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Carbonatites and related mineral deposits

Andrew Wygralak

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CARBONATITES AND RELATED MINERAL DEPOSITS

**(NOTES BASED ON UNTRANSLATED RUSSIAN PUBLICATIONS AND
DISCUSSIONS WITH RUSSIAN GEOLOGISTS)**

PREFACE

Information contained in these notes was compiled in 1977, during my UNESCO scholarship in the Soviet Union when I had access to geological literature on the subject that was largely unknown in the West. However, under prevailing secrecy during the communist regime I was not allowed to see any carbonatite-related deposits because they were classified as strategically important. These notes result from compilation of the Soviet literature available to me at the time as well as from many discussions with Russian geologists interested in carbonatites. I made this compilation years ago originally in Polish, and I am unable to quote some of the references now. I am also not involved in study of carbonatites anymore and I am not familiar with the latest developments in this field of geology. I decided to release these notes as an NTGS Record hoping that someone studying carbonatites today may still find some useful information here.

Andrew S. Wygralak
Northern Territory Geological Survey

INTRODUCTION

The term 'carbonatite' was introduced by Brogger (1921) for carbonate rocks of endogenic origin from the Fen region of Norway. Later, this term was extended to all carbonate-rich rocks genetically associated with magmatic processes. Some authors used this term also to describe sedimentary rocks altered during the metamorphic processes. Currently the term 'carbonatite' is used to describe carbonate rocks of endogenic origin, genetically and spatially associated with alkaline and ultrabasic intrusive or extrusive rocks and characterised by specific REE mineralisation and unique mineral parageneses (Ginsburg *et al* 1958, Kapustin 1971, Smirnov *et al* 1968).

There are 25 known provinces containing about 200 alkaline-ultrabasic complexes and carbonatites (Ternovoy 1974, Frolov 1975). These complexes are a subject of significant interest as they host large, sometimes unique in size, deposits of Nb, Ta, the cerium group of REE, apatite, phlogopite and vermiculite as well as Fe, Cu, Zn, Pb, Ti, Zr, Mo, Th, U, barite, fluorite mineral pigments and some other mineral commodities. In the 1970s, carbonatite-related deposits of Nb and Ce group of REE became the most important sources of these commodities, downgrading to second place placers and granitoid-related deposits.

GEOLOGICAL POSITION OF ALKALINE-ULTRABASIC COMPLEXES

Such complexes typically occur in tectonically re-activated portions of platforms. Most characteristic feature is their close spatial relation to the intersection of deep crustal structures with other tectonic elements such as consolidated platform margins or tectonic troughs (Erofeyev and Matveyenko 1976).

Chemical, isotopic and geophysical signatures of hyperbasite rocks, which often form significant part of alkaline-ultrabasic complexes, indicate that the source of magma was located at a minimum depth of 100-150 km (upper mantle). The strongly alkalic character of rocks results from prolonged, multi-stage intrusive processes causing significant differentiation of magma.

Development of carbonatite-bearing alkaline-ultrabasic complexes requires three necessary conditions (Smirnov *et al* 1968):

- presence of rigid portions of continental crust
- development or re-activation of deep folds and fractures
- slow, multi-stage intrusive process allowing differentiation of magma along deep structures.

There are three types of structural setting favourable for formation of such complexes:

1. Marginal parts of platforms. Magma intruded through deep crustal fractures, formed along boundaries between stable platforms and geosynclinal basins. Intrusions took place during uplift of geosynclinal basins. Alkaline-ultrabasic complexes formed in this scenario usually are circular or oval in shape, have a concentric structure and are located

on platforms, up to several hundred kilometres from the margin (eg North Africa, West Brasil, Karelo-Kolska region in former USSR).

2. Boundaries between platforms and consolidated orogenic zones. Here such complexes are associated with folds parallel to platform margins. They occur in both re-activated portions of platforms and adjacent post-orogenic zones. The typical shape is elipsoidal or, less frequently, linear (Sette-Dabanska and Eastern Sajan provinces in the former USSR).

3. Rift zones. Complexes have circular or elipsoidal form. A typical example is the East African province (**Figure 1**).

Within a province, alkaline-ultrabasic complexes tend to occur in clusters, suggesting association with a single magmatic source. They have a range of ages including Precambrian (Aldan province in the former USSR), Palaeozoic (Nevada), Mesozoic (East Brazil, West Africa) and Cainozoic (East Africa) but they always appear towards the end of a particular stage of magmatic activity (Ginsburg *et al* 1958, Frolov 1975). The complexes vary in size from less than one km² to 56 km². An exception is Gulinski complex in Siberia which covers 2000 km².

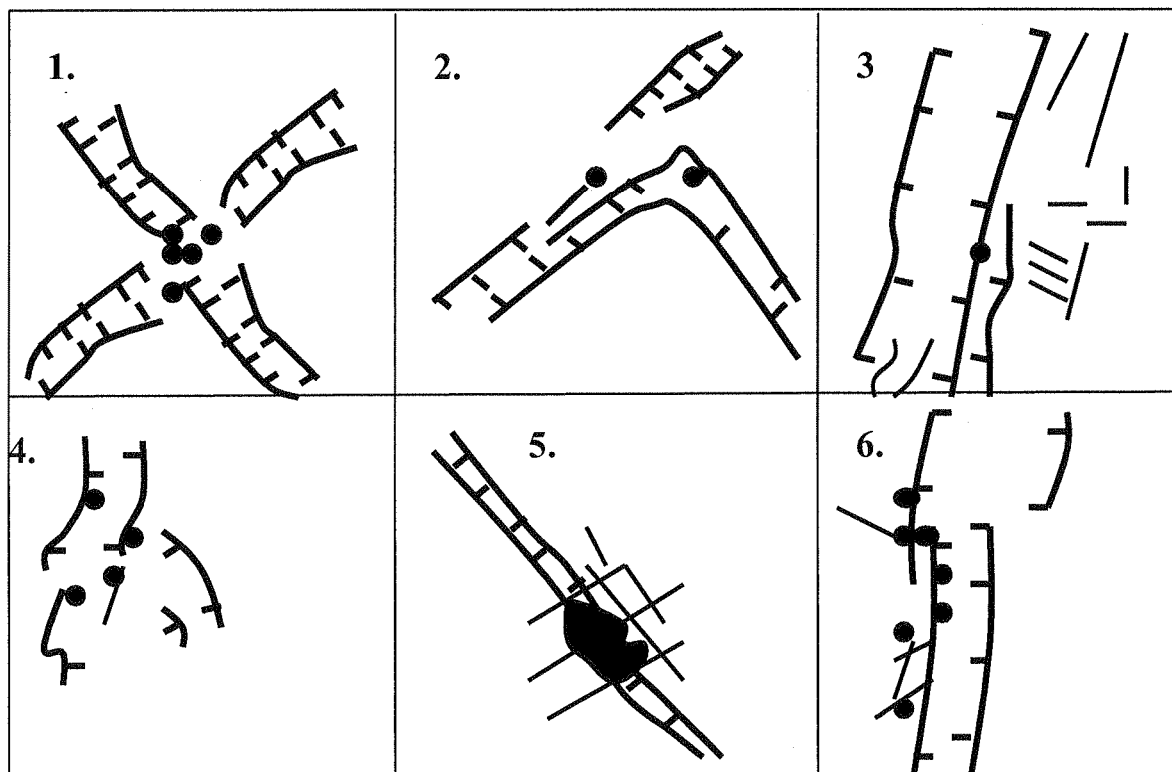


Figure 1 Structural setting of alkaline-ultramafic and carbonatite complexes related to rift zones (after Frolov 1975). 1. Intersection of two massifs - Museni, Songwe, Mbea, Nkombwa and Naczendezwaja (Africa); 2. Converging rifts - Dorowa, Shawa (Africa); 3. Rift cut by zone of transversal folds - Kaiserstuhl (Germany); 4. Partition of rift - Kaluwe, Naczomba, Mbambuto, Chazweta (Africa); 5. Intersection of deep fractures differing in age - Nizne Sajany (USSR); 6. En echelon faults near rift margin - Toror, Napak, Moroto, Kadam, Budeda, Bukusu, Sukulu (Africa).

STAGES OF DEVELOPMENT AND GEOLOGY OF ALKALINE-ULTRABASIC COMPLEXES

Such complexes have complex, polygenetic structure. They include intrusive alkaline and ultrabasic rocks, silicified metasomatic rocks, carbonatites, post-carbonatite facies, as well as an array of dykes and veins of differing composition. In some provinces they also include effusive and eruptive rocks.

There are two stage of formation of these complexes - a magmatic stage and a post-magmatic (metasomatic-hydrothermal) stage. Four petrological phases can be distinguished during the magmatic stage (Ginsburg *et al* 1958, Kapustin 1971, Smirnov *et al* 1968):

1. Hyperbasite phase (the oldest). This phase is dominated by intrusions of pyroxenite, olivinite and, less frequently, peridotite and dunite. The rocks are enriched in titanomagnetite, chromium, nickel and cobalt. In some cases there is also an increased concentration of perovskite and, rarely, platinum group metals.
2. Alkali-hyperbasite phase. During this phase biotite peridotites, pyroxenites and menilitic rocks are intruded.
3. Iolite-meltejgite phase. Nepheline and pyroxene-rich rocks prevail during this phase.
4. Alkali-syenite phase. Nepheline and alkali-syenite rocks dominate.

Each of these phases may form a separate intrusion. Each phase is also followed by a suite of dykes comprising several petrographical types.

The post-magmatic, metasomatic-hydrothermal stage is divided into three phases:

1. Metasomatic phase. This phase includes formation of metasomatic rocks developing after hyperbasites, alkalic hyperbasites and in some cases after ijolites, meltejgites and alkaline syenites. Due to strong calcitic metasomatism some of these rocks have composition similar to skarns. Further progression of this process leads to development of carbonatites.
2. Carbonatite phase.
3. Post-carbonatite phase. Veins and apophyses of calc-silicate rocks are formed. They intersect carbonatites and host veins of typical hydrothermal minerals including barite and fluorite. Such veins occur also in exocontacts of the complexes.

The above two development stages of alkali-ultramafic complexes are followed by a hypergenic stage which involves formation of a weathered cover.

Development of complexes affects surrounding rocks, sometimes causing their complete alteration. The most extensive changes occur in exocontacts, particularly if the surrounding rocks are silica-rich (eg slate, sandstone, granite or granitic gneiss). The size of alteration aureole depends on several factors including size of an intrusion, intensity of fractures in the surrounding rocks and chemical differences between intruding magma and surrounding rocks.

Usually contact aureoles are tens to hundreds of metres wide, but in some cases may reach several kilometres. The contact metasomatic processes are known under a general term of fenitisation and the resulting rocks are called fenites.

Fenitisation is a multiphase process. Each intrusive stage is reflected in changes in exocontact. These changes are superimposed on each other and are difficult to distinguish. Generally fenitisation involves development of alkali amphiboles (diopside, egrine, augite), replacement of quartz by pyroxene, and albitisation (Kapustin 1971, Smirnov *et al* 1968). The resulting rocks are alkalic syenites and granites, petrographically similar to intrusive rocks of these types.

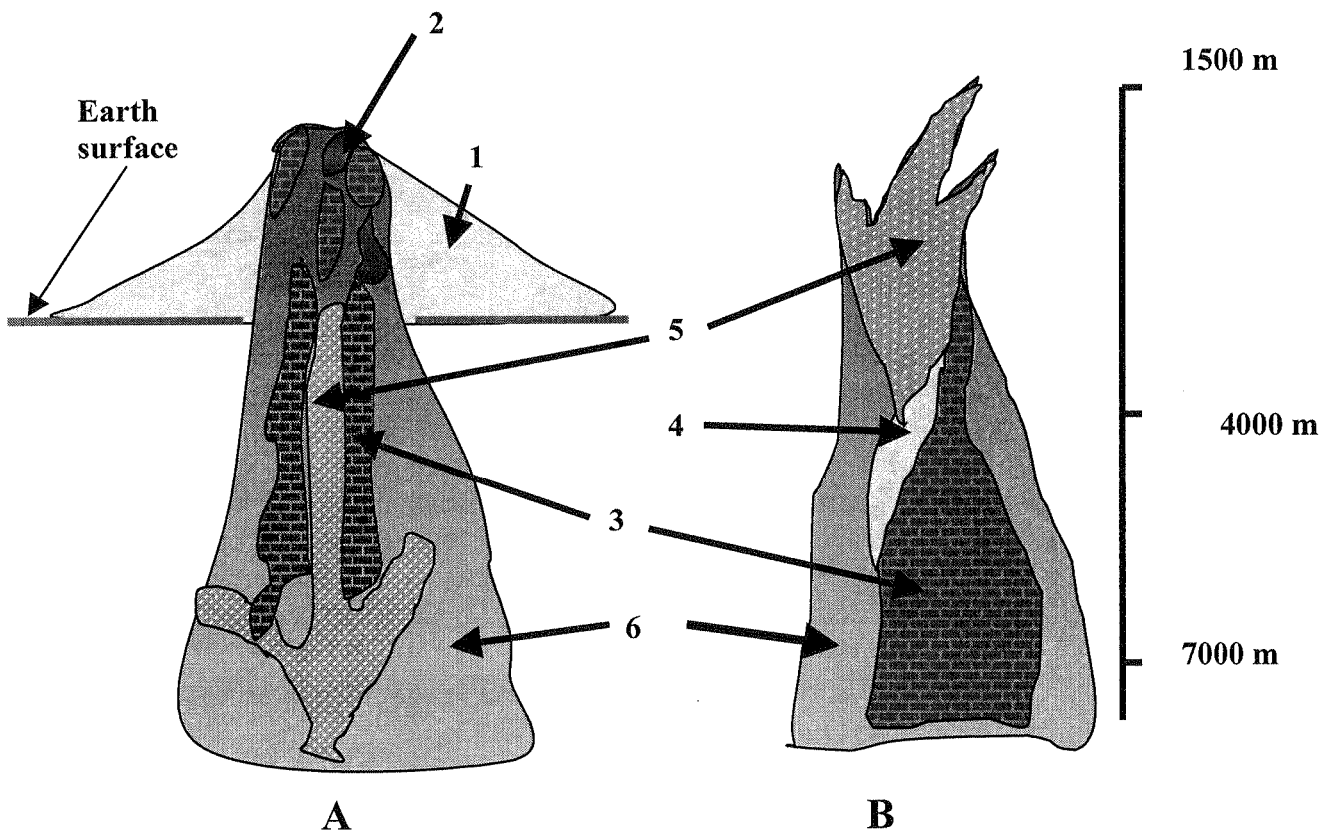


Figure 2 Two types of alkali-ultramafic complexes (simplified after Smirnov *et al* 1968).

A Cross section of uneroded exposed complex. **B** Cross section of 'blind' complex.

1 Effusive rocks and tuffs, 2 Vent facies rocks, 3 Carbonatite, 4 Iolite and meltegitte, 5 Syenite, 6 Hyperbasite.

An open type represents volcano-plutonic complexes developed when an intrusion reached the earth surface (**Figure 2**). They form volcanic vents filled with eruptive, effusive and intrusive rocks including carbonatite. This type of complex is common in carbonatite provinces of Africa.

Blind complexes formed under hypabyssal conditions. Most often they occur in the contact zones between platforms and consolidated orogenic zones.

Both types show specific zonation which can be normal or reversed (**Figure 3**). Normal zonation occurs in complexes with the youngest rocks in the centre. Complexes with reverse zonation have the oldest rock phase in the centre.

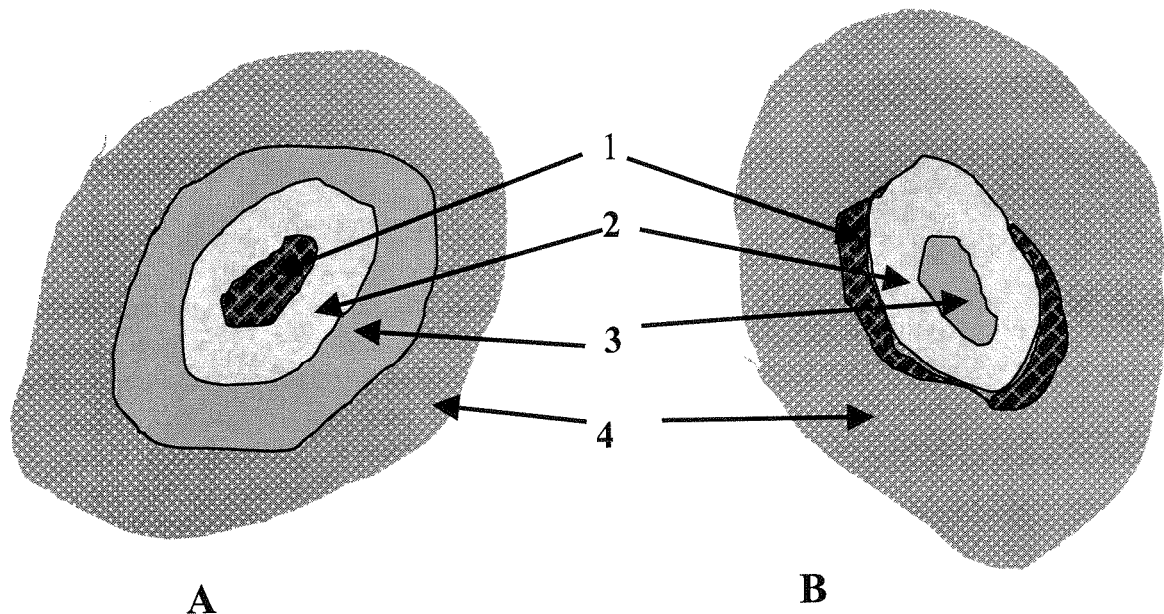


Figure 3 Normal (A) and reverse (B) horizontal zoning of complexes. 1 Carbonatite, 2 Ijolite and melteigite, 3 Ultrabasite, 4 Fenite.

The complexes form five morphological types – concentric, excentric, linear, polycentric and complex (**Figure 4**).

The proportional content of particular rock types differs depending on the degree of erosion of each complex. In deeply eroded complexes olivine and piroxene rich rocks (hyperbasites) prevail. Complexes moderately eroded are dominated by jacupirangite, melteigite, ijolite and carbonatite rocks. When erosion is shallow the main rock types include nepheline and alkaline syenite and their dyke equivalents, as well as carbonatite. Non-eroded volcanic, open type complexes are characterised by dominating eruptive rocks along with fonolitic, nephelinite and sometimes also carbonatite lavas.

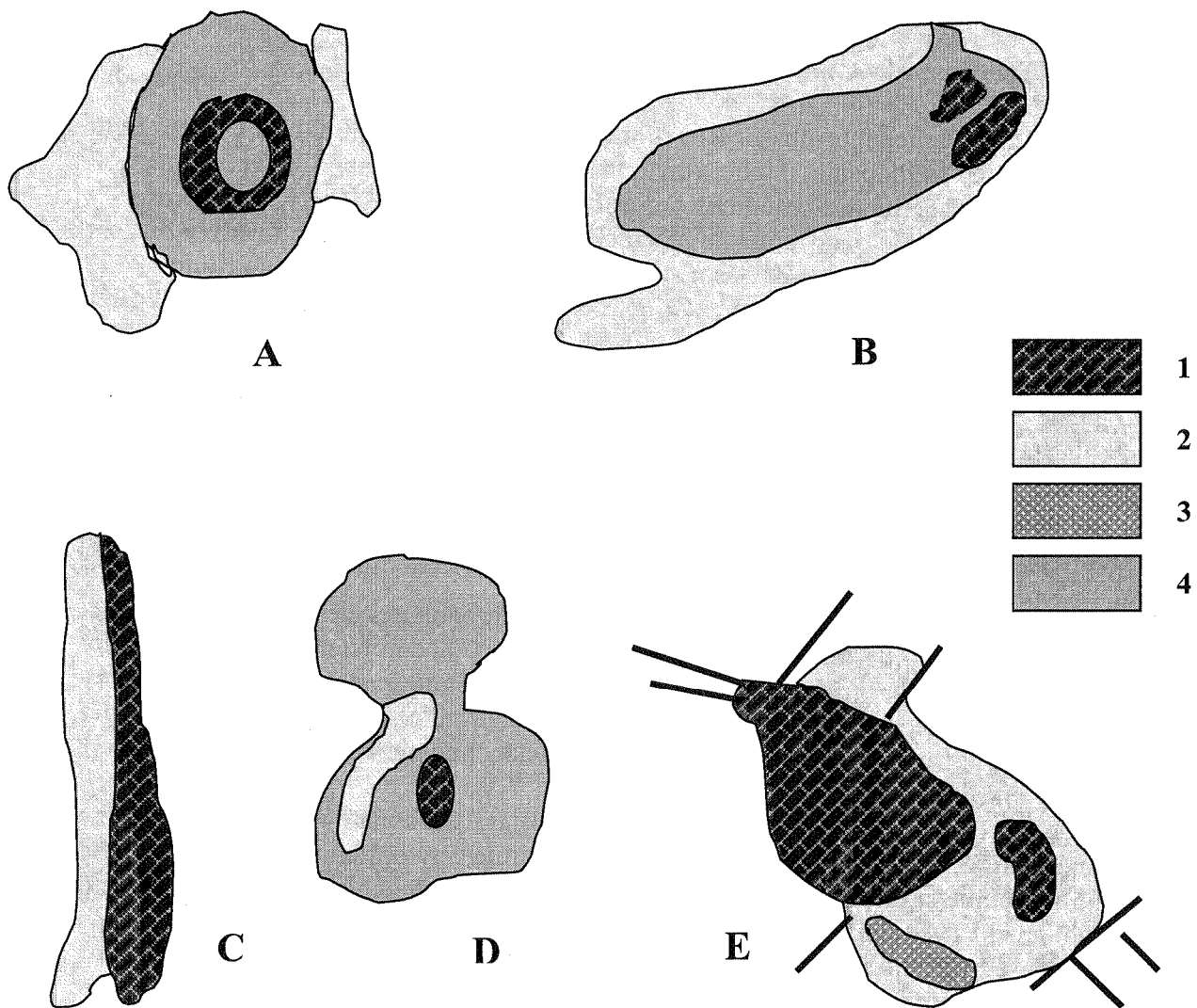


Figure 4 Morphological types of complexes. **A** Concentric (Shawa in Africa), **B** Excentric (Wuorijarvi et Kola Peninsula), **C** Linear (Hek in Settle Daban province of former USSR), **D** Polycentric (Yacupiranga in Brasil), **E** Complex (Nizne Sajany in former USSR).

1 Carbonatite, 2 Ijolite, meltejgite and jacupirangite, 3 Syenite, 4 Ultrabasite.

DEVELOPMENT OF CARBONATITES AND ASSOCIATED MINERALISATION

Mineral composition of carbonatites indicates that they formed at the decreasing temperature range of $>500^{\circ}\text{C}$ to below 100°C . Four phases can be distinguished during the carbonatite phase of complex formation:

1. Early calcite carbonatite phase. Rocks of this phase contain 30-70 % calcite. Dark minerals such as diopside, augite, forsterite, biotite, nepheline and magnetite as well as apatite are common. Sometimes perovskite is also present. The rocks are usually coarse grained (some dark minerals reach size of 5-10 cm) and have massive or, less frequently, banded texture. Metasomatic replacement of diopside augite by forsterite and then by biotite is common. Co-existence of calcite and nepheline indicates temperature of formation above 550°C .
2. Calcite carbonatite phase. The amount of dark minerals decreases, diopside augite is replaced by diopside, and biotite is substituted by phlogopite. Accessory minerals include titanium and zircon minerals (cyrtolite, baddeleyite) as well as minerals containing tantalum, niobium, uranium and thorium (hatchettolite, pyrochlore). The rocks are coarse to medium grained and have a directional or banded texture.
3. Phase of late calcite and dolomite carbonatite. Carbonatites developed during this phase have complex mineral assemblages. Pyroxene and forsterite are replaced by alkali amphiboles, serpentine minerals and talc. Dolomite is also present. Accessory minerals include magnetite, ilmenite, apatite, chondrodite, pyrite, sphene, rutile and REE minerals (pyrochlore, lueshyte, eshynite, lyndochite, fersmite and zircon).
4. Phase of late dolomite and ankerite carbonatites. Carbonate content reaches its maximum (85-95 % and more). Calcite is substituted by dolomite, ankerite, siderite and sometime strontianite. Silicates (aegirine, arfvedsonite, chlorite and epidote) and aluminosilicates (albite, grossular) comprise not more than 3-5 % of rock volume. In this phase hydrothermal minerals such as fluorite, barite and sphalerite also appear, as do niobium minerals (columbite, pyrochlore) and commonly significant amounts of REE carbonates including bastnaesite, parisite, burbankite, carbocernaite, cordylite and lanthanite. Carbonatites of this phase are fine grained and have banded textures.

Compositional evolution of carbonatites involves a gradual change from calcite through dolomite and ankerite to siderite. Some workers (eg Pecora 1956) divide carbonatites into two types of different economic value: apatite-magnetite type and carbonatites with industrial concentration of REE.

All carbonatites are characterised by elevated concentration of Nb, Ta, Zr, REE (mostly Ce group), U, Th, Sr, Ba, Sc and some other elements. Some of these elements form their own minerals (Nb, Zr), some form isomorphic enrichments (Ta, Sc) and some occur in both these forms (Zabin 1971). The typical concentration of selected elements compared with their average content in sedimentary carbonates is given in **Table 1** below:

Table 1 Concentration of selected elements in carbonatites compared with sedimentary carbonates.

Element	Concentr. factor	Element	Concentr. factor
Nb	6500 x	La	500 x
Ba	260 x	Ce	140 x
Zr	50 x	Y	3 x

REE mineralisation in massifs varies greatly from nearly none to very significant. Early, high temperature carbonatites often have increased concentration of Nb, Ta, Zr and Ti; late carbonatites concentrate REE, Sr, Ba and chalcophile elements. The REE minerals also evolve. Initially carbonates prevail (burbankite), then fluorocarbonates (bastnaesite, parisite), followed by phosphates (zircon) and finally silicates (orthite).

MINERAL DEPOSITS ASSOCIATED WITH ALKALI-ULTRABASIC COMPLEXES AND CARBONATITES

Detailed classification of mineral deposits associated with such complexes was developed by Heinrich (1966). He divided all deposits into four groups: pre-carbonatite, carbonatite-related, post-carbonatite and exogenic. Thirty types of deposits representing three mineral associations are distinguished within these groups: perovskite-titanomagnetite, apatite-magnetite-phlogopite and polymetallic.

Deposits associated with alkali-ultrabasic massives and carbonatites include the following mineral commodities:

Niobium

Carbonatite deposits are the most important source of this element. The main mineral is pyrochlore, sometimes columbite and rarely niobium-bearing perowskite-dysanalyte (Oka deposit in Canada). The largest carbonatite niobium deposits are Tapira and Araxa in Brasil (8.7 Mt N₂O₅ and 5.6 Mt N₂O₅ respectively; de Kun 1962). Other significant deposits include Oka in Canada (0.1 Mt of N₂O₅), Mrima in Kenia (0.7 Mt of N₂O₅), Sukulu in Uganda (0.4 Mt of N₂O₅) and Kaiserstuhl in Germany (7000 t of N₂O₅). The average grade of these deposits ranges 0.1 – 0.15 % N₂O₅, but in weathered cover of carbonatites containing pyrochlore it may reach 3-4 % N₂O₅.

REE

Carbonatite deposits of REE are characterised by significantly enriched cerium group elements, in particular La, Ce and Nd, over the rest of the REE. Such deposits usually contain a resource of 0.1-1.0 Mt and sometimes more. A deposit unique in size is Mountain Pass deposit in USA with a resource of tens of Mt. In early calcite carbonatites, REE are concentrated in pyrochlore, dysanalyte and apatite. The largest concentration, however, is associated with late ankerite and siderite carbonatites where REE occur as fluorocarbonates (parisite, bastnaesite) and less frequently as phosphates (monazite, florencite).

Apatite

There are two types of carbonatite-related apatite deposits. The first type is associated with metasomatic apatite-magnetite-phlogopite and apatite-magnetite-forsterite rocks. Such deposits are known, for example, from Kola Peninsula in Russia (Kowdor), and from Africa (Bukusu in Uganda, Polabora in RPA). The second type occurs in weathering cover of carbonatites. This type is known from Brasil (Yacupiranga) and East Sayan province of the former USSR.

Phlogopite and vermiculite

Phlogopite concentrates mainly in pegmatite-like phlogopite-olivine and phlogopite-diopside rocks. Vermiculite forms in weathering cover of these rocks. Large deposits of phlogopite and vermiculite are known from the Kola Peninsula in Russia (Sebljawr, Wuorijarwi, Kowdor). Their reserves reach several million tons.

Tantalum and uranium

These elements concentrate mainly in hatchetolite where their contents range from 5 to 27 %. A characteristic feature of this association is the constant Ta/U ratio, equal to 1:1. This allows a quick estimate of Ta contents using radiometric methods.

Thorium

This element is widespread in carbonatites. It occurs mostly as dissemination in pyrochlore, where its normal concentration ranges from 0.1-0.5 % but may reach as much as 12 %. Thorium occurs also in thorite, uranothorite and monazite.

Titanium

Similar to niobium, enrichment in titanium is also characteristic for alkali-ultrabasic complexes and carbonatites. The most common minerals of this element include perovskite and titanomagnetite. These two minerals form disseminations or massive ore bodies in pyroxenite, olivinite and meltejgite. Typical deposits contain several million tons of ore grading 5-20% TiO₂ and 10-30 % Fe (Frolov 1975).

Iron

Many complexes contain forsterite-apatite and phlogopite-apatite rocks with significant amount of magnetite. Complexes such as Kowdor and Wuorijarwi on the Kola peninsula or Polabora and Bukusu in Africa contain up to 70-80 % of magnetite and an Fe resource of hundreds of millions of tons. Another type of iron deposit is hematite bearing carbonatites, such as Fen in Sveden or Kalkfeld in Namibia. Significant amounts of iron are also associated with perovskite-titanomagnetite rocks.

Copper

Although copper sulphides occur in many complexes, their economic concentration is known only from the Polabora deposit in RPA (325 Mt @ 0.69% Cu; Tuttle and Gittins 1966).

Lead and zinc

Many late phases of carbonatites are enriched in Pb, Zn and Co. Only rarely, however, does such enrichment reach economic levels. Zn and Pb are mined from one of the deposits in Russian Siberia (unidentified).

Molybdenum

This element also tends to concentrate in late carbonatites where its concentration may reach as much as 0.03 % (Chilwa in Malawi, Songwe in Tanzania).

Zirconium

Main minerals of this element in carbonatite deposits include zircon, baddeleyite and zirkelite.

Aluminium

Alkali-ultrabasic complexes contain nepheline-rich rocks such as ijolite and urtite which potentially are a large source of aluminium. To date they are not utilised because of technological reasons.

Other commodities

Ankerite and siderite carbonatites are also a source of mineral paints (Fe ochres), barite and celestine. Other commodities associated with alkali-ultrabasic complexes and carbonatites include asbestos, soda, salt, high grade calcium carbonate for production of cement, and feldspar for ceramic purposes.

FACTORS CONTROLLING DISTRIBUTION OF MINERALISATION

In spite of the multiphase character of mineralisation in alkaline-ultrabasic complexes, a close relationship between the type of rock and character of hosted mineralisation is maintained. Crystallochemical and magmatic factors control distribution of mineralisation during the early stages. During later stages structural control becomes increasingly important and metasomatically altered rocks are closely related to systems of concentric fractures. At the carbonatite stage mineralisation is fully controlled by structural and lithological factors.

Early calcite carbonatites usually host Ta and Nb mineralisation whereas later ankerite and siderite carbonatites tend to contain REE deposits. In early carbonatites mineralisation is usually controlled by concentric fractures. In later carbonatites mineralisation tends to be associated with linear fractures. Most mineralisation is contained within the complexes but some late deposits of thorium and REE also occur in exocontacts.

Mineralisation shows clear vertical zonation (**Figure 5**). Less pronounced is horizontal zonation. Both types of zonation are often strongly overprinted by multiphase magmatic and subsequent metasomatic and hydrothermal processes.

Analytical study of physical properties of rocks indicated an inverse relation between ore potential and porosity of carbonatites (Frolov 1975).

PROVENANCE OF CARBONATITES

The provenance of carbonatites is still controversial. Early hypotheses advocated primary sedimentary origin. Carbonatites were considered to be either limestone xenoliths incorporated into alkali-ultramafic magma, or deeply buried sedimentary carbonate rocks which under pressure behaved as salt diapires. The sedimentary origin was subsequently disputed because carbonatites occur also in regions where there are no carbonate rocks in the entire stratigraphic sequence. Also the sedimentary hypothesis was inconsistent with increased concentration of P, REE, Nb and Ta in the carbonatite rocks. A final argument against the sedimentary provenance was delivered by isotopic composition of oxygen and strontium (Frolov 1966, Ginsburg *et al* 1958).

More recent studies suggest either a magmatic or hydrothermal-metasomatic origin of carbonatites (Tuttle and Gittins 1966). The first hypothesis postulates that carbonatites represent the final stage of differentiation of peridotitic magma, occurring in the upper mantle (Zabin 1971). The hydrothermal-metasomatic hypothesis suggests that carbonatites develop as a result of metasomatic reaction of silicate rocks with post magmatic carbonate rich fluids.

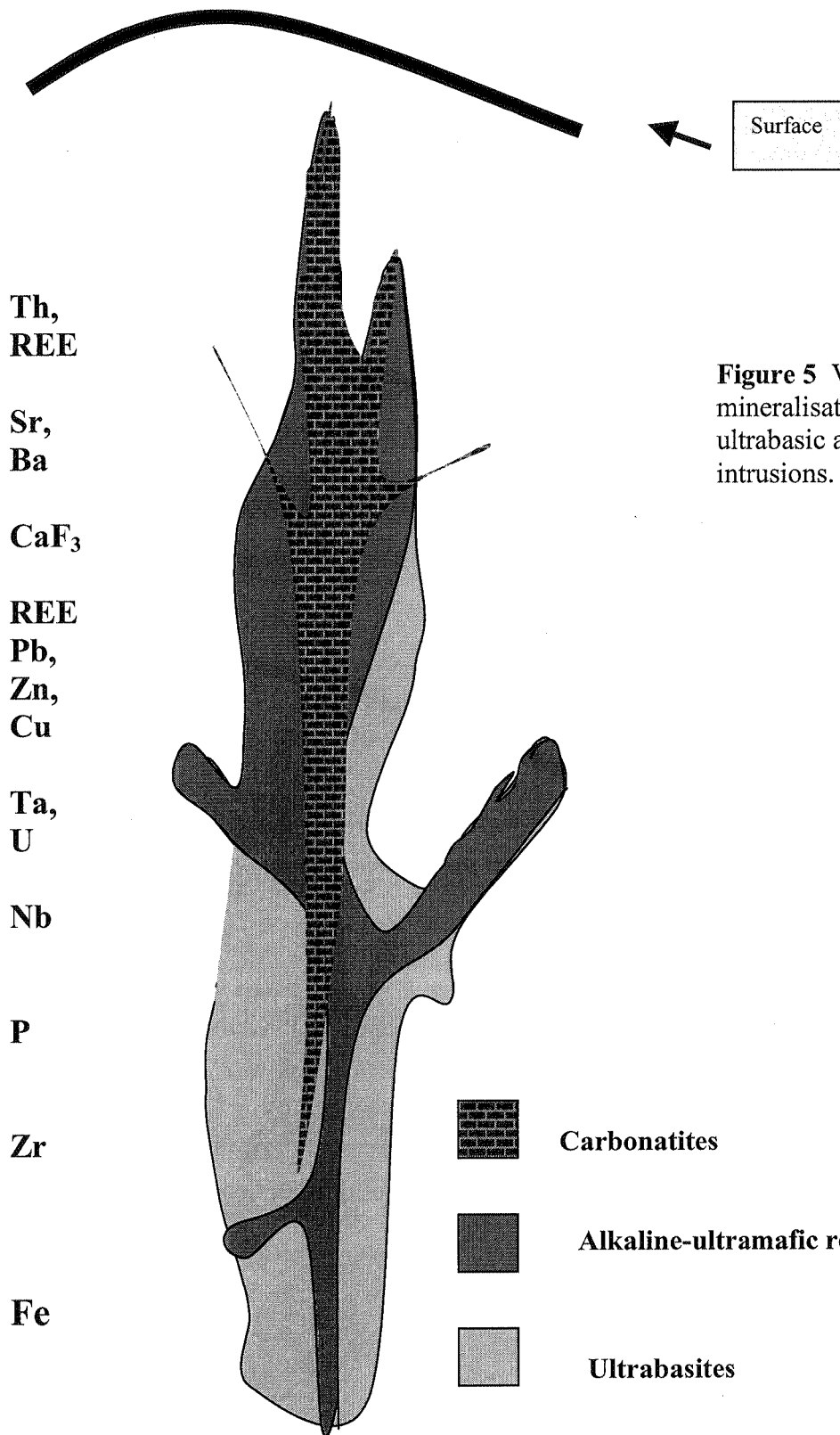


Figure 5 Vertical zonation of mineralisation in alkalic-ultrabasic and carbonatite intrusions.

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Mineral deposits associated with alkali-ultrabasic complexes and carbonatites

Deposit type	Main mineral association	Host rock	Shape of orebodies and type of ore	Mineral commodities		Examples	
				Major	Minor		
ENDOGENIC	1	2	3	4	5	7	
							Magmatic
	Perovskite-magnetite	Pyroxenite, olivinite, sometimes meltejjite	Irregular orebodies with massive or disseminated mineralisation	Ti, Fe	REE	Iron Hill (USA), Yacupiranga (Brasil)	
		Nepheline	Urtite, ijolite	Stockworks and dykes	Al		
		Phlogopite	Ultrabasic, meltejjite, ijolite	Irregular orebodies	Phlogopite, vermiculite	P	Kowdor, Guli, Odichinca (former USSR)
		Apatite-magnetite	Apatite-magnetite-forsterite rocks	Concentric and cone-shaped orebodies with massive or disseminated mineralisation	Fe, P	Ta, Zr, Nb	Kowdor (former USSR), Sukulu, Bukusu (Uganda), Polabora (RPA)
	Apatite-pyroxchlore	Alkalic and nepheline syenites, ijolite	Lensoidal, cone-shaped and circular orebodies with disseminated mineralisation	Nb, P		East Siberia (former USSR)	

					Nb, Ta	Zr	Nemegosenda (Canada), East Siberia (former USSR)
	Pyrochlore-hatchettolite	Alkalic and nepheline syenites, fenite	Linear orebodies with disseminated mineralisation				
Early carbonatic	Calcite	Calcite carbonatites	Massive, stockworks, veins, zones of veining	Calcite	Calcite	Calcite	Tororo (Uganda), Kowdor (former USSR)
	Pyrochlore	as above	stockworks, cone-shaped and linear orebodies with disseminated mineralisation	Nb	P, Th	P, Th	Araxa (Brasil), Oka (Canada), East Siberia (former USSR)
	Hatchettolite-pyrochlore	Calcite carbonatites and apatite-magnesite-forsterite rocks	as above	Ta, Nb	U, P	U, P	East Siberia (former USSR)
Late carbonatic	Bornite-chalcopyrite	Calcite and dolomite carbonatites	Stockworks, semi-circular and vein-like orebodies with disseminated mineralisation	Cu		P	Polabora (RPA)
	Sphalerite-galena	Calcite, dolomite, ankerite and siderite carbonatites	Stockworks	Zn, Pb		REE, Mo	East Siberia (former USSR)
	Parisite-bastnaesite-monazite	as above	as above	REE		Th, Pb, Zn, Mo	Kangankunde (Malawi)

EXOGENIC (weathering cover)										
	Residual	Apatite	Weathering cover of carbonatites	Lenses, irregular or elongated orebodies	P		Fe, vermiculite	Karelo-Kolska Province in former USSR		
		Vermiculite	Weathering cover of alkalic intrusives and carbonatites	as above	Vermiculite		P	as above		
		Barite	Weathering cover of siderite and ankerite carbonatites	as above	Barite		Fe-ochres used for mineral paints	Kowdor (former USSR)		
	Residual-infiltrative	Apatite-staffelite	Weathering cover of carbonatites	as above	P		Vermiculite, Fe	Karelo-Kolska Province in former USSR		

