21. GRANITIC PEGMATITES

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W.D. Sinclair

INTRODUCTION

Pegmatites are holocrystalline rocks typically composed of igneous rock-forming minerals that are, in part, very coarse grained, although some are extremely varied in grain size (Jahns, 1955). They are commonly granitic in composition, consisting mainly of quartz, feldspar, and mica, but more mafic varieties composed of olivine, pyroxene, and plagioclase also occur. Mafic pegmatites, however, have negligible economic significance and are not considered in this review.

A general classification scheme for granitic pegmatites based on their environments of formation and mineralogical features as suggested by Ginsburg (1984) and modified by Černý (1990, 1991b), is summarized in Table 21-1. Abyssal and muscovite class pegmatites are commonly mineralogically simple. Abyssal pegmatites consist mainly of quartz and feldspar, and are generally barren or poorly mineralized with regard to rare elements such as niobium, tantalum, rare-earth elements, yttrium, and beryllium. Muscovite class pegmatites contain extensive reserves of mica and feldspar and are in some cases enriched in uranium and rare-earth elements. Many of the pegmatites of the northeastern and central Grenville zones, Ontario likely belong to the muscovite class, but others contain significant rare element minerals and for these a transitional classification between muscovite class and rare element pegmatites is probably more appropriate (Černý, 1990). Miarolitic (gem-bearing) pegmatites are extremely rare in Canada.

Sinclair, W.D.
1996: Granitic pegmatites; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 503-512 (also Geological Society of America, The Geology of North America, v. P-1).

The emphasis in this review is on rare element pegmatites, which are mineralogically complex and typically enriched in lithophile elements and rare metals such as beryllium, lithium, rubidium, cesium, tin, tantalum, niobium, rare-earth elements, and uranium. They also contain industrial minerals such as feldspar and mica. Rare element pegmatites have been subdivided by Černý (1990, 1991b) into rare-earth, beryl, complex, albite-spodumene, and albite types; in this review, however, they are considered as a single group.

Canadian examples of rare element pegmatites include the Tanco pegmatite, Manitoba (tantalum, lithium, cesium); uranium-bearing pegmatites of the Bancroft area, Ontario; and lithium-bearing pegmatites in the Preissac-Lacorne area, Quebec and the Yellowknife area, Northwest Territories. Notable foreign examples include the tin-spodumene belt, North Carolina, U.S.A. (lithium); the Manono and Kitotolo pegmatites, Zaïre (lithium, tin); the Bikita pegmatite, Zimbabwe (lithium, cesium); the Kamativi pegmatite, Zimbabwe (tin); the Uis pegmatite field, Namibia (tin); the Greenbushes pegmatite, Australia (tantalum, niobium, tin, lithium); and the pegmatite fields of the Afghan Hindukush (lithium, tantalum, cesium).

IMPORTANCE

Pegmatite deposits account for nearly all historical Canadian production of tantalum, cesium, and lithium, and contain most of the known reserves of these commodities. The Tanco pegmatite, for example, contains the largest known concentration of pollucite [$(Cs,Na)_2(Al_2Si_4)O_{12}\cdot H_2O$] and was the world's largest tantalum producer in the 1970s (Crouse et al., 1984). Production of uranium from pegmatites in the Bancroft area has been of minor importance and present reserves are limited. Feldspar and mica have been produced in the past from numerous pegmatites in Ontario and Quebec, but production in recent years has been sporadic and of minor economic significance.

Table 21-1. Classification of pegmatite deposits (from Ginsburg, 1984; Černý, 1990, 1991b).

Pegmatite class	Environment of formation	Metamorphic facies of host rocks	Relationship to parent granites	Economic minerals
Miarolitic (gem-bearing)	~1-2 kbar	Greenschist	Within or peripheral to subvolcanic granitic plutons	Quartz crystals, beryl, topaz, tourmaline
Rare-element	~2-4 kbar	Lower amphibolite (Abukuma-type)	Peripheral to granitic intrusions	Spodumene, amblygonite, petalite, lepidolite, pollucite, beryl, columbite-tantalite, microlite, wodginite, uraninite, cassiterite, xenotime, gadolinite
Muscovite	~5-8 kbar	Upper amphibolite (Barrovian-type)	No obvious association with granitic intrusions in many cases	Muscovite, feldspar, uraninite
Abyssal	~4-9 kbar	Granulite (Barrovian- to Abukuma-type)	May be associated with migmatitic granite	Feldspar, quartz

On a world scale, pegmatites have been a major source of beryllium, lithium, cesium, tantalum, muscovite mica, and feldspar, and a minor source of uranium, yttrium, rare-earth elements, tin, and tungsten. Miarolitic pegmatites are an important source of gemstones such as beryl (emerald), topaz, and tourmaline.

SIZE AND GRADE OF DEPOSITS

Pegmatite deposits that have been commercially exploited range in size from thousands to millions of tonnes. Deposits in Ontario and Quebec that were mined in the past for feldspar and sheet mica were small and these are no longer in production for the most part. In other parts of the world, however, production from small pegmatite deposits is significant, particularly for beryllium and tantalum in Brazil and in many African and Asian countries.

Examples of pegmatite deposits in Canada that are significant for either their production or reserves of tantalum, cesium, lithium, and uranium are listed in Table 21-2 and shown in Figure 21-1; important foreign examples are included in Table 21-2 for comparison. Grade-tonnage relationships are shown in Figure 21-2. Quantitative data are unavailable for extensive pegmatite fields with sizable reserves of rare metals in Afghanistan (Hindukush), northern Australia (Finnis River), central Finland and Sweden, Russia, Ukraine, and China.

GEOLOGICAL FEATURES

Geological setting

Pegmatites and associated host rocks throughout the world range in age from early Precambrian to Tertiary. In Canada, the majority of commercially interesting pegmatites are Late Archean (Kenoran) or Late Proterozoic (Grenvillian) in age; some pegmatites are associated with Phanerozoic intrusive rocks but are of only minor commercial significance. Most pegmatites occur in orogenic belts, although the type of pegmatite formed differs according to the nature of its geological setting. Abyssal class pegmatites typically occur in migmatitic rocks of upper amphibolite to granulite facies metamorphism. Muscovite class pegmatites occur in slightly lower grade Barrovian-type metamorphic terranes, mainly amphibolite facies. For both abyssal and muscovite class pegmatites, the host rocks represent deeply eroded root zones of orogenic belts. Rare element pegmatites occur in less deeply eroded Abukuma-type metamorphic terranes, generally of cordierite-amphibolite facies. They are commonly peripheral to larger granitic plutons that, in many cases, represent the parental granite from which the pegmatite was derived. The Late Archean pegmatites of the Superior Province are typically localized along deep fault systems which in many areas coincide with major metamorphic and tectonic boundaries. For example, rare element pegmatites associated with the Ghost Lake batholith in northwestern Ontario occur within thrust-faulted and, in places, migmatized rocks of the Sioux Lookout Terrane, which forms the boundary between the Winnipeg River and Wabigoon subprovinces (Breaks and Moore, 1992).

Form of deposits

Many pegmatites occur as dyke-like or lenticular bodies but they range considerably in both shape and size. Pegmatites in high grade metamorphic rocks form irregular, tabular to ellipsoidal bodies that are typically conformable to the foliation of the host rocks. Some pegmatites in lower grade metamorphic rocks are conformable with the host rocks, but others occupy discordant, crosscutting structures such as tension faults. Pegmatites formed within larger granitic bodies have bulbous to highly irregular shapes.

Most pegmatites range in size from a few metres to hundreds of metres long and from 1 cm to several hundred metres wide, although a few pegmatites are much larger. The Tanco pegmatite, for example, is a subhorizontal body 1440 m long, as much as 820 m wide, and slightly more than 100 m thick. The main FI pegmatite dyke in the Yellowknife district is more than 2000 m long and averages about 8 m wide. Pegmatite dykes on the Quebec Lithium property in the Preissac-Lacorne district are as much as

Table 21-2. Production/reserves of selected Canadian and foreign pegmatite deposits.

Deposit	Production/reserves	Comments/references
Canadian deposits		
Tanco mine, Manitoba	a) 1.9 Mt; 0.216% Ta_2O_5 b) 6.6 Mt; 2.76% Li_2O (in spodumene + petalite) c) 0.3 Mt; 23.3% Cs_2O d) 0.8 Mt; 0.20% BeO	Reserves (Crouse et al., 1984)
Preissac-Lacorne area, Quebec	19 Mt; 1.25% Li_2O	Production plus reserves from the (former) Quebec Lithium property (Flanagan, 1978)
FI (J.M.-Lit), Yellowknife district, N.W.T.	13.9 Mt; 1.19% Li_2O	"Identified paramarginal resources" (Lasmanis, 1978)
Thor (Echo), Yellowknife district, N.W.T.	8.4 Mt; 1.5% Li_2O	"Identified paramarginal resources" (Lasmanis, 1978)
Violet, Herb Lake area, Manitoba	5.9 Mt; 1.2% Li_2O	Reserves (Williams and Trueman, 1978)
Nama Creek, Georgia Lake area, Ontario	3.9 Mt; 1.06% Li_2O	Reserves, North and South zones (Pye, 1965)
Lac la Croix, Ontario	1.4 Mt; 1.3% Li_2O	Reserves (Mulligan, 1965)
Madawaska mine, (formerly Faraday mine), Bancroft district, Ontario	4.5 Mt; 0.09% U_3O_8	Production 1957-1964 and 1976-1982 (Carter and Colvine, 1985)
Foreign deposits		
Tin-spodumene Belt, North Carolina	a) 26 Mt; 1.5% Li_2O	Measured and indicated reserves, Kings Mountain, Foote Mineral Co. (Kunasz, 1982)
	b) 30.5 Mt; 1.5% Li_2O	Reserves, Bessemer City, Lithium Corporation of America (Company news release, 1976)
Bikita, Zimbabwe	10.8 Mt; 3.0% Li_2O	Reserves (Wegener, 1981)
Kamativi, Zimbabwe	100 Mt; 0.114% Sn, 0.603% Li_2O	"Maximum inferrable reserves of a single pegmatite" (Bellasis and van der Heyde, 1962)
Uis, Namibia	87 Mt; 0.134% Sn	Mineable plus possible reserves (Mining Magazine, November, 1983, p. 291)
Greenbushes, Australia	a) 28 Mt; 0.114% Sn, 0.043% Ta_2O_5, 0.031% Nb_2O_5	Underground reserves (Knight and Wallace, 1982)
	b) 33.5 Mt; 2.55% Li_2O	Proven and probable reserves (Knight, 1986)
Manono-Kitotolo, Zaire	35 Mt; 1.3% Li_2O	Reserves proved by systematic exploration (Evans, 1978)
Minas Gerais and Ceara states, Brazil	106 Mt; 0.04% BeO	Estimated in situ ore (Soja and Sabin, 1986)

600 m long and 30 m wide. The Bikita pegmatite in Zimbabwe is 1.8 to 2.1 km long and 300 m wide (Martin, 1964). The main pegmatite at Greenbushes, Australia is more than 2 km long and as wide as 230 m (Hatcher and Bolitho, 1982).

Internal structure

Many pegmatites are unzoned and relatively uniform in both composition and texture; however, rare element pegmatites in particular can have complex internal structures. In the 1940s, geologists of the United States Geological Survey devised a system to describe these internal structures (Cameron et al., 1949). Although revisions to this system have been suggested (e.g. Černý, 1982a; Norton, 1983), it is still widely used. According to this system, internal units in complex pegmatites consist of a sequence of zones, mainly concentric, which conform roughly to the shape of the pegmatite, and differ in mineral assemblages and textures. From the margin inward, these zones consist of a border zone, a wall zone, intermediate zones, and a core zone. The border zone is thin, averaging a few centimetres wide, and typically aplitic in texture. The border zone in some pegmatites is metasomatic in part, but in many cases it represents a chilled margin of the pegmatite. The wall zone is wider and coarser grained than the border zone and marks the beginning of coarse crystallization characteristic of pegmatites. The wall zone consists mainly of quartz, feldspar, and muscovite, although lesser biotite, apatite, tourmaline, beryl, and garnet may also be present. Intermediate zones, where present, are more complex

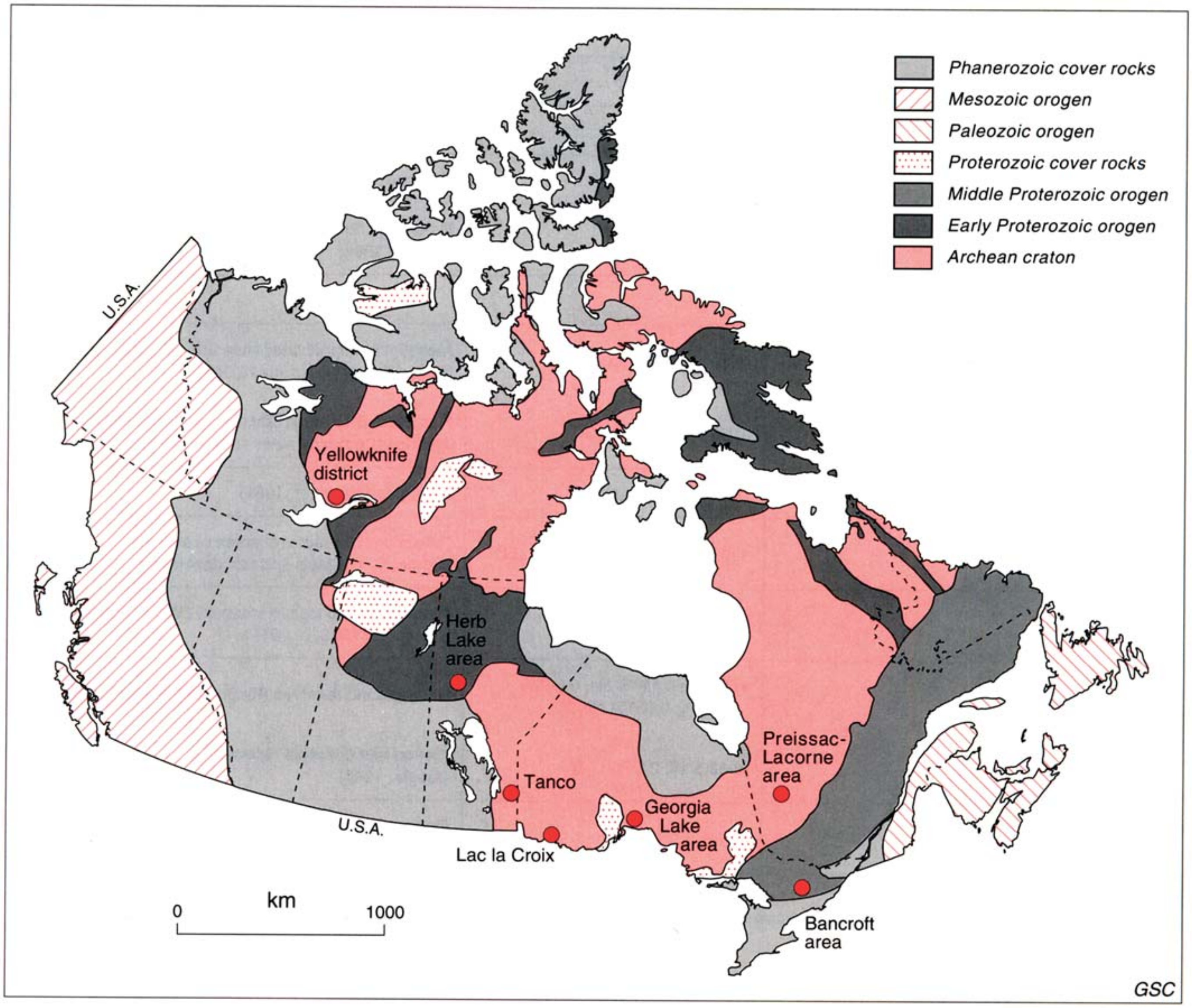

Figure 21-1. Distribution of selected pegmatite deposits in Canada.

mineralogically and contain a variety of economically important minerals such as sheet mica, beryl, spodumene, amblygonite, lepidolite, columbite-tantalite, and cassiterite. In the intermediate zones of some pegmatites, individual crystals of quartz, feldspar, mica, apatite, beryl, tourmaline, spodumene, and other minerals may be metres or even tens of metres in maximum dimension. The core zone consists mainly of quartz, either as solid masses or as euhedral crystals. Not all of the above zones are necessarily present in every pegmatite; however, zones that do occur are generally in the sequence described. In addition to these concentric zones, other internal features such as replacement bodies and fracture fillings may be present.

At the Tanco pegmatite, nine internal zones and an exomorphic zone of metasomatic alteration have been documented (Crouse et al., 1984). The distribution of these zones is shown in Figure 21-3 and their compositional characteristics are summarized in Table 21-3. Some of the zones (2, 4, 5, 6, 7, 8) are considered to have formed mainly by primary crystallization, whereas others (1, 3, 9) have features that suggest they are metasomatic in origin (Černý, 1982b, 1989a). However, this classification is oversimplified; features indicative of partial metasomatism are present in the primary zones (Černý, 1982b) and recent studies of the saccharoidal albite unit (zone 3) indicate that it is primary rather than replacive in origin (London, 1986; Thomas and Spooner, 1988). Minerals of commercial interest in the various zones are indicated in Table 21-3. The most recent mining activity at Tanco has been centred mainly on the saccharoidal albite zone (for tantalum) and the upper intermediate zone (for spodumene).

Regional zoning

Some pegmatites associated with granitic intrusions, particularly rare element pegmatites, are distributed in zonal patterns around such intrusions. In general, the pegmatites most enriched in rare metals and volatile components are located farthest from the intrusions (Trueman and Černý, 1982; Černý, 1989b); this relationship is shown schematically in Figure 21-4.

An example of horizontal zoning that fits this pattern occurs in the Ross Lake area, Northwest Territories, where five zones peripheral to the Redout Lake granite were defined by Rowe (1952), and subsequently modified and described in greater detail by Hutchinson (1955), Meintzer (1987), and Wise (1987). According to these authors, zone I (closest to the Redout Lake granite) contains giant pegmatites characterized by graphic granite; in zone II, pegmatites contain graphic granite and beryl; pegmatites of zone III contain beryl but not graphic granite; zone IV pegmatites contain beryl and niobium- and tantalum-bearing minerals; and pegmatites of zone V are characterized by spodumene and rare grains of columbite.

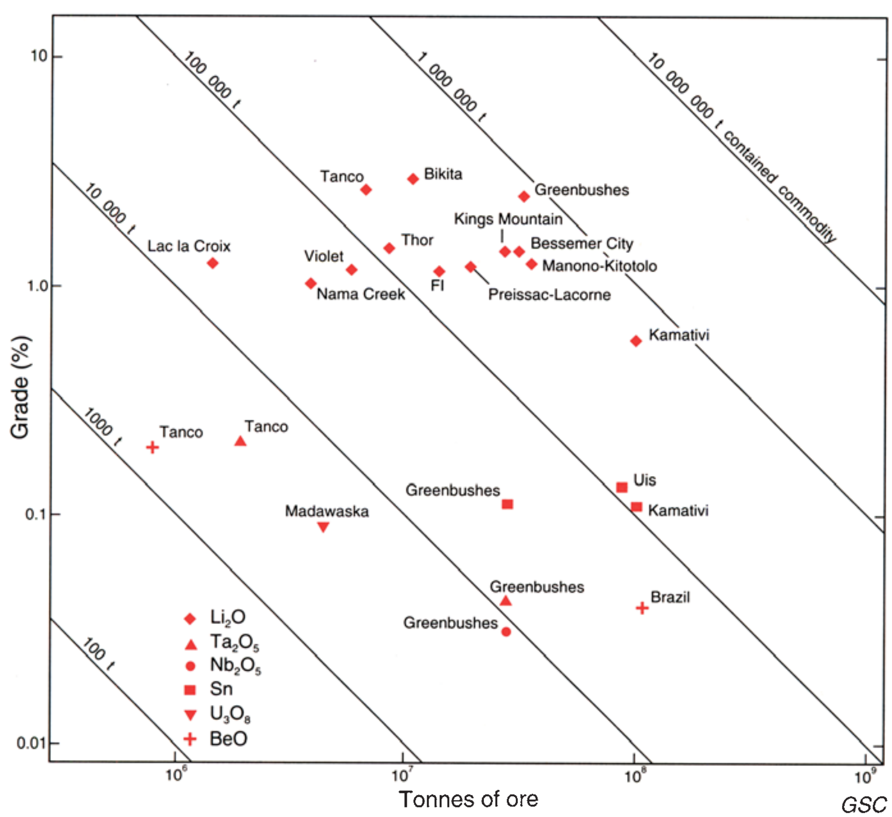

Figure 21-2. Grade versus tonnage diagram for pegmatite deposits (data are from Table 21-2).

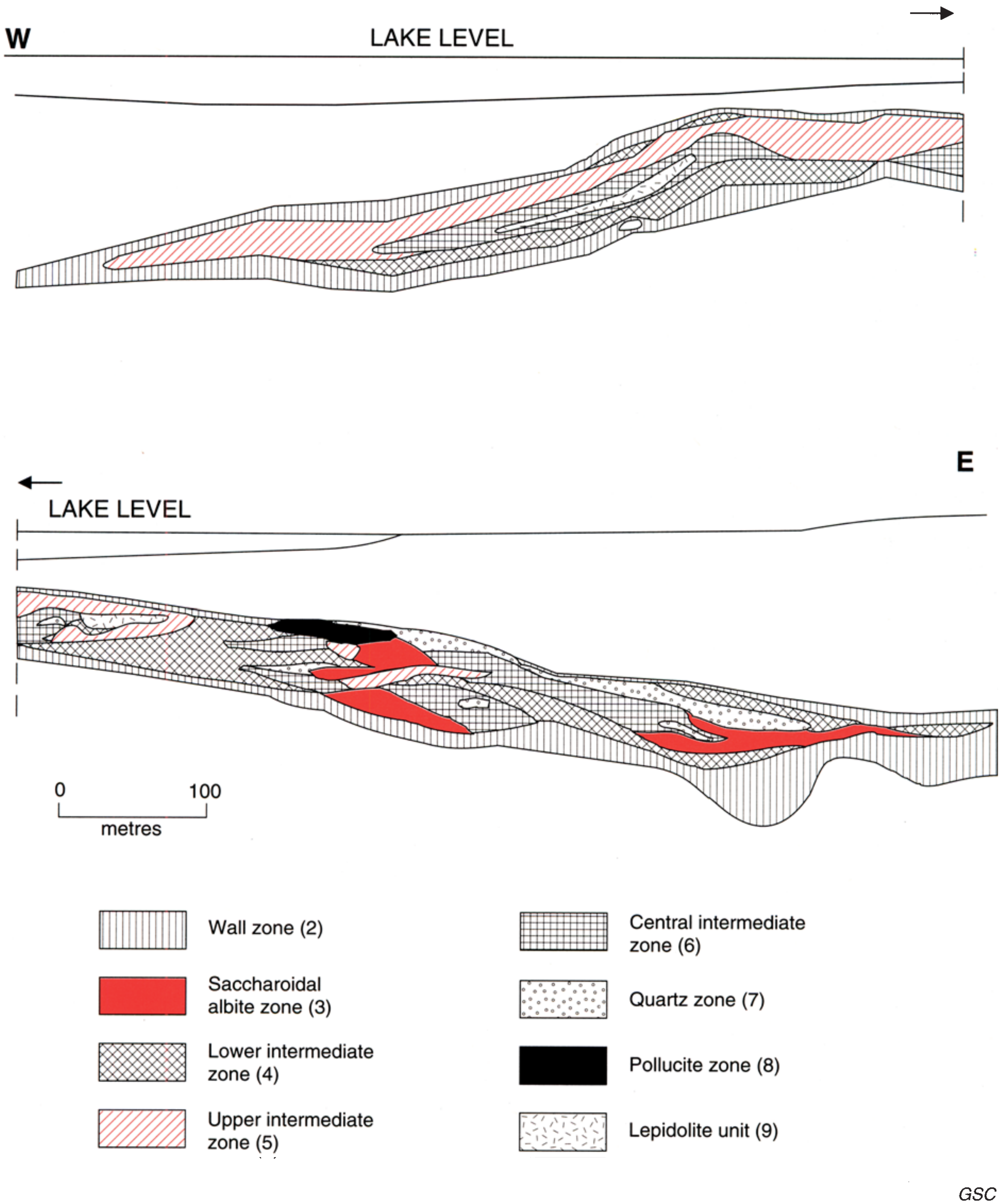

Figure 21-3. Representative longitudinal west-east section through the Tanco pegmatite, Manitoba (modified from Crouse et al., 1984). The host rock amphibolite is not patterned; the exomorphic zone and border unit are relatively thin and are not shown. The main zones that have been mined are shown in red; these are the saccharoidal albite zone (tantalum) and the upper intermediate zone (spodumene).

Table 21-3. Mineral zones in the Tanco pegmatite (from Crouse et al., 1984).

Zone	Main constituents*	Minor to rare constituents*
Exomorphic zone	Biotite, tourmaline, holmquistite	Arsenopyrite
1. Border unit	Albite, quartz	Tourmaline, apatite, biotite, beryl, triphylite
2. Wall zone	Albite, quartz, muscovite, Li-muscovite, microcline-perthite	**Beryl**, tourmaline
3. Saccharoidal albite zone	**Albite**, quartz, muscovite	Muscovite, **Ta-oxide minerals**, **beryl**, apatite, tourmaline, cassiterite, ilmenite, zircon-hafnon, sulphides
4. Lower intermediate zone	Microcline-perthite, albite, quartz, spodumene, amblygonite	Li-muscovite, lithiophilite, lepidolite, petalite, Ta-oxide minerals
5. Upper intermediate zone	**Spodumene, quartz, amblygonite**	Pollucite, lithiophilite, microcline-perthite, albite, Li-muscovite, petalite, eucryptite, Ta-oxide minerals
6. Central intermediate zone	**Microcline-perthite**, quartz, **albite**, muscovite	Lithiophilite, apatite, spodumene
7. Quartz zone	**Quartz**	Spodumene, amblygonite
8. Pollucite zone	**Pollucite**	Quartz, spodumene, petalite, muscovite, lepidolite, albite, microcline, apatite
9. Lepidolite unit	**Li-muscovite, lepidolite**, microcline-perthite	Albite, quartz, **beryl**, **Ta-oxide minerals**, cassiterite, zircon-hafnon

* Minerals outlined in **bold type** occur in economic or potentially economic quantities in the zones indicated.

Chemical composition

The chemical compositions of most pegmatites are similar to those of differentiated granitic rocks with respect to major elements, except that pegmatites tend to have lower total Fe, MgO, and CaO, and higher Al_2O_3 (Černý, 1991b). Rare element pegmatites, however, display extreme fractionation and enrichment in lithophile elements such as Li, Rb, Cs, Tl, Be, Nb, Ta, and Ga, and volatiles such as B, F, and P (Černý et al., 1985). Some rare element pegmatites, for example, contain as much as 2% Li_2O, 1% Rb_2O or more, 1.5% Cs_2O, 0.8% B_2O_3, and 1% F (Černý, 1982a). Pegmatites in high grade metamorphic rocks have high contents of Ca, Ba, Sr, Fe, Mn, Ti, and, in some cases, B, F, and rare-earth elements, but the content of rare metals in these pegmatites is low.

DEFINITIVE CHARACTERISTICS

Pegmatites are recognized by their granitic composition and by their highly variable grain size, including extremely coarse crystals. Rare element pegmatites, found in medium grade metamorphic terranes, contain dispersed rare metal-bearing minerals.

GENETIC MODEL

Pegmatites are generally considered to form by primary crystallization from a volatile-rich, siliceous melt (e.g. Jahns, 1955; Jahns and Burnham, 1969; Černý, 1982b, 1991b; London, 1990, 1992). In the case of rare element pegmatites, these melts are related to highly differentiated granitic magmas and represent strongly fractionated residual melts rich in silica, alumina, alkali elements, water and other volatiles, lithophile elements, and rare metals. According to Černý (1991a), the lithology of the source rocks for these melts is a major control on the ultimate composition of subsequently formed rare element pegmatites: undepleted upper crustal lithologies result in peraluminous granites that give rise to pegmatites enriched in lithium, cesium, and tantalum (e.g. Tanco), whereas depleted lower crustal rocks generate metaluminous to peralkaline granites that are parental to pegmatites enriched in niobium and rare-earth elements (including yttrium). Muscovite and abyssal class pegmatites, which occur in high grade metamorphic terranes, crystallized from melts that likely resulted from partial melting of their host rocks. These anatectic melts were also

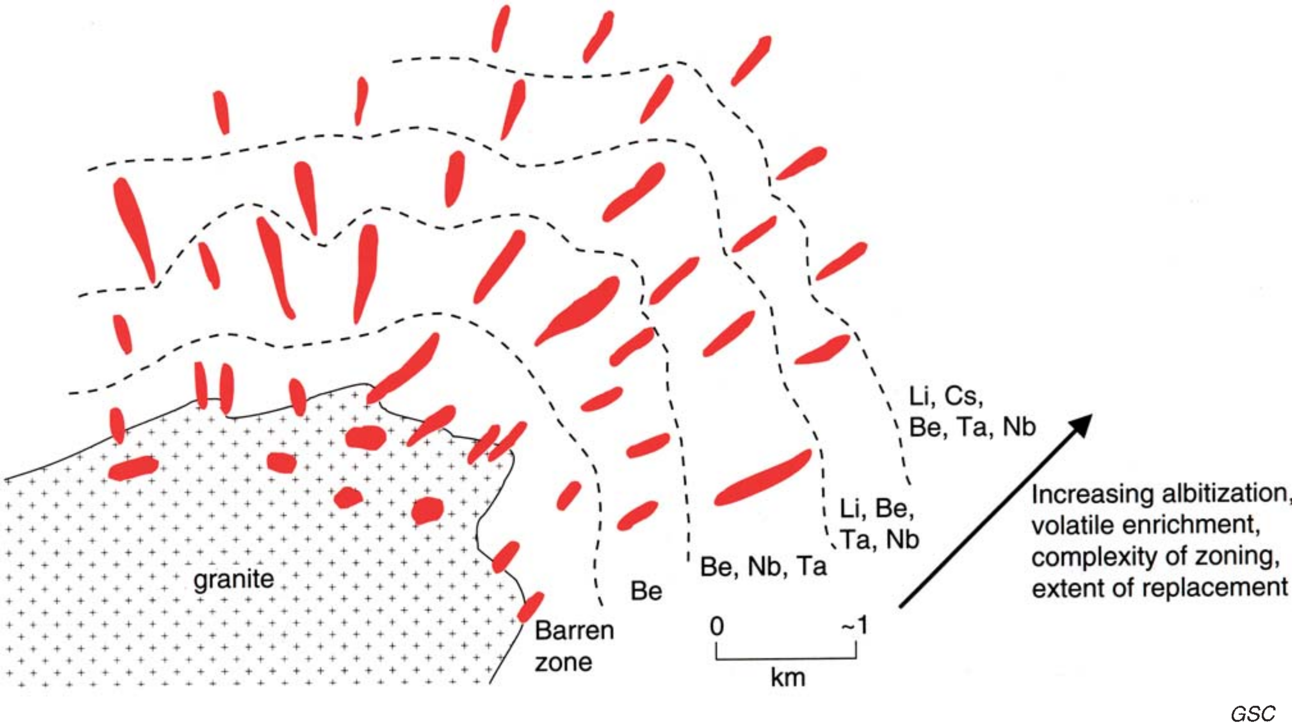

Figure 21-4. Schematic representation of the regional zonation of pegmatites (red) around a granite intrusion (modified from Trueman and Černý, 1982).

siliceous and volatile-rich, but the pegmatites they produced are not as highly fractionated and have no appreciable content of lithophile elements and rare metals.

According to Jahns and Burnham (1969), crystallization of pegmatite-producing melts takes place mainly under closed-system conditions, from the contacts of the pegmatite inward to produce concentric mineral zones. Some of these zones are sufficiently enriched in rare elements to be of commercial interest. Progressive evolution of a coexisting supercritical aqueous phase during this crystallization facilitates the growth of large crystals and provides a means to concentrate elements not easily incorporated in silicate minerals. This aqueous phase can react with earlier-formed minerals at various stages of pegmatite formation to produce metasomatic zones that are enriched in lithophile elements and rare metals. Fracture fillings may also form at various stages, and represent intermittent open-system conditions that probably occur briefly during pegmatite crystallization. As a further modification of this model, London (1990, 1992) has shown that highly fractionated pegmatites of the Tanco type crystallized largely from homogeneous melts enriched in B, P, F, and Li, and extremely enriched in H_2O. He also suggested that many "metasomatic" units are possibly primary, and that separation of aqueous fluid may, in fact, be very late in the consolidation history of pegmatites.

RELATED DEPOSIT TYPES

Pegmatites appear to represent a transitional phase between granitic intrusions and quartz veins. For example, zones of pegmatitic texture occur in several types of granite-related deposits, such as "stockscheider" associated with tin- and tungsten-bearing stockworks and greisens, and pegmatitic zones in felsic intrusions associated with porphyry copper and porphyry molybdenum deposits. Such pegmatitic zones, however, generally do not host significant mineralization.

Geochemical characteristics of tin- and tungsten-bearing granites (e.g. "specialized" granites of Tischendorf, 1977) and of felsic intrusions associated with porphyry molybdenum deposits resemble those of fertile granites that generate rare element pegmatites (Černý and Meintzer, 1988); intrusions associated with most porphyry copper deposits, however, are more mafic in composition and are substantially different geochemically.

Peraluminous to subalkaline rare metal granites with associated lithium, beryllium, niobium, and tantalum, as well as tungsten and tin mineralization (Pollard, 1989), are the closest relatives to pegmatite deposits. Some rare metal granites display pegmatitic cupolas that suggest an origin from pegmatitic melts that did not separate from their plutonic parent (Černý, 1992).

EXPLORATION GUIDES

Exploration guidelines for rare element pegmatites (Trueman and Černý, 1982; Černý, 1989b, 1991c) include the following:

1. Geological setting: rare element pegmatites typically occur in rock suites of medium grade Abukuma-type metamorphic facies, along fault systems and lithological boundaries, or closely associated with anorogenic granitoid plutons.

2. Regional zoning: identification of zonal patterns of pegmatite distribution can help isolate specific areas of interest.
3. Fractionation: mineral assemblages and chemistry of individual minerals in pegmatites indicate fractionation levels and economic potential.
4. Geochemical approaches: primary dispersion aureoles in host rocks (e.g. Li, Rb, Cs, Be, B), secondary dispersion halos in overburden, and light plus heavy minerals in stream sediments (e.g. beryl, spodumene, tourmaline, columbite-tantalite) help identify target areas at both regional and local scales.
5. Geophysical approaches: radiometric surveys may be useful for identifying parent granites and/or associated pegmatites that are enriched in U and Th. Gravity surveys can be used to outline pegmatites in host rocks of contrasting density.

ACKNOWLEDGMENT

P. Černý reviewed the paper and provided many constructive comments.

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Printed in Canada