.85	7.05
Ce	43	20	97	76	46	16.5	8	18.5
Nd	29.5	14	44	39	5.5	<5	<3.5	6.5
Sm	5.9	2.83	9.59	6.79	7.25	2.95	1.64	4.69
Eu	<0.07	<0.06	0.18	0.25	0.18	<0.08	<0.08	<0.05
Dy	9.85	5.75	12.05	6.3	8.9	7.15	2.55	5.85
Yb	4.35	2.45	7.5	4.95	4.7	3.35	1.3	2.7
Lu	0.62	0.32	0.92	0.59	0.56	0.32	0.13	0.26
Y	53	14	88	35	61	40	17	32

* from Černý et al. (1981); ** not detected. 1. metarhyolite, Peterson Creek Formation, anal. BRGB-5; 2. metarhyolite, Peterson Creek Formation, anal. 74-8; 3. Lac-du-Bonnet leucogranite, anal. SR-95; 4. Lac-du-Bonnet leucogranite, anal. PG-137; 5. Tin Lake fine-grained leucogranite, anal. TNL-31; 6. Greer Lake fine-grained leucogranite, anal. GLW-38a; 7. Tin Lake pegmatitic leucogranite, anal. TL-1006; 8. Greer Lake pegmatitic leucogranite, anal. GL-1003.

In conclusion, current activities in the district have revealed that the leucogranites, at least in part, are pegmatitic; detailed investigation may prove the regional relationships to be much more complex than outlined above (J.S.D. Parker, pers. comm. 1981, Card 1981).

Summary. The rare-element pegmatites of the Superior Province, as classified in Table 8, can be correlated with Kuzmenko's (1976) general subdivision of magmatogenic pegmatites, with our classes 1 to 4 corresponding to his types 1 to 4, respectively. The whole population of pegmatites of the Superior Province may possibly be considered a giant-size pegmatite province of Gordiyenko's (1974) Li-, Cs-bearing type A, because of the widespread occurrences of pollucite. Such a designation definitely applies to the western part, west of the Kapuskasing Subprovince. In the eastern part, there is only a single occurrence of pollucite on record, but there is a potential for further discoveries of highly fractionated pollucite-bearing pegmatites in this largely unexplored region.

Internally, three pegmatite belts may be distinguished within the province: (1) the Li,Rb,Cs, Ta,Be,Sn-bearing English River pegmatite belt, (2) the Li,Be(Nb-Ta)-bearing Quetico pegmatite belt, and (3) the less distinct Li,Be,Mo(Nb-Ta, Cs)-bearing Pontiac pegmatite belt; each of these belts also includes the pegmatitic occurrences disposed along the outside of their boundaries. Definition of belt-size units is not feasible at present in the northern Sachigo and Opatica subprovinces owing to insufficient exploration and lack of regional geological understanding. It is mainly in these regions that a great potential remains, even for surface pros-

TABLE 11. CORRELATION OF ACCESSORY MINERAL CONTENT AND SOME GEOCHEMICAL CHARACTERISTICS OF PARENT GRANITOID ROCKS AND THEIR PEGMATITE AUREOLES IN THE WINNIPEG RIVER PEGMATITE DISTRICT*

	Major intrusion			Associated pegmatites		
Typical accessory minerals	Local mineralization	Avg. whole rock K/Rb,K/Cs Mg/Li	Typical accessory minerals	Rare-element association	Avg. K/Rb,Cs (ppm) in blocky K-feldspars	Geochemical type (Table 8)
Marijane Lake biotite granite			Border pegmatites			
zircon, allanite	-	173; 13,250 83	zircon, thorite, uraninite, allanite	U,Th,Zr,REE	150; 23	1
?			Lac-du-Bonnet group (LdB)			
			spodumene ((triphylite))	Li	14; 580	2
Lac-du-Bonnet leucogranite			Shatford Lake group (SHL)			
zircon, allanite monazite, ((garnet))	((Be))	190; 18,400 28	beryl, garnet, topaz, allanite, monazite, zircon, thorite, uraninite, columbite-tantalite, gadolinite, cassiterite	Be,Nb/Ta,Sn, REE,U,Th,Zr/Hf	66; 61	3B
Tin Lake pegmatitic granite (TL)			Birse Lake group (BIS)			
garnet ((tourmaline))	((Mo))	176 6,800 49	tourmaline, beryl	Be((Li,Nb/Ta))	119; 52	3A
Greer Lake and Eaglenest pegmatitic granites			Greer Lake and Eaglenest Lake groups (GL,ENL)			
garnet, cordierite, (gahnite)	Be,Nb/Ta,Li,Rb,Cs	81; 4,750 5.3	garnet, cordierite, beryl, columbite-tantalite (gahnite, monazite, zircon, cassiterite)	Be,Nb/Ta ((Li,Sn))	40; 125	3A
Osis Lake pegmatitic granite (OL)			Rush Lake group (RL)			
garnet, tourmaline, apatite, (triphylite)	((Li))	131; 2,800 11.5	tourmaline, beryl, spodumene, petalite, amblygonite, triphylite, (Nb/Ta-oxide minerals, cassiterite) ((pollucite))	Li,Rb,(Cs),Be, Sn,Nb/Ta,F,B	50; 265	4
(unexposed; presumed pegmatitic granite)			Bernic Lake group (BL)			
			tourmaline, beryl petalite (spodumene, eucryptite), lepidolite, pollucite, cassiterite, Nb/Ta-oxide minerals, amblygonite, triphylite	Li,Rb,Cs,Be, Sn,Nb/Ta, F,B	9.5; 1262	4

*adjusted after Černý et al. (1981) ; ( ) rare, (( )) very rare.

pecting. However, geochemical exploration for hidden bodies should reveal new deposits also in the better-known belts in the south.

The granites parental to rare-element pegmatites are typically biotite–muscovite-, muscovite-, or muscovite–garnet-bearing, silicic, peraluminous, potassic to sodic, late-tectonic to post-tectonic stocks and plutons of small to intermediate size; they are characterized by increased Li, Rb, Cs, Be, Sn, B and Ga contents. These granites and the accompanying pegmatite swarms should be sought (1) along large-scale structural breaks, particularly the deep faults bounding and crossing major sedimentary troughs, and along subprovince boundaries marked by high geothermal gradients, (2) along margins of regional batholiths bordered by greenstone belts, (3) inside the metasedimentary subprovinces in areas of steep thermometamorphic gradients, and (4) mainly in regions of greenschist-facies metamorphism as represented by chlorite, muscovite, andalusite, cordierite, anthophyllite and staurolite in metapelites. In the first two cases, greenstone belts were the preferred hosts, providing structural traps in the waning stages of tectonic activity. In the third case, the anatectic granites commonly appear nearly autochthonous within their meta-

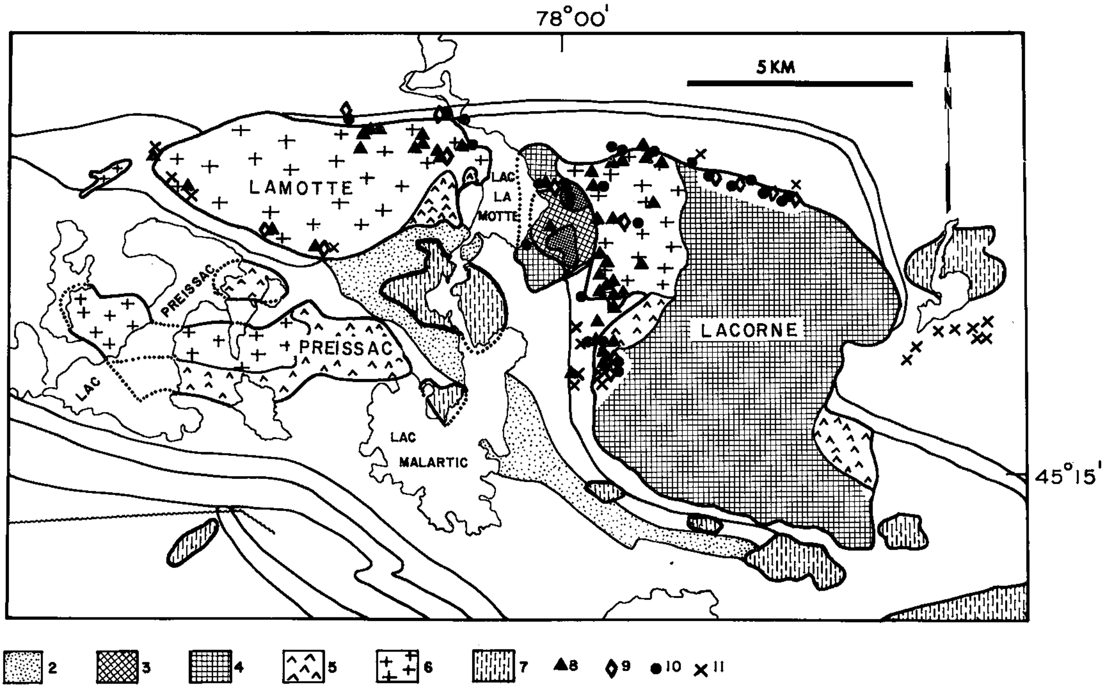


FIG. 33. The Preissac–Lacorne pegmatite field. Blank areas are undivided greenstone-belt schist and minor paragneiss, 2 gabbro, serpentinite, 3. hornblende diorite, 4. hornblende monzonite, 5. biotite granodiorite, 6. leuco-granite, 7. satellitic and unrelated granitic rocks, 8. beryl-bearing pegmatite, 9. Nb–Ta-bearing pegmatite, 10. spodumene pegmatite, 11. molybdenite-bearing pegmatite. After Siroonian *et al.* (1959), Mulligan (1965) and Dawson (1966).

TABLE 12. CHEMICAL COMPOSITION OF THE MAIN PHASES OF THE PREISSAC-LACORNE BATHOLITH

	1	2	3	4
SiO_2	59.64	67.94	73.69	73.05
Al_2O_3	16.06	16.49	14.54	17.21
TiO_2	0.53	0.28	0.07	
Fe_2O_3	1.81	1.03	0.37	0.23
FeO	3.59	1.71	1.03	
MnO	0.10	0.03	0.03	
MgO	4.11	1.34	0.43	0.48
CaO	5.12	3.05	1.19	1.29
Li_2O				1.64
Na_2O	5.00	5.08	4.24	5.02
K_2O	2.77	2.28	3.69	1.47
P_2O_5	0.24	0.12	0.03	
CO_2	0.00	0.06	0.06	
H_2O	0.76	0.13	0.44	
	99.73	99.54	99.81	100.39
Li(ppm), whole rock*				
Preissac	7	50	87	
Lamotte		83	127	
Lacorne		25	248	

Li(ppm), micas in leucogranite**	biotite	muscovite
Preissac	1530	1110
Lamotte	2640	2260
Lacorne	3010	3050

1 - hornblende monzonite, Dawson (1966); average of 11 analyses
2 - granodiorite, Dawson (1966); average of 29 analyses
3 - leucogranite, Dawson (1966); average of 34 analyses
4 - spodumene pegmatite, Rowe (1953); Lacorne Lithium Property
* Siroonian et al. (1959); averages of up to 14 analyses
** Siroonian et al. (1959): averages of up to 13 analyses

TABLE 13. REGIONAL ZONING OF PEGMATITES IN THE PREISSAC-LACORNE FIELD*

Relation to contacts**	Pegmatite type (Table 8)		Shape and internal structure	Characteristic accessory minerals
interior	barren	-	irregular to fracture-filling; homogeneous to poorly zoned	garnet
interior	Be(±Nb-Ta)	3A	fracture-filling; well zoned	garnet, beryl (columbite-tantalite)
marginal to exterior	Li(Be,Nb-Ta)	2	fracture-filling; poorly to well zoned	spodumene, beryl (garnet, tourmaline, columbite-tantalite, Li-micas)((pollucite, fluorite, bismuth, sphalerite, molybdenite))
exterior	Mo(±Be,Bi)	5A	fracture-filling; poorly to well zoned; transitional into feldspar-poor quartz veins	molybdenite (pyrite, bismuthinite, beryl, tourmaline)

* After Vokes (1963), Mulligan (1965)
** This relates to the outer contacts of internally complex plutons, not necessarily to the contacts of parental intrusive phases (leucogranites).

sedimentary sources, and the pegmatites may have entered earlier structures dilated during granite segregation and intrusion.

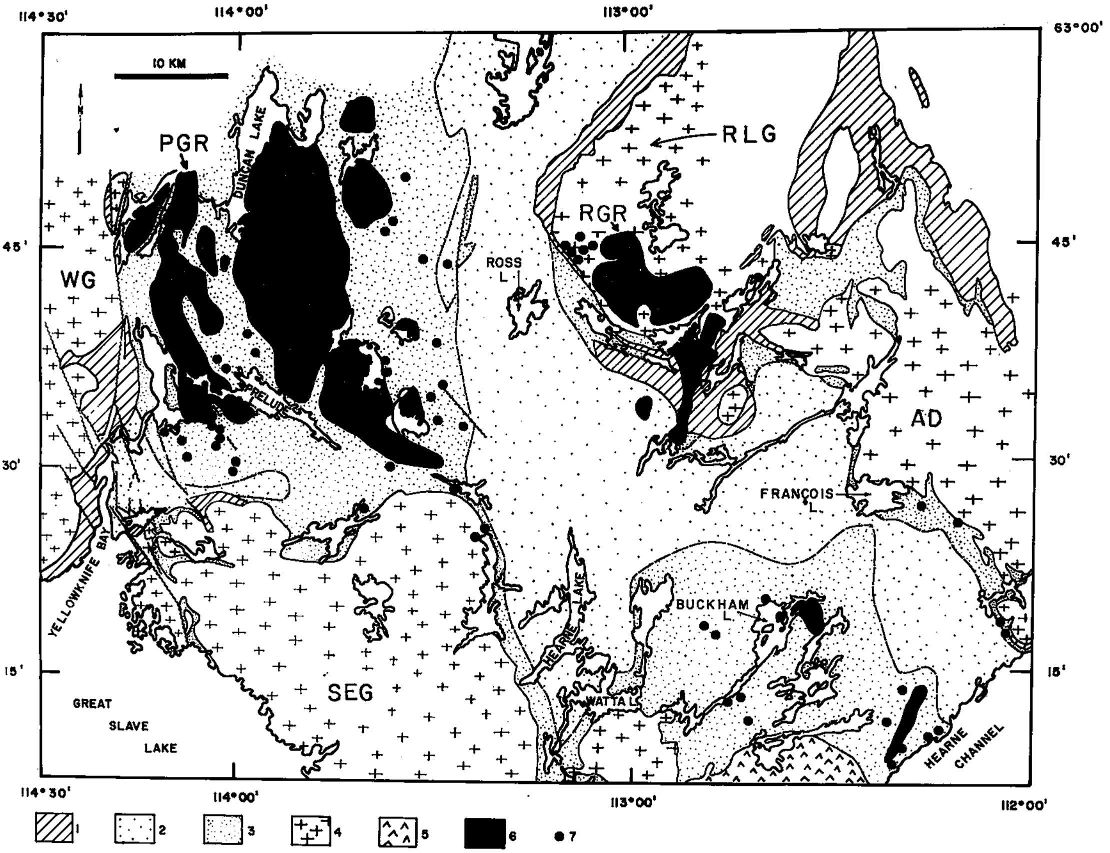


FIG. 34. The Yellowknife pegmatite field. 1. metavolcanic rocks, 2. greenschist-facies metasediments, 3. cordierite–andalusite–sillimanite-bearing thermal aureoles in metasediments, 4. tonalite, granodiorite, granite, 5. Blachford Lake alkalic complex, 6. (pegmatitic) biotite–muscovite granite and leucogranite, 7. pegmatite bodies and groups. WG Western granodiorite. SEG Southeastern granodiorite, PGR Prosperous Lake granite, RLG Ross Lake granodiorite, RGR Redout Lake granite, AD Eastern granite. After Mulligan (1965), Green & Baadsgaard (1971), Dawson (1974), Ramsay & Kamineni (1977), Lasmanis (1978) and Drury (1979).

The Slave Province

To date, only a single pegmatite-bearing region has been identified in this province. The Yellowknife pegmatite field is located in its southernmost part and extends over an area of approximately 8,000 km². However, beryl occurrences near Lac-de-Gras and Aylmer Lake and spodumene at Clinton–Colden Lake suggest the presence of additional pegmatite districts (Lord 1951, Henderson *et al.* 1982). The following compilation of data on the Yellowknife field is based mainly on papers by Joliffe (1944), Rowe (1952), Hutchinson (1955), Boyle (1961), Kretz (1968), Green & Baadsgaard (1971), Ramsay & Kamineni (1977), Lasmanis (1978), Drury (1979) and Jenner *et al.* (1981), and on a current investigation by R. E. Meintzer and P. Černý (unpubl. data). The age data are quoted mainly from Green & Baadsgaard (1971).

The Yellowknife pegmatite field. This pegmatite field is hosted by the basal metavolcanic rocks and superposed metasediments of the Yellowknife Supergroup (Fig. 34). The subordinate metavolcanic rocks (2.67 Ga) outcrop only as a segmented fringe of the complexly folded metasedimentary sequence, probably uptilted by the intrusion of syntectonic to late-tectonic tonalite–granodiorite–granite batholiths (2.64–2.59 Ga). The Western, Southeastern, and Ross Lake granodiorites and the granite east of François Lake delineate the extent of the pegmatite field. Numerous small stocks to batholiths of biotite–muscovite granite (2.575 Ga), with a pegmatitic facies along their margins and accompanied by pegmatite swarms, perforate the metasedimentary rocks and the margin of the Ross Lake granodiorite. Most of these post-tectonic granites were emplaced along the axes of north- to northwest-trending crossfolds.

The metasediments comprise a monotonous sequence of metagreywacke and metapelite metamorphosed to the greenschist facies, with the chlorite–muscovite assemblage upgraded locally to biotite–garnet–staurolite-bearing amphibolite-facies assemblages. These areas of increased grade are due to incipient thermal doming, followed by intrusion of granodiorite and granite. Contact-metamorphic effects of these late plutons superimposed over the earlier assemblages produced an inward-zoned sequence of cordierite (gedrite), andalusite and sillimanite. The variable extent of these thermal aureoles suggests that the process was much more intense around the post-tectonic granites than at the borders of the early granodiorite and granite batholiths.

The syntectonic batholiths have variable abundances of plagioclase–quartz–K-feldspar–hornblende (or biotite, or both). The biotite–muscovite granites are much more diversified in mineralogy: the ratio K-feldspar/plagioclase is somewhat variable, as is the biotite/muscovite ratio and the spatial distribution of the micas (Kretz *et al.* 1982). Garnet and tourmaline are widespread in some granites but may be absent in others. Beryl and spodumene occur sporadically in the outer pegmatitic portions of the granites.

Chemical compositions of the main types of granitoid rocks are shown in Table 14 and in Figure 35. The silicic, potassic and peraluminous bulk composition of the late granites is clearly distinct from the more intermediate compositional characteristics of the earlier tonalites and granodiorites. The granites are also distinguished from the syntectonic batholiths by the Rb/Sr ratios and REE abundances. Drury (1979) proposed a derivation by partial melting at mantle depth for the syntectonic batholiths, and a high degree of partial melting of the Yellowknife metasediments for the generation of the post-tectonic granites (Fig. 10). This mode of formation of the latter type of granite is also supported by Jenner *et al.* (1981).

TABLE 14. CHEMICAL COMPOSITION OF THE PRINCIPAL GRANITOID ROCKS OF THE YELLOWKNIFE PEGMATITE FIELD

	1	2	3	4	5	6	7	8	9
SiO_2 (%)	68.39	68.35	59.45	65.52	65.90	71.15	72.10	71.44	74.09
Al_2O_3	15.71	15.49	19.02	16.29	16.34	14.92	15.00	14.85	14.30
TiO_2	0.33	0.26	0.80	0.38	0.51	0.28	0.13	0.13	0.14
Fe_2O_3	3.08*	2.36*	0.78	3.64*	0.44	0.31	1.56*	1.54*	0.18
FeO			4.56		4.01	1.99			0.99
MnO	0.06	0.07	0.08	0.05	0.04	0.05	0.03	0.05	0.02
MgO	0.85	1.34	2.02	1.26	1.18	1.02	1.21	1.23	0.31
CaO	2.36	1.69	5.69	3.68	2.87	1.70	0.91	0.88	0.82
Na_2O	4.91	4.15	4.60	3.63	4.00	4.48	3.93	3.82	3.61
K_2O	2.41	4.18	1.64	2.75	3.20	2.79	4.95	5.15	5.08
P_2O_5	0.06	0.10	0.14	0.09	0.24	0.08	0.09	0.12	0.26
CO_2			0.06		nd	0.30			0.0
H_2O-			0.06		0.06	0.04			0.04
H_2O+			0.82		1.08	0.68			0.23
			99.72		99.87	99.79			100.07
Corundum(CIPW)			0.0		0.0	2.33			2.00
Rb (ppm)	49	118		72			252	346	
Sr	196	279		247			64	66	
Ba	679	936		669			491	544	
Th	8	11		4			37	36	
La	15	24		19			41	45	
Ce	22	45		30			73	75	
Nd	10	19		16			28	24	
Sm	2.4	3.3		3.4			5.6	4.5	
Eu	0.6	0.78		0.95			0.48	0.47	
Gd	nd	3.0		2.7			nd	nd	
Tb	0.3	0.4		0.3			0.75	0.72	
Tm	0.2	0.1		0.1			0.2	0.2	
Yb	0.67	0.91		0.52			1.81	1.55	
K/Rb	408	294		317			163	123	
Rb/Sr	0.25	0.42		0.29			3.94	5.24	

* total Fe as FeO; nd not detected. 1. granodiorite, Western granodiorite (Drury 1979, anal. 2); 2. granite, Western granodiorite (Drury 1979, anal. 1); 3. tonalite, Southeastern granodiorite (Green & Baadsgaard 1971, anal. 2); 4. granodiorite, Southeastern granodiorite (Drury 1979, anal. 3); 5. granodiorite, Southeastern granodiorite (Green & Baadsgaard 1971, anal. 3); 6. granodiorite, Ross Lake granodiorite (Green & Baadsgaard 1971, anal. 4); 7. granite, Prosperous Lake granite (Drury 1979, anal. 4); 8. granite, Prosperous Lake granite (Drury 1979, anal. 5); 9. granite, Prosperous Lake granite (Green & Baadsgaard 1971, anal. 7).

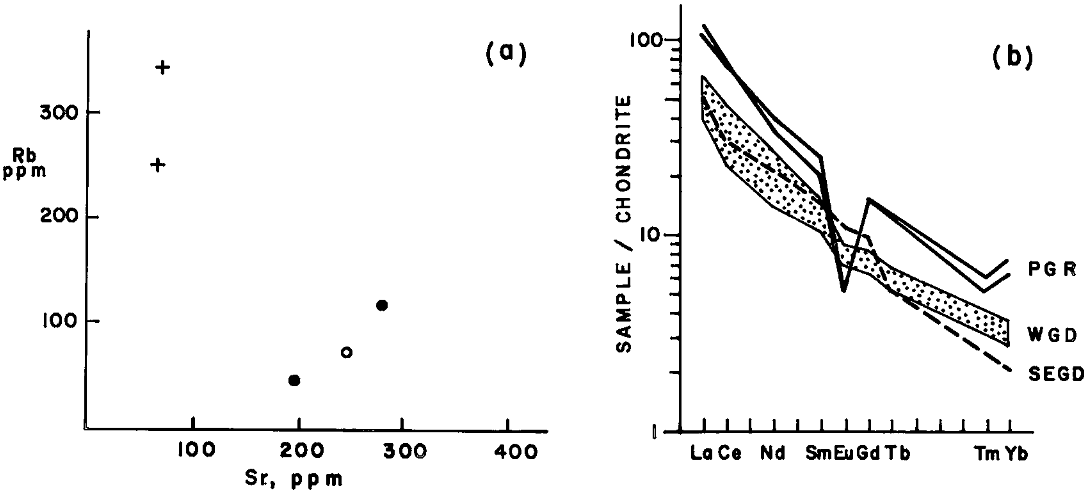


FIG. 35.(a) Plot of Rb *versus* Sr of the granitic rocks of the Yellowknife pegmatite field; pegmatitic granites (crosses), Western granodiorite units (solid dots) and Southeastern granodiorite (open circle), (b) REE abundances in the post-tectonic Prosperous Lake granite (PGR), and in the early-tectonic Western granodiorite (WGD) and Southeastern granodiorite (SEGD). From data by Drury (1979).

The rare-element pegmatites are more or less tightly clustered around the late granite plutons, within their contact aureoles. They also occur in a narrow zone along the southwestern margin of the eastern granite batholith. Structural control of the pegmatites is complex, including different types of fracture sets, bedding, foliation and pre-existing intrusive contacts. As documented by Kretz (1968, Figs. 5, 16) on a relatively small scale, the structural control can be expected to have been widely different across the pegmatite field.

From a gross geochemical viewpoint, the Yellowknife pegmatites belong to Kuzmenko's (1976) types 2, Li(Be,Nb–Ta), and 3, Be(Nb–Ta), with Sn rather low in both types. Characteristic accessory minerals, variable in abundance depending on the pegmatite type and area, are spodumene (up to 25%), beryl, columbite–tantalite, tapiolite, garnet and tourmaline; sporadically found are gahnite, andalusite, cordierite, lithiophilite and amblygonite. Only rarely are lepidolite, scheelite, cassiterite, fluorite, zircon and (unconfirmed) petalite encountered.

Despite the lack of detailed information on the mineralogy of some of the pegmatite swarms (particularly those in the southeast), and the general absence of trace-element data, three principal types of pegmatite populations can be tentatively distinguished. (1) In the Prosperous Lake – Prelude Lake area, most of the mineralized pegmatites consist of large, poorly zoned to homogeneous bodies with abundant spodumene and beryl; they occur in local dyke swarms; Nb–Ta-oxide minerals are scarce; regional zoning of pegmatite types around the granites is developed only locally. (2) East and west of Ross Lake, beryl and Nb–Ta-oxide minerals are much more abundant; internal zoning of rare-element pegmatites is better developed; a classic regional zoning is developed around the Redout Lake granite (Hutchinson 1955), with an outward sequence of barren, Be-, Be,Nb–Ta-, and Li,Nb–Ta-bearing pegmatites. (3) Between Buckham Lake, François Lake and Hearne Channel, most pegmatites are well zoned; Nb–Ta-oxide minerals are widespread; the only occurrence of petalite reported in the whole field, suggestive of a low-pressure regime, is suspected to occur in this area; regional zoning is not evident.

The above sequence of pegmatite areas is marked by decreasing size of outcrop of the granites that are potentially or actually parental to the pegmatites. The three granite-*cum*-pegmatite groups may possibly represent horizontal sections through essentially identical intrusive systems but at three different vertical levels. Sizeable hidden bodies of granite are indicated by the wide contact-metamorphic aureole in the third area, out of proportion to the small granite intrusions. This suggests that this area, near Hearne Channel, could be the most promising for exploration, with a potential for discovery of additional highly fractionated but largely hidden pegmatites.

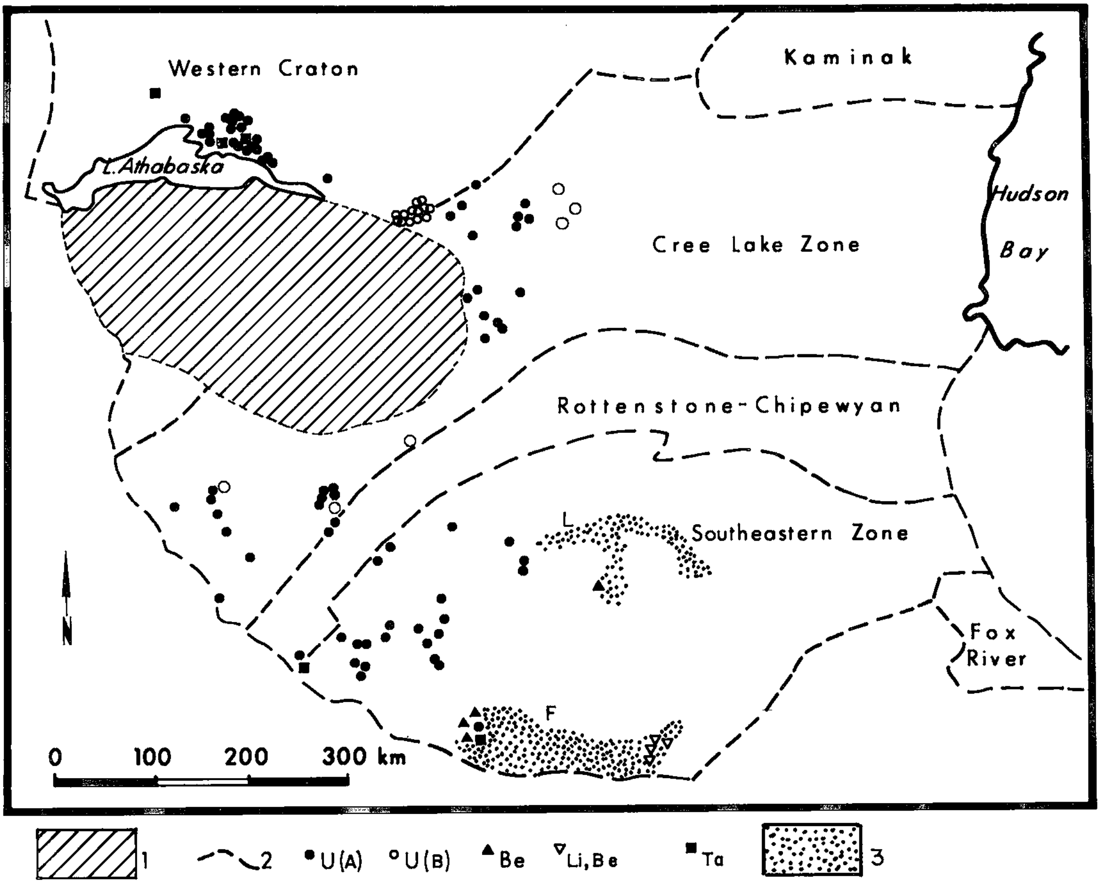


FIG. 36. Distribution of mineralized pegmatites in the southwestern part of the Churchill Province. 1. Athabaska basin, 2. subprovince boundaries, 3. greenstone belts: L Lynn Lake, F Flin Flon. U(A) U-bearing pegmatites in remobilized basement; U(B) U-bearing pegmatites in metapelites. Compiled from Beck (1969), Sibbald (1975), Weber *et al.* (1975b), Sibbald *et al.* (1977), Tremblay (1978) and other sources.

The Churchill Province

Mineralized pegmatites are sporadically distributed in this province; they have been reported only in its southwestern part (Fig. 36). However, the areal restriction may be apparent only, owing to insufficient exploration. Several recent finds of uranium mineralization in Melville Peninsula, the Nonacho Belt (N.W.T.) and the Labrador Fold Belt (Quebec) suggest possibilities in the northern and eastern parts of the Churchill Province (Ruzicka 1978, 1979). Isolated occurrences of columbite (Lord 1951) and lepidolite (R. Mulligan, pers. comm. in Bell 1978) on Baffin Island may also be significant.

Two principal types of rare-element pegmatites can be distinguished in the southwest: (1) the U–Th-bearing pegmatites widespread in most structural subprovinces in Saskatchewan and Manitoba, and (2) the Li–Be-bearing pegmatites confined to the Southeastern Zone Subprovince (Fig. 36).

U–Th bearing pegmatites. Sibbald (1975), Sibbald *et al.* (1977) and Tremblay (1978) distinguished two types of radioactive pegmatites: (1) those generated by Hudsonian remobilization of Archean basement, and (2) those derived from and located within graphitic pelitic gneiss of the Proterozoic (Aphebian) succession.

Remobilization of gneissic and granitoid rocks of the Archean basement produced a multitude of leucocratic, alaskitic granites and pegmatites with elevated contents of U and Th. They are

TABLE 15. CHEMICAL COMPOSITION OF GRANITES ASSOCIATED WITH RADIOACTIVE PEGMATITES, BEAVERLODGE AREA, CHURCHILL PROVINCE*

	1	2	3	4	5	6
SiO_2	70.60	72.00	73.80	74.20	75.10	72.10
Al_2O_3	15.20	15.50	15.90	15.10	13.95	15.20
TiO_2	0.34	0.26	0.06	0.07	0.14	0.14
Fe_2O_3	1.18	0.61	0.95	0.10	0.37	0.54
FeO	1.73	1.80	0.40	0.36	1.07	0.91
MnO	0.01	0.04	0.03	0.02	0.02	0.02
MgO	0.26	0.74	0.14	0.15	0.50	0.20
CaO	1.11	0.99	0.44	0.45	0.37	0.90
Na_2O	3.30	4.03	4.97	8.40	2.88	3.00
K_2O	5.73	4.50	2.53	0.86	5.31	5.21
P_2O_5	0.07	0.04	0.02	0.09	0.02	0.10
H_2O	1.07	0.96	1.30	0.49	1.59	1.07
	100.60	101.47	100.54	100.29	101.32	99.39
CIPW corundum	1.72	2.23	4.24	-	2.84	3.23
K/Rb	205	225	105	108	483	306

1 - Wilson Lake granite, part of a large migmatite-granite complex; anal. no. 7
2 - Higginson Lake granite, large elliptical intrusion; anal. no. 16
3 - Murmac Bay granite sill; anal. no. 5
4 - Gravel pit pegmatitic granite, conformable with enclosing amphibolite; anal. no. 11
5 - Athona mine granite, forked sill in metagabbro; anal. no. 3
6 - Cayzor granite, sill in chlorite-sericite schist; anal. no. 14

*From Beck (1969)

widespread in the Western Craton, Cree Lake Zone and Southeastern Zone subprovinces, but missing in the Proterozoic plutonic Rottenstone–Chipewyan Subprovince. The granites range from nebulous autochthonous masses through masses representing increased degrees of aggregation of granitic materials to clearly intrusive, cross-cutting bodies. In this succession, the granites tend to become more silicic and leucocratic, less calcic and Rb-enriched, but the K-feldspar/plagioclase ratio varies erratically (Beck 1969); some of the most fractionated alaskitic bodies are distinctly sodic. Table 15 illustrates the broad range of the alkali elements in some of the segregated to allochthonous granites that occur in terranes containing radioactive pegmatites (data from Beck 1969).

The mineralized pegmatites form occasional segregations within the granites, in which cases they are considered fractionation products of the anatectic melts (Sibbald *et al.* 1977). However, most of the pegmatites are conformable with migmatitic gneiss and foliated granitoid rocks and can be regarded as direct products of partial melting (Tremblay 1978). Cross-cutting dykes are subordinate, but some of them carry the most diversified mineralization known in this pegmatite type, which is otherwise fairly simple. Oligoclase, K-feldspar and quartz are associated with biotite and subordinate muscovite; late albite is rare. Apatite, fergusonite, allanite, molybdenite, pyrite, pyrrhotite, pyrochlore–microlite, thorite, uranothorite, uraninite, monazite, xenotime, zircon, hematite and ilmenite have been recognized as accessory minerals (Robinson 1955, Watkinson & Mainwaring 1976). Uraninite and other radioactive species are closely associated with biotite.

Radioactive pegmatites located in Early Proterozoic (Aphebian) graphitic pelitic gneisses are rather restricted in their abundance as well as in regional distribution. They are only known from the Cree Lake Zone Subprovince, particularly from the vicinity of its boundaries with the neighboring subprovinces (Fig. 36; Sibbald *et al.* 1977, Weber *et al.* 1975b). The pegmatite bodies are mostly conformable with their gneissic hosts, and homogeneous to crudely zoned. Oligoclase, subordinate K-feldspar, quartz, biotite and subordinate muscovite are the rock-forming constituents. Garnet, zircon, titanite and apatite are common; microscopic uraninite associated with biotite, molybdenite and pyrite are the least abundant species (Mawdsley 1951, Sibbald 1975). Pegmatites of this type appear to have been derived by metamorphic segregation from or anatexis of the enclosing metasediments (Sibbald 1975, Weber *et al.* 1975b). No evidence is available to suggest an origin by fractionation from a magma. The uranium was probably syngenetic with the metapelite sequences, particularly the black shale horizons, and it was readily mobilized under conditions of incipient anatexis.

Li–Be-bearing pegmatites. Occurrences of pegmatites of this type are restricted to the two greenstone belts of the Southeastern Zone Subprovince (Fig. 36). Only a single occurrence of beryl has been recorded from the Lynn Lake belt (Mulligan 1965), but pegmatites are more abundant and diversified in the Flin Flon belt. Beryl-bearing pegmatites with biotite, muscovite, garnet, monazite, magnetite and rare columbite–tantalite occur at the western termination of the belt near Birch Portage (Mulligan 1965, Radcliffe & Campbell 1966), and a field of Li–Be-bearing pegmatites is located in its eastern extremity at Wekusko Lake (Fig. 37). Both fields are located in severely faulted areas that have steep metamorphic gradients. No further generalities can be deduced from two isolated areas; some details on the second area are presented below.

The Wekusko Lake pegmatite field. Most of the information on the geology and petrology of this field comes from Bailes (1971, 1975, 1980), Moore & Froese (1972), Froese & Gasparrini (1975), Froese & Moore (1980), Bell (1978), Shanks (1979) and Černý *et al.* (1981); the last

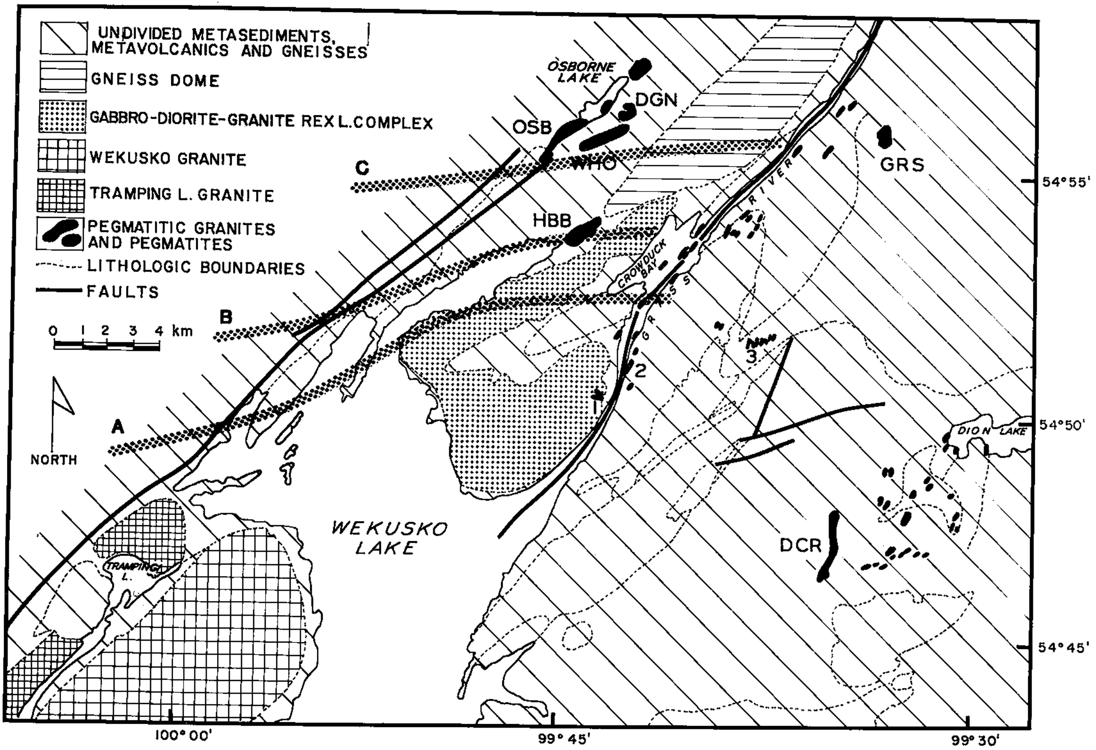


FIG. 37. The Wekusko Lake pegmatite field: 1. Sherritt Gordon pegmatites, 2. Violet–Thompson pegmatites, 3. Green Bay pegmatites. Pegmatitic granites: OSB Osborne Lake, DGN Doughnut, WHO White Owl, HBB Herb Bay, GRS Grass River, DCR Dion Creek. Metamorphic isograds: A. staurolite-in, B. sillimanite-in, C. staurolite-out. Simplified from Černý *et al.* (1981).

paper also deals with the pegmatites and their regional setting.

The predominant rocks within the pegmatite field belong to two metavolcanic–metasedimentary sequences typical of greenstone belts, the Amisk and Missi groups. Their complex lithologies are not distinguished in Figure 37. Paragneiss and migmatite in the eastern and southeastern extremities of the area covered by Figure 37 may represent high-grade counterparts of the metasediments. In general, however, metamorphic grade increases from a metapelitic chlorite + garnet assemblage predominant in the south through staurolite-in, sillimanite and staurolite-out isograds to beginning metatexis along the northern margin.

A series of granitoid intrusions is largely, but not totally, confined to a northeasterly-trending belt bounded by prominent fault systems (Fig. 37). The syntectonic gneiss dome in the northeastern part of this belt belongs to the earliest intrusions emplaced during the peak of regional dynamometamorphism. It probably represents a diapiric rise of low-density rhyolitic volcaniclastic rocks (Bailes 1980). The Rex Lake pluton central to the region is a late-tectonic gabbro – diorite – granodiorite (– granite) complex that preceded the intrusion of the Wekusko and Tramping Lake biotite granites in the southwestern part of the belt. These are late- to post-tectonic, rarely showing indications of post-consolidation deformation.

A series of pegmatitic granite intrusions closely follows the two fault zones. They are distributed over the whole metamorphic gradient, from the metapelitic chlorite + garnet assemblage in the south across the staurolite-in, sillimanite, and beyond the staurolite-out isograds. Most of the pegmatitic granites are elongate, ovoid to crescentic in shape, and have forcibly deflected the neighboring schists. Those along Grass River are smaller, lenticular and conformable with the enclosing schists and with the strike of the regional fault. K-feldspar, plagioclase (An_{3-8}) and quartz are accompanied by subordinate muscovite ± biotite,

TABLE 16. CHEMICAL COMPOSITION OF LATE GRANITES OF THE WEKUSKO LAKE PEGMATITE FIELD*

	1	2	3	4	5	6	7	8
SiO_2	73.30	74.25	76.60	76.00	75.10	74.60	74.70	74.70
Al_2O_3	13.60	12.75	12.08	12.72	13.65	13.48	14.74	14.72
TiO_2	0.16	0.20	0.14	0.15	0.11	0.18	0.0	0.0
Fe_2O_3	1.06	1.12	0.63	0.48	0.25	0.40	0.45	0.30
FeO	1.40	1.36	0.84	0.96	0.92	0.84	0.32	0.38
MnO	0.04	0.03	0.02	0.02	0.02	0.01	0.04	0.01
MgO	0.52	0.47	0.20	0.23	0.15	0.29	0.06	0.05
CaO	1.93	1.48	0.57	0.58	0.73	0.70	0.44	0.59
Na_2O	3.35	3.13	2.95	2.90	4.25	3.80	4.30	4.10
K_2O	3.75	4.18	5.18	4.92	4.22	4.52	4.30	4.78
P_2O_5	0.02	0.04	0.02	0.05	0.05	0.04	0.10	0.03
CO_2	0.11	0.20	0.17	0.30	0.14	0.18	0.06	0.03
H_2O	0.49	0.64	0.50	0.47	0.34	0.70	0.57	0.35
	99.73	99.85	99.90	99.78	99.92	99.74	100.08	100.24
Li	36	56	24	35	95	25	82	23
Rb	65	78	88	107	177	93	171	233
Cs	4.0	2.8	3.5	2.4	2.4	0.5	11.7	3.7
Be	1.6	1.8	1.6	1.6	2.0	0.3	2.9	1.3
Sr	114	98	26	32	51	48	46	36
Ba	1077	894	1019	841	617	448	3	39
Pb	7	4	2	4	18	21	15	22
Ga		17	22		25		20	45
Zr	208	181	190	202	108	139	10	27
Sn	4	nd**	5	11	4	nd	9	12
K/Rb	479	445	489	381	198	403	209	170
K/(Csx100)	78	124	123	170	146	750	30	107
K/Ba	29	39	42	49	57	84	11900	1018
Rb/Sr	0.6	0.8	3.4	3.3	3.5	1.9	3.7	6.5
Mg/Li	86	50	50	40	10	68	5	13
Al/Ga		3965	2904		2888		3900	1731
La		18.25		26.8	14.3	18.9		
Ce		35.5		55.5	23.0	32.0		
Nd		24.5		45.0	17.0	24.0		
Sm		5.14		6.66	2.31	3.18		
Eu		0.76		0.49	0.21	0.24		
Dy		6.25		9.6	2.2	2.65		
Yb		4.7		6.45	0.75	0.65		
Lu		0.55		0.78	0.07	0.11		
Y	43	33	46	61	nd	nd	nd	13

* after Černý et al. (1981). ** not detected. 1. Wekusko granite, anal. 94-1; 2. Wekusko granite, anal. 17-1; 3. Tramping Lake granite, anal. 193-1; 4. Tramping Lake granite, anal. 197-1; 5. Osborne Lake fine-grained leucogranite, anal. 244-1; 6. Osborne Lake fine-grained leucogranite, anal. 2112-1B; 7. Grass River pegmatitic leucogranite, anal. 143-1A; 8. Osborne Lake pegmatitic leucogranite, anal. 72-1.

garnet and sporadic tourmaline. Interlayering of granitic, aplitic and pegmatitic units is common.

The compositions of the late-tectonic granites are given in Table 16 and Figures 38 and 39. The Wekusko and Tramping Lake granites are closely related on a calc-alkalic trend, the latter differing mainly by more advanced plagioclase fractionation. The leucogranite facies of the pegmatitic granites cannot be related to any of the plutonic bodies; the pegmatitic granites were evidently generated by a different process. In keeping with the general petrochemical character of other intrusive rocks and of greenstones in the region, the granitoid rocks also are rather primitive in terms of fractionation of rare-alkali elements (Table 16).

Rare-element pegmatites are found in three localities confined to the chlorite + garnet area in the southern part of the field (Fig. 37). In contrast to the forcible intrusive style of the pegmatitic granites, the Li–Be-bearing pegmatites are fracture-filling bodies related to different dilation systems in a fairly complex structural setting. Despite the distances separating them and some differences in internal structure, all three groups of pegmatites have nearly identical mineral compositions and overall geochemical character. K-feldspar, albite, quartz and muscovite are associated with spodumene (up to 23%) and accessory biotite, beryl, garnet, tourmaline and apatite; altered triphylite is rare. The general level of fractionation, as shown by major and rare-alkali elements in rock-forming minerals, increases from the Sherritt Gordon group to the northeastern Green Bay pegmatites (1 and 3 on Fig. 37, respectively). However, even pegmatites of this last group do not approach the levels of fractionation attained by spodumene-rich pegmatites in other pegmatite fields with complex rare-element specialization (*e.g.*, in the Winnipeg River district, Table 10).

Genetic affiliation of the Wekusko Lake peg-

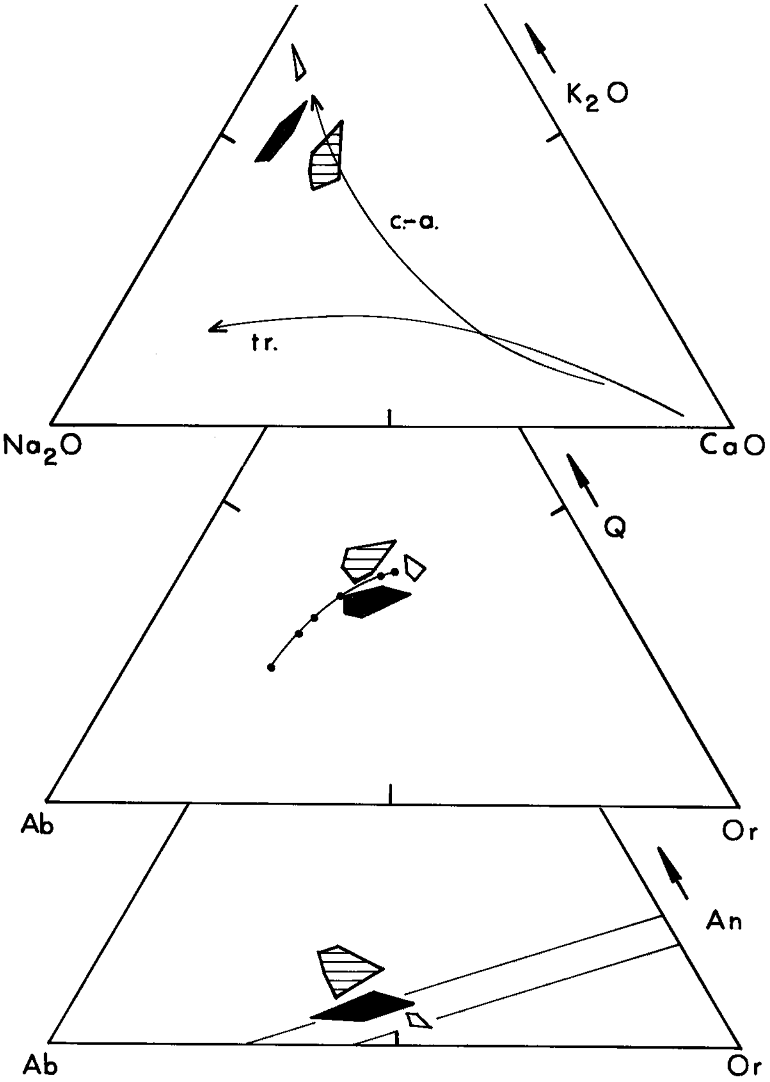


FIG. 38. Na_2O–K_2O–CaO, Ab–Or–Q and Ab–Or–An mesonorm diagrams for granitoid rocks of the Wekusko Lake pegmatite field: Wekusko granite (ruled field), Tramping Lake granite (open field), and fine-grained leucogranite of the pegmatitic granites (black field); tr. trondhjemitic trend, c.-a, calc-alkaline trend. In the Ab–Or–Q mesonorm diagram, thin line connecting solid dots marks granitic minima and eutectics from 1 to 10 kbar. In the Ab–Or–An mesonorm diagram, the low-temperature trough covers the range of 1 to 10 kbar. After Černý *et al.* (1981); see Fig. 30 for references to experimental data.

matites is uncertain. A link to the pegmatitic granites is a possibility but is rendered questionable by differences in paragenesis and in structural affinities. The source rocks that generated the Li–Be-pegmatites are probably not exposed at the surface.

Summary. In the Churchill Province, the U–Th, REE(Zr,Nb–Ta,Mo)-bearing pegmatites generated from remobilized Archean basement and the U-Th(Zr,Ti,Mo)-bearing pegmatites in graphitic pelitic gneiss are commonly anatectic. However, the first kind does occur locally with-

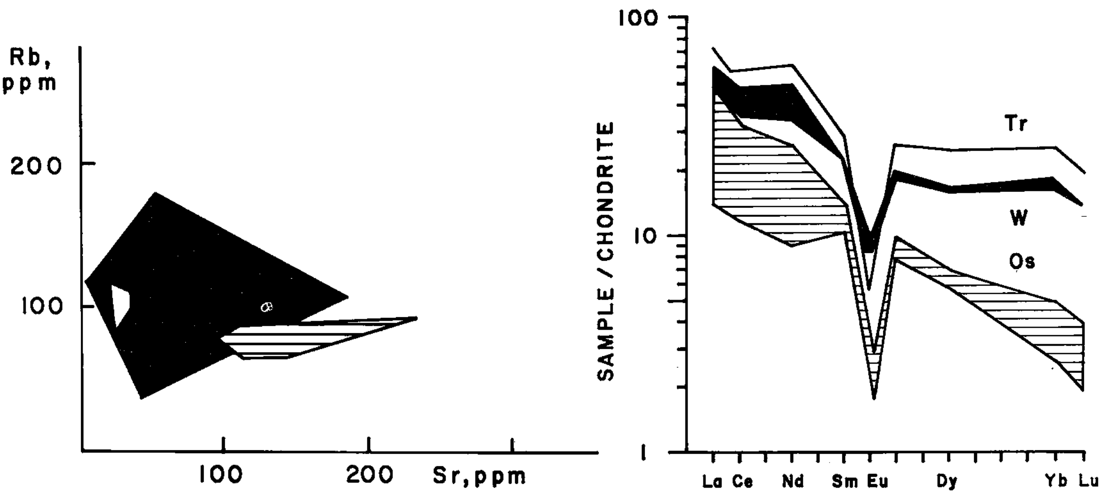


FIG. 39. (a) Plot of Rb *versus* Sr for the granitoid rocks of the Wekusko Lake pegmatite field. Symbols as in Figure 38. (b) REE abundance in the Tramping Lake granite (Tr), Wekusko granite (W) and fine-grained leucogranite of the pegmatitic granite intrusions (Os). After Černý *et al.* (1981).

in anatectic granite and may represent a product of their fractionation. Both types can be expected wherever the combined requirements of source lithology, metamorphic grade and structure are realized. A delicate interplay of structural and metamorphic factors is evidently necessary to produce significantly large deposits of these two types. Both types are widespread but, so far, not economic. The northern extensions of the Western Craton and Cree Lake Zone subprovinces and other lithologically related subprovinces in northern Churchill Province could harbor more occurrences of both types.

As for the Li–Be-bearing pegmatites, they belong to Kuzmenko's (1976) categories 2 and, partly, 3. Major occurrences of this type are restricted to the greenstone belts of the Southeastern Zone Subprovince. With the general lack of information about their parent granitoid rocks, it is only possible to speculate that silicic, per-aluminous, Ca-poor granites enriched in rare alkalis similar to those found in pegmatite-generating sequences of other greenstone belts, may be the progenitors. If the primitive fractionation levels characteristic of the Wekusko Lake field prove to be predominant in the granitoid rocks of the Flin Flon and Lynn Lake belts, the chances of finding more diversified pegmatite mineralization will be slim. However, better prospects are suggested by the Baffin Island occurrences mentioned earlier.

Grenville Province

The southwestern extremity of the Grenville Province hosts the classic pegmatite fields that have been intermittently investigated since the beginning of the century. However, geochemical and petrological studies have been neglected in the past, and the existing mineral and locality descriptions are not conducive to a clear-cut distinction of different pegmatite districts and groups. Defining the genetic affiliation of the Grenville pegmatites is also a problem. There is a general preference expressed in the literature for an anatectic origin based on stratigraphic, metamorphic and structural considerations. However, a total absence of pegmatites generated by igneous fractionation within the complex igneous and metamorphic terranes represented in the Grenville Province is difficult to imagine; this consideration, as well as the lack of geochemical data, leaves the present interpretation open to some doubt. Thus the following treatment of the Grenville pegmatites has to be general and descriptive.

Granitic and related pegmatites of the Grenville Province yield ages between 1.1 and 0.9 Ga (Lumbers 1979), coincident with the waning stages of the Grenvillian high-grade metamorphism, and at concluding stages of the major intrusive events. The pegmatites are restricted to four subprovinces: the Central Gneiss Belt, the Grenville Front Tectonic Zone, the Central

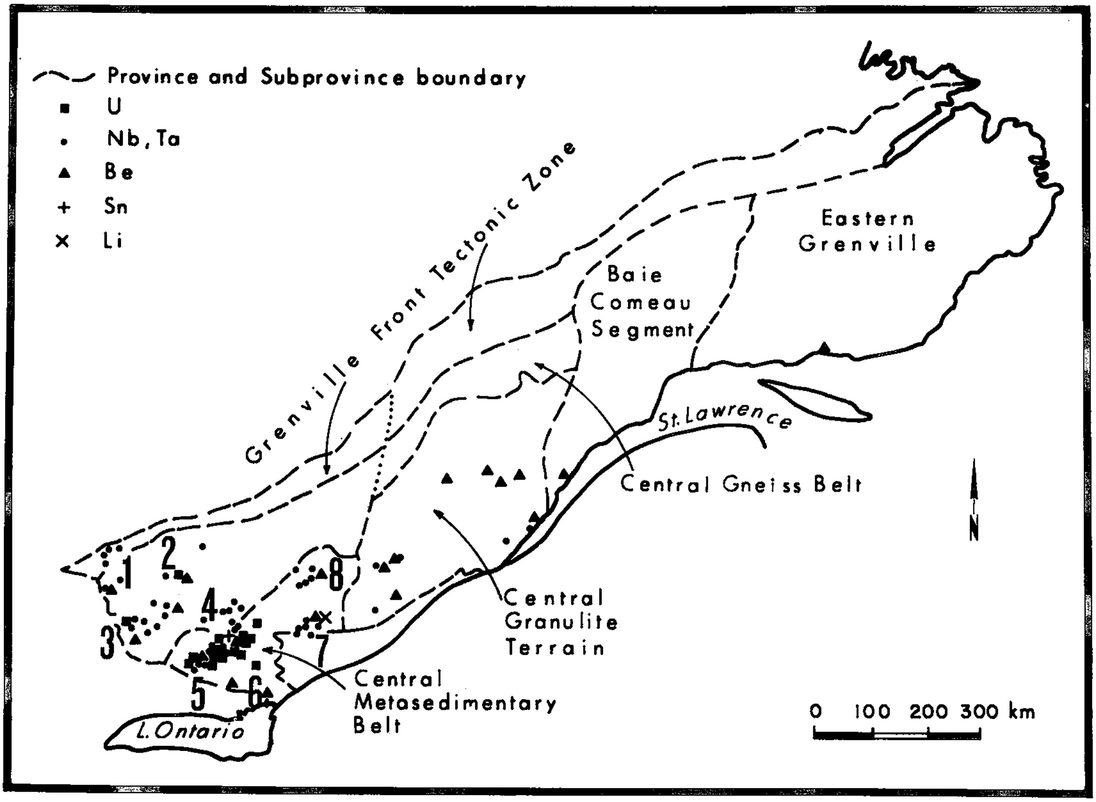


FIG. 40. Distribution of mineralized pegmatites in the Grenville Province. 1. the Sudbury–Britt field, 2. the Mattawa district, 3. the Parry Sound field, 4. the Madawaska field, 5. the Bancroft field, 6. the Perth–Verona field, 7. the Gatineau–Buckingham field, 8. the Mont-Laurier field. Compiled from Ellsworth (1932), Spence (1932), Dawson (1974), Mulligan (1961, 1965, 1968, 1975) and Robertson (1978).

Metasedimentary Belt and the Central Granulite Terrain (Fig. 40).

In the Central Gneiss Belt, four pegmatite-bearing areas can be delineated: the Sudbury–Britt field (1), which appears to extend into the Grenville Front Tectonic Zone, the Mattawa district (2), the Parry Sound (3), and an ill-defined Madawaska field (4 in Fig. 40). The pegmatites have a granitic composition; they range from biotite- and biotite–muscovite- to muscovite-bearing, with tourmaline and garnet being particularly distinctive of pegmatites of the Mattawa district. Rare-element mineralization is very subordinate, with an assemblage of Nb–Ta,Ti,REE,Y(U,Th,Zr,Be) minerals (Ellsworth 1932). Euxenite, polycrase, pyrochlore, betafite, samarskite, fergusonite, monazite, columbite, thucholite, allanite, thorite, uraninite, zircon and beryl are characteristic; pyroxene, hornblende and sulfides occur sparsely. A recent find of autochthonous anatectic U-bearing pegmatites in metasediments at Parry Sound represents, to date, an isolated occurrence (Robertson 1978).

Four pegmatite fields may be suggested in the Central Metasedimentary Belt Subprovince: the Bancroft field (5), the Perth–Verona field (6), the Gatineau–Buckingham field (7) and the Mont-Laurier field (8 in Fig. 40). However, pegmatites appear to be widespread throughout this subprovince, and a final subdivision is not feasible at present. No economic rare-element concentrations are known from the Perth–Verona, Gatineau–Buckingham and Mont-Laurier fields, all of them having produced only ceramic materials. Beryl and minor Nb–Ta,Ti, U–Th-mineral occurrences characterize the first of these fields; minerals of REE, Nb–Ta, Ti and Th are typical of the second, along with the only Li-bearing pegmatite in the Grenville Province (Mulligan 1965); sparse Nb–Ta, REE and Ti mineralization is found in the

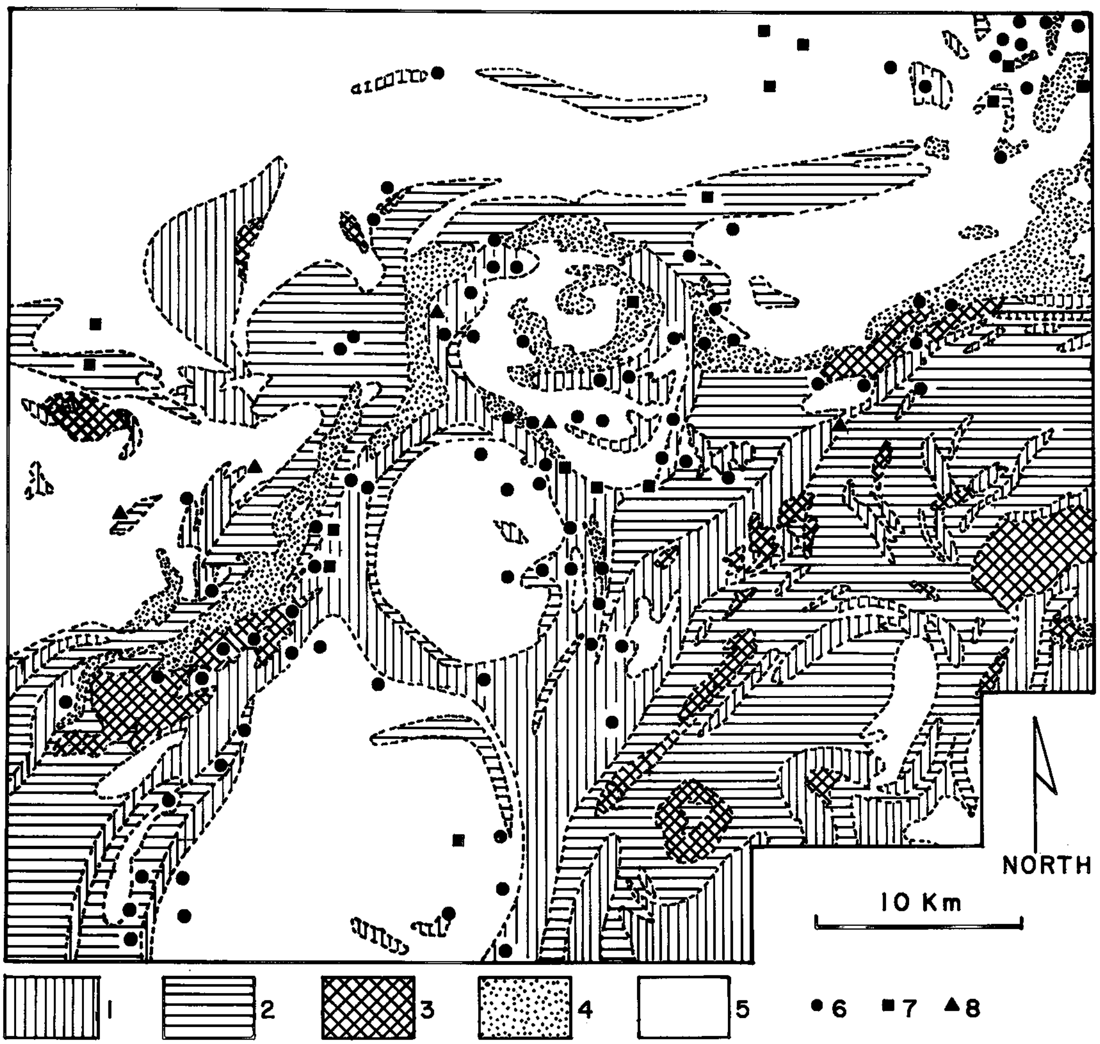


FIG. 41. Central part of the Bancroft pegmatite field (no. 5 in Fig. 40), with mineralized pegmatites concentrated around gneissic domes; 1. metasedimentary-metavolcanic sequence, 2. marble, 3. metagabbro, 4. metasyenite, 5. gneissic granitoid rocks, 6. U-bearing pegmatites, 7. Nb–Ta-bearing granitic pegmatites, 8. Nb–Ta bearing syenitic pegmatites. Geology compiled from G.S.C. and O.D.M. maps.

third. Tourmaline is common in the pegmatites of the Central Metasedimentary Belt, in contrast to its near-absence in the Central Gneiss Belt. Recent investigations in the Perth–Verona field have led to the discovery of extensive uranium mineralization in anatectic pegmatites in the Sharbot Lake area (Ford 1982, Ford & Charbonneau 1979). This type of U-bearing pegmatite is also known from the Mont-Laurier field (Henderson 1982). The Bancroft pegmatite field is the largest, most densely populated and best mineralized in the subprovince; a brief description is given below.

Little is known about the pedominantly Be-bearing pegmatites scattered in the Central Granulite Terrain Subprovince and farther to the northeast (Fig. 40). Judging from the minerals associated with beryl (tourmaline, garnet, muscovite, locally topaz: Mulligan 1968), these pegmatites evidently are of a simple granitic composition, and most of them lack the mineralization in U, Th, Nb–Ta, REE, Ti and Zr typical of the other subprovinces.

The Bancroft pegmatite field. The pegmatites of this field are associated with a series of partly mobilized, high-grade granitoid and syenitoid gneiss bodies, some of which display prominent domal structures (Fig. 41). The pegmatites are contained within these gneisses or in the adjacent metasediments. Most of the pegmatites are conformable with the fabric of the enclosing rocks and relatively homogeneous internally. The less common fracture-filling bodies that cut across regional structures tend to be better differentiated and zoned. A simple classification of U-bearing pegmatites of the field was developed by Satterly & Hewitt (1955): A zoned, B unzoned, B–1 red, B–2 white; it is still in use today (Robertson 1978), although other classification schemes have started to appear (Masson & Gordon 1981, Storey & Vos 1981).

A granitic to syenitic range of bulk compositions reflects the wide range in silica content of the pegmatites, even to the point of appearance of abundant feldspathoids. The ubiquitous presence of pyroxene, hornblende and biotite relates the pegmatite compositions to the amphibolite (or higher) metamorphic grade of the enclosing sequences. Rare-element mineralization comprises a variety of U, Th, Nb–Ta, REE, Y, Ti, Zr and Be species (uraninite, uranothorite, thorite, euxenite, polycrase, columbite, pyrochlore–microlite, allanite, magnetite, beryl, garnet, monazite, titanite and zircon: Ellsworth 1932, Satterly & Hewitt 1955, Masson & Gordon 1981, Ford 1982). Other typical accessory minerals are garnet, scapolite, magnetite, fluorite, sulfides of Fe, Cu, Mo and Pb, calcite and, locally, anhydrite and gypsum (Little 1969). Most of the uraninite is intergrown with magnetite or the somewhat altered mafic minerals (Haynes 1979). More exotic assemblages of minerals, with corundum, nepheline, cancrinite, sodalite, scapolite, garnet, anhydrite, *etc.*, are restricted to the interior of the nepheline syenite belts along the northwestern boundary of the Central Metasedimentary Subprovince (Fig. 41).

Despite earlier correlations of pegmatite occurrences with high metamorphic grade (Lumbers 1964), the Bancroft pegmatite field has been related to igneous differentiation until recently (Little *et al.* 1972, Robertson 1974). More recent work suggests that the pegmatites could have been generated during the Grenvillian deformation, which mobilized Early Proterozoic basement gneisses and their cover, locally yielding mantled gneiss domes (Bright 1977, Lumbers 1975b). However, Masson & Gordon (1981) suggested that differentiation of granitoid melts could also provide some of the uranium and other rare elements.

Summary. In conclusion, it can be said that the pegmatites of the Grenville Province deserve much more attention in future than they have received in the past. Better understanding of their geochemistry and origin is required in the well-prospected southwestern part of the province, and new discoveries can be expected in the relatively unexplored central and northeastern parts. However, a severely limited distribution of pegmatites can be expected in the predominantly unfavorable terranes of granulite-facies metamorphism.

URANIUM AND THORIUM IN GRANITOID PLUTONS

In addition to the uranium–thorium-bearing pegmatites described in the previous section, potentially important concentrations of uranium and thorium are found also in many Archean and Proterozoic granitoid and some syenitoid plutons in the Superior, Slave, Churchill, Bear and Grenville provinces (Darnley 1982, Gandhi 1978, Ruzicka 1979). Many of these plutons have only recently been located by extensive regional airborne radiometric surveys carried out by the Geological Survey of Canada as part of the Uranium Reconnaissance Program. Follow-up geological and geochemical investigations on the ground are still in progress. Consequently, the nature, age and genesis of the uranium-bearing plutons and the nature, distribution, habit and control of uranium mineralization are poorly documented. It should be stressed, also, that granitoid plutons may be the ultimate source of uranium now found in sedimentary and other nongranitoid hosts (Ruzicka 1982).

Two main types of uranium mineralization have been recognized: 1) veins, and 2) dispersed mineralization. Vein deposits are best documented from the Bear Province, where pitchblende ± quartz veins occupy subsidiary fractures associated with major faults (Gandhi 1978). These veins occur in both Early Proterozoic rocks of the Great Bear batholith and adjacent country rocks; some veins contain important concentrations of Ag, Bi, Co, Ni and Cu and have been mined (Badham 1975). The mineralization was apparently deposited by hydrothermal solutions derived from the Great Bear batholith (Badham 1975, Ghandi 1978), although Gandhi (1978) stated that the Ag, Bi, Co, Ni and Cu represents a later mineralizing event unrelated to the granitoid rocks.

Other uraniferous veins have been reported from Early Proterozoic plutons in and adjacent to the East Arm Fold Belt, a subprovince of the Churchill Province that is an eastward extension of the Bear Province onto the craton. These occurrences include: 1) actinolite + apatite + magnetite + hematite ± uraninite veins in quartz monzonite laccoliths within the fold belt; these laccoliths are texturally and compositionally similar to the earliest phases of the Great Bear batholith (Badham 1978, Gandhi & Prasad 1982); and 2) albite veins that are in part associated with pegmatite in late peralkaline syenite of the gabbro – granite – peralkaline granite – syenite Blachford Lake complex in the Slave Province at the margin of the fold belt; these veins are mineralogically complex and contain fluorite, carbonate, zircon and rare minerals rich in Ta, Nb, Be, Li, Th, Y, U and REE (Davidson 1978, 1982). These vein deposits appear to be genetically related to the evolution of the magma, although the final deposition in veins is probably the result of late hydrothermal activity (Davidson 1982, Gandhi & Prasad 1982). Uranium appears to be a minor constituent in the deposits in the Blachford Lake complex but, according to company reports (Highwood Resources Ltd.), the complex may contain a major Nb–Ta deposit.

Vein deposits, both in plutons and in country rocks, may be an integral part of the emplacement and cooling of uraniferous granitoid plutons (Darnley 1982). Such plutons, defined by Darnley (1982) as those containing 8 ppm or more U, will cool more slowly than nonuraniferous plutons because of heat generated by radioactive decay. As a function of prolonged cooling, any hydrothermal convection systems generated by the heat of the pluton will be more long-lived, with a consequent higher possibility of development of vein deposits containing uranium and other elements (Darnley 1982). On the other hand, uraniferous vein-deposits may result also from epigenetic processes, either supergene or hydrothermal (Maurice 1982).

Dispersed mineralization is best documented from the Superior, Churchill and Grenville provinces, but also occurs in the Bear Province. The uranium–thorium-bearing plutons are equigranular to porphyritic, fine- to coarse-grained, in part pegmatitic sills, dykes, stocks and batholiths. Most are granite, but the composition ranges from tonalite to leucogranite (commonly referred to as alaskite) (Bond & Breaks 1978, Breaks 1982, Hauseux 1977, Maurice 1982, Sibbald *et al.* 1977, Weber *et al.* 1975b, 1982). Pegmatites, in the form of both discrete dykes and irregular patches, are common constituents of many uranium-bearing plutons. In some plutons, uranium is concentrated in the pegmatite phase (Sibbald *et al.* 1977, Rimsaite 1982), but late-tectonic Proterozoic intrusions (Burwash & in other plutons there is no preferential concentation of uranium in pegmatite.

The tectonic positions and structures of uranium-bearing plutons differ from province to province. In the Superior Province, many of the plutons are poorly foliated, unmetamorphosed, late-phase, syntectonic or late-tectonic bodies (Bond & Breaks 1978, Breaks 1982, Weber *et al.* 1982), some of which were emplaced in the deep mesozone. In the Churchill Province, they range from metamorphosed gneissic, Archean basement plutons to massive, Cape 1981, Sibbald *et al.* 1977, Soonawala *et al.* 1979, Weber *et al.* 1975b). Uranium in association with fluorite is concentated in the contact-metamorphic aureoles around some late-tectonic, fluorite-bearing plutons (Miller 1979). In the Grenville Province, many uranium-bearing plutons are foliated to gneissic as a result of superimposed metamorphism (Hauseux 1977), but relatively undeformed plutons have been reported also (Kerswill & McConnell 1982).

The data available at present indicate that uranium mineralization is dominantly disseminated uraninite (Darnley 1982, Hauseux 1977, Kerswill & McConnell 1979, Ruzicka & Littlejohn 1981, Soonawala *et al.* 1979, Weber *et al.* 1975b), but pitchblende and uranothorite have also been reported (Hauseux 1977, Kerswill & McConnell 1982); phosphuranylite stain is associated with many occurrences (Bond & Breaks 1978, Hauseux 1977). In many plutons the uraninite is associated with magnetite (Hauseux 1977), with biotite, chlorite, and locally garnet (Bond & Breaks 1978, Delpierre 1982, Kerswill & McConnell 1979, 1982), with concentrations of accessory minerals such as sphene, zircon, allanite and apatite (Bond & Breaks 1978, Schau & Ashton 1979), or with molybdenite, pyrite and fluorite associated with garnetiferous biotite-rich schlieren (Kerswill & McConnell 1982). In plutons in which the uranium and thorium contents are anomalous but only several times background, the uranium and thorium appear to be incorporated largely in the radioactive accessory minerals zircon, allanite, titanite, monazite and thorite (Burwash & Cape 1981, Charbonneau 1982). Characteristic features of many uranium-bearing plutons are the presence of smoky quartz, quartz lenses, pervasive alteration (including deep reddening of feldspars), muscovite in addition to biotite, cordierite, garnet and sillimanite in some plutons, and negative Bouguer gravity anomalies (Bond & Breaks 1978, Breaks 1982, Darnley 1982, Hauseux 1977, Kerswill & McConnell 1979).

Some uranium-bearing plutons, however, are characterized by whitened rather than reddened feldspars (Breaks 1982).

The ratio U/Th is variable from pluton to pluton and within plutons (Delpierre 1982, Rimsaite 1982). Reported values from a few plutons in the Superior and Churchill provinces are in the range 0.1–0.2 (Charbonneau 1982, Maurice 1982) but Breaks (1982) and Delpierre (1982) have reported values greater than 2. In the Grenville Province, U/Th ranges from 0.2 to 4, with many values greater than 1 (Ford 1982, Kerswill & McConnell 1979, Rimsaite 1982). Charbonneau (1982) has suggested that an increase in the ratio U/Th of a pluton with increasing U content is indicative of uranium mobilization; such plutons may host epigenetic uranium deposits. On the other hand, a decrease in the ratio U/Th with increasing Th indicates that the distribution of U and Th within the pluton was fixed at an early stage of magmatic evolution (Charbonneau 1982).

In most radioactive plutons, the uranium is unevenly distributed. The highest concentrations are generally in irregular to lenticular areas up to several metres long; many of the lenticular areas are concordant with foliation and gneissosity (Bond & Breaks 1978, Hauseux 1977). In some plutons the mineralization has been partly redistributed into fractures and faults (Kerswill & McConnell 1982, Maurice 1982). In the Churchill Province, uranium contents of 15 to 30 ppm have been reported over large areas by Sibbald *et al.* (1977), Soonawala *et al.* (1979) and Weber *et al.* (1975b), but local concentrations of more than 1% uranium also are present. In the Grenville Province, plutons in the Johan Beetz area of Quebec contain 100–200 ppm uranium with an estimated reserve of several hundred million tonnes (Ruzicka 1979).

The origin of the uranium mineralization in Proterozoic plutons is generally ascribed to anatexis and remobilization of uranium-bearing sedimentary units, older granitoid plutons or unspecified Archean gneisses (Hauseux 1977, Kerswill & McConnell 1979, 1982, Sibbald *et al.* 1977, Weber *et al.* 1975b). The anatexis concentrated uranium from the parental rocks. The origin of uranium in the Archean plutons is unknown, although Burwash & Cape (1981) proposed that mineralization in at least one Archean pluton of the Churchill Province was the result of assimilation of uranium-bearing sedimentary rocks by the pluton and later remobilization and concentration of the uranium during Proterozoic deformation.

CONCLUSIONS

For ease of understanding, the accounts of the geology and most of the mineral deposit types have been summarized at the end of the appropriate sections. This information will not be repeated here.

In the Canadian Shield, granitoid plutons are extensive but poorly documented. They range in age from Archean to Middle Proterozoic and differ considerably in their compositions, habits, sizes, emplacement depths and positions in tectonic cycles. There are both similarities and differences among the granitoid plutons in the various structural provinces. Certain types of plutons are hosts for, or are genetically associated with, many mineral deposits, particularly those of Cu, Mo, Au, Ag, U, Th, Be, Cs, Li, Ta, Nb and lanthanide elements. However, except for pegmatite deposits, mineral deposits in or associated with granitoid plutons have not been studied as a discrete class. Their genetic relationships with associated plutons and the nature of assumed parental plutons are even more poorly documented. Integrated geological and geochemical investigations are essentially nonexistent, although research is in progress on uranium-bearing granitoid plutons. Thus, the metallogeny of granitoid rocks in the Canadian Shield is largely descriptive, and it offers a fertile field for both research and prospecting.

As a first approximation, future prospecting for Cu, Mo, and Au–Ag in granitoid rocks should be concentrated in greenstone-belt terranes, particularly the Archean of the Superior and Slave provinces. Only a few granite-related deposits are currently known in the Slave Province, but this may reflect inaccessibility rather than lack of deposits. The less extensive Archean and Proterozoic greenstone belts of the Churchill and Grenville provinces are also favorable targets for exploration. The volcanomagmatic units of the Bear Province are apparently unfavorable for this type of mineralization.

Pegmatite deposits are widespread in the Superior, Slave, Churchill and Grenville provinces; the more inaccessible parts of these provinces, particularly in the Churchill Province, should be actively prospected for new pegmatite fields. Paragneiss–granitoid subprovinces of the Superior Province appear to be the most favorable loci, but greenstone sequences in other types of subprovince should not be overlooked.

The genetic control for uranium mineralization in granitic plutons is largely unknown. To date the most extensive and richest deposits are in the Churchill and Grenville provinces.

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