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CARBONATITE OCCURRENCES OF THE WORLD: MAP AND DATABASE

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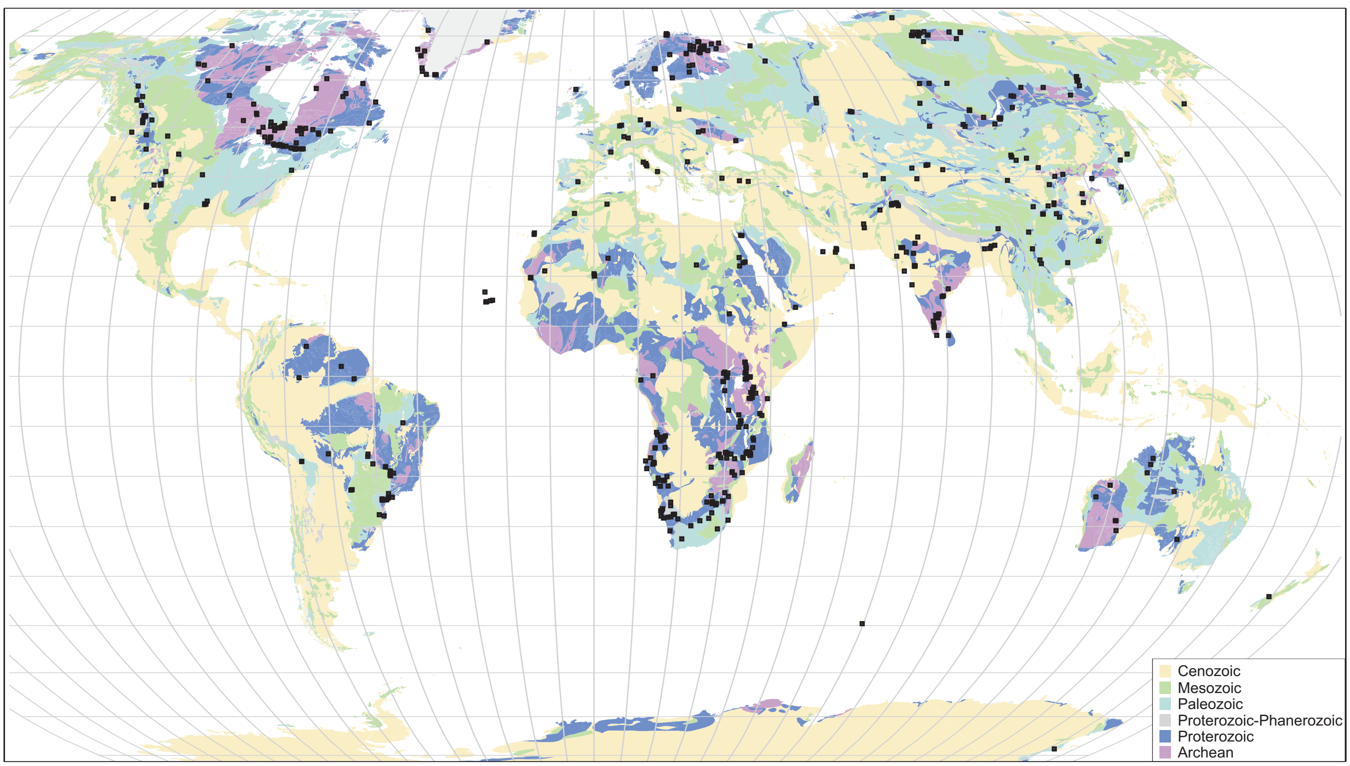

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Cover Figure. World map showing all known carbonatite localities.

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INTRODUCTION

There has been a steady increase over the last century in the number of known occurrences of carbonatite. Recognition of these rocks as magmatic in origin got off to a slow start with only the carbonate-rich rocks at Alnö (Högbom, 1895), Fen (Brögger, 1921), and Kaiserstuhl (Soellner, 1927) being appreciated as igneous, although critics were numerous and often influential (e.g. Bowen, 1924). A major advance, at least in numbers, was achieved by the publication by Dixey et al. (1937) of descriptions of carbonatite and associated fenite at 11 localities in the Chilwa Province of Malawi. Remarkably, in that paper it was also suggested that limestone at Kalkfeld, Okorusu, Phalaborwa, Lokupoi Hill (Napak), Toror, and Tororo were also carbonatite, and thus the carbonatite story can be said to have gathered momentum. After the 2nd World War the demand for strategic materials gave an impetus to the exploration for further occurrences. The development of mining at Phalaborwa and Mountain Pass, in particular, established the economic potential of some carbonatite occurrences.

In 1956, Pecora listed 32 carbonatite occurrences while by 1966 Gittins was able to describe some 200. However, Heinrich (1966) claimed to have listed 320 localities, although his numbers by country and continent appear to sum to only 214 localities. Woolley (1989) was aware of 330 carbonatite occurrences worldwide and in a later paper (Woolley, 2003) put the number at approximately 450. The present work includes descriptions of 527 occurrences. The absolute number of known carbonatite occurrences is, of course, of little importance, but we suggest, having in hand a compilation including the location, basic information, and key references of all known occurrences will be of considerable utility. Although the database does not include information such as chemical analyses, isotope data, or experimental results on carbonatitic systems, it should provide pertinent baseline information for research in many fields. For instance, the geographical coordinates can be used in studies of spatial distribution, a subject area in which there is continuing interest. Although the detailed geological and tectonic contexts of the described occurrences could obviously not be given, the accompanying map does display a simplified geological base from which some 'feel' for geological context can be drawn. The nature of the silicate rocks associated with each carbonatite occurrence is outlined in the descriptions and many authors believe that there are genetic implications in these associations (e.g. Woolley, 2003; Woolley and Kjarsgaard, 2004, 2008), although others, (e.g. Gittins and Harmer, 2003), consider that this belief is misplaced. Results of the age dating of the carbonatite occurrences are fully catered for in the database, as is information on carbonatite types (i.e. calcio-, magnesio-, and ferro-carbonatite) and their attendant mineralogy (which is described in some detail). These different facets of carbonatite petrology should be helpful in comparative work. The great diversity of the carbonatite occurrences, whether they occur in multiple complexes or as small isolated dykes, whether there is a broad suite of associated silicate rocks or none, whether there is a single or a range of carbonatite compositions and types, and whether the occurrence is intrusive, extrusive, or includes both, are all features that can be gleaned from the database and are considered to be of petrogenetic importance. Many geologists are, of course, particularly interested in the economic aspects of carbonatite occurrences, as they are repositories for a broad range of useful commodities. Although it is appreciated that the economic information given here is brief, and that a number of papers have been published addressing the economic aspects of carbonatite, the comprehensive nature of the database may draw the attention of economic geologists to occurrences of which they were unaware. For all these reasons it is hoped that those interested in carbonatite will find the database and accompanying map useful.

DATA SOURCES

The initial sources of the data used in this compilation comprise the three published volumes having the titles 'Alkaline Rocks and Carbonatites of the World', namely Part 1: North and South America (Woolley, 1987), Part 2: Former USSR (Kogarko et al., 1995), and Part 3: Africa (Woolley, 2001). However, new localities continue to be described and the content of these volumes is updated with the present compilation. This is clearly illustrated by the first (North and South America) volume, to which 32 new localities have now been added, with Canada accounting for no fewer than 25 of these. For localities not covered by Alkaline Rocks and Carbonatites of the World volumes 1, 2, and 3 (i.e. the rest of the world), we have used the descriptions already written for the proposed volume 4 in the above series (Woolley, work in progress), which comprise full descriptions for those occurrences found in the United Kingdom, Finland, Norway, Sweden, Poland, Germany, Spain, Italy, Czech Republic, Bulgaria, Turkey, Yemen, United Arab Emirates, Oman, Afghanistan, India, Pakistan, Sri Lanka, China, Mongolia, Vietnam, Korea, Australia, New Zealand, Antarctica, Kerguelen, Canary Islands, and Cape Verdes. For all other occurrences, literature research has been undertaken to sufficient depth to write the descriptions found in the accompanying database, and to allow for plotting on the world map. These new descriptions are based on the primary sources and not on the secondary sources referred to above.

OMITTED LOCALITIES

A few localities that have been described in the literature as carbonatite have been omitted. These fall into two groups, the first of which comprises two localities in India and one in Pakistan for which we have been unable to trace details. The Indian occurrences are Puga Valley and Mirzapur. Sukheswala and Viladkar (1978, p. 280) note that carbonatite has been reported from the Puga Valley, Ladakh, Kashmir, and it is quoted in Viladkar (2001, Table 1) but we have been unable to pinpoint this locality and S. Viladkar (pers. comm., 2003) tells us that he has not been able to find any further information. This locality, if it should prove to be real, would be of great interest as it lies in the northern Himalayan part of India, far from other Indian carbonatite occurrences but close to occurrences in adjacent Pakistan. The Mirzapur occurrence is given in Viladkar (2001, Table 1, no. 5) but the reference quoted is not in the reference list and Professor Viladkar has been unable to enlighten us further. It is reported as "carbonatite associated with kimberlite", but in the absence of a fuller reference and geographical coordinates this occurrence has also been omitted. Again it appears to lie in a part of India in which carbonatite is otherwise absent (Viladkar, 2001, Fig. 1) and so would be particularly interesting, if only spatially, if confirmed.

An occurrence in Pakistan called 'Jhambil' is referred to in Tilton et al. (1998) and, indeed, they give isotope data on specimens apparently derived from this locality. Professor Tilton was unable to furnish locality details and we have been unsuccessful in gleaning information from Pakistan. The location is apparently close to the border with Afghanistan but in the absence of coordinates we have omitted Jhambil from the database, although the evidence is that this locality does indeed exist.

The second group of omitted occurrences comprises those for which a carbonatitic origin is in doubt. The most abundant representatives of this group comprise metamorphosed and deformed limestone, which have often been mineralized. These have been omitted unless relatively unambiguous evidence has been cited for a carbonatitic origin. The occurrences at Mkwisi and Keshya in Zambia are assumed to be carbonatite, but the reader is referred to alternative points of view cited in Woolley (2001). Bedded limestone units associated with the Bishoftu craters in the Debre Zeyt District of Ethiopia are now considered to be hot spring deposits, but were thought at one time to be the products of carbonatite magma (Woolley, 2001). Perhaps the most interesting of the omitted occurrences is that of Jabal El Arab in Syria, which has been described as a carbonatite occurrence by Mahfoud and Beck (1995). However, in our opinion, this locality represents the interaction of basaltic magma with evaporite: a most fascinating occurrence but not carbonatitic. In this context we note that the database does contain approximately forty-seven localities where the information supporting the validity of the occurrence being a carbonatite is somewhat limited. Although the inclusion of these localities in the database is somewhat subjective, this is noted in the locality description, and we hope that this provides a stimulus for further research on these occurrences.

WORLD CARBONATITE DISTRIBUTION MAP AND DIGITAL DATABASES

The contents and arrangement of the databases and maps that comprise this Open File Report are as follows.

Databases

Word™ and PDF Files

a) A 'master carbonatite' file containing brief descriptions of all 527 carbonatite occurrences. This file is arranged alphabetically by continent and country [MasterCarbonatite.doc].
b) A file containing all references cited in the above description file, arranged alphabetically by continent and country [MasterCarbonatiteReferences.doc].
c) This introduction [Introduction.pdf], which contains links to the Word™ and Excel™ files, as well as the various maps and figures.
d) An index list of all localities, arranged in alphabetical order [Index.doc].
e) A file containing all references cited in the carbonatite economic deposit Excel™ file (c) (see next section) [EconomicCarbonatiteReferences.doc].

Excel™ Files (Tables)

a) A file containing, in tabular form, a list of all carbonatite occurrences with their I.D. number, locality name, continent, country, latitude, longitude, and age. [Carbonatite.xls].
b) A file containing, in tabular form, information on the nature of the silicate rocks associated with each carbonatite occurrence and also the Woolley and Kjarsgaard (2008) silicate rock association classification. [SilicateRocks.xls].

c) A file listing the carbonatite occurrences of economic interest with details of the economic minerals and commodities. [EconomicCarbonatite.xls].
d) A file listing all occurrences of extrusive carbonatite containing mantle materials, with some petrological and mineralogical details of the latter. [ExtrusiveCarbonatiteMantle.xls].
e) A file containing, in tabular form, an index list of all localities, arranged in alphabetical order [Localities.xls].

Maps

1. A world geological map, in hard copy as well as digital format [WorldCarbonatiteMap.pdf, WorldCarbonatiteMap.cdr], with all 527 carbonatite occurrences plotted and identified by name and number. The backdrop is the generalized bedrock geology of the world.
2. The maps included in the this file [Introduction.pdf] are available separately in .pdf and .cdr formats:
   a) World carbonatite distribution map (all carbonatite occurrences) and world map discri-minating magmatic and carbohydrothermal carbonatite occurrences (Figs. 1, 2) [Figure1.pdf, Figure2.pdf, worldcarbFig1-11_13_20-22.cdr].
   b) A suite of nine world maps showing magmatic carbonatite associated with specific silicate rock associations, i.e., melilitite (melilitolite), nephelinite (ijolite), basanite (alkali gabbro), phonolite (feldspathoidal syenite), trachyte (syenite), kimberlite, lamprophyre, carbonatite with no associated silicate rocks, and carbonatite with ultramafic cumulates (Figs. 3-11) [Figure3.pdf to Figure11.pdf, worldcarbFig1-11_13_20-22.cdr].
   c) A suite of seven maps showing ages of carbonatite occurrences for the world, including separate maps for North America (including Greenland), South America, Europe and Russia west of the Ural Mountains, Africa, Asia and Russia west of the Ural Mountains, and Australasia and Antarctica (Figs. 13-19) [Figure13.pdf to Figure19.pdf, worldcarbFig1-11_13_20-22.cdr, worldcarbFig14.cdr to worldcarb19.cdr].
   d) A suite of three world maps showing carbonatite occurrences that are, or have been, exploited economically, or are of economic interest (Figs. 20-22) [Figure20.pdf to Figure22pdf, worldcarbFig1-11_13_20-22.cdr].

RANGE OF DATA INCLUDED IN THE DATABASE

For reasons of space the amount of information that could be given on each occurrence had to be limited, particularly in view of the large number of localities described (527). It was necessary, therefore, to select what we consider the most useful attributes while, of necessity, excluding those, such as petrography and chemical analyses, which tend to be discursive and voluminous, and petrogenesis, which, although it may be interesting, is often contentious and, unfortunately, tends to date quickly. The headings under which the descriptions are organized are listed here, followed by a brief outline of what information is given and the main constraints.

I.D. number
Location name
Alternative name
Continent
Country
State/Province/Territory
Latitude
Longitude
Carbonatite type
Magmatic style
Associated silicate rocks
Age
Age reference
Mineralization
Woolley volume reference
Notes
General reference

Locality Numbers and Order of Continents, Countries, and Localities within Countries

Each locality has been given a unique number to facilitate linking the plotted points on the map with the descriptions. The order of continents is alphabetical, as is the order of countries within a continent. We have placed Russia under Asia because, although much of that country (west of the Urals) is within Europe, the greater area comprises part of Asia. Occurrences found in oceanic areas have been grouped under "Oceanic Islands". The full continent and country list is given in Table 1.The unique I.D. number for each locality (from 1 to 527) follows this arbitrary arrangement. Within an individual country the numbers of occurrences within that country generally run from north to south and west to east in a relatively smooth sequence so that location points can be found rapidly on the world map.

Occurrence Coordinates

Coordinates are given, to the nearest minute, for the approximate centre of the complex. For large, and particularly for oddly shaped complexes, there is some arbitrariness in choosing the centre, but the coordinates cited are certainly within a kilometre of the centre, however defined. It should be noted that in the Word™ master file [MasterCarbonatite.doc] descriptions of the coordinates are given in degrees and minutes, while in

Table 1. Continents and countries that are included in the database, in the order of the sequence adopted, and the number of occurrences per country.

Africa		**N America**		**Asia**		**Europe**	
Algeria	1	Canada	77	Afghanistan	4	Bulgaria	1
Angola	14	Greenland	12	China	27	Czech Republic	2
Burundi	1	United States	23	India	29	Finland	7
Congo (DR)	4			Iran	1	France	1
Egypt	6	**S America**		Kazakhstan	2	Germany	5
Gabon	2	Bolivia	3	Kirgystan	2	Italy	5
Kenya	9	Brazil	22	Korea	1	Norway	5
Libya	1	Guyana	1	Mongolia	5	Poland	1
Malawi	14	Paraguay	2	Oman	1	Spain	1
Mali	6	Venezuela	1	Pakistan	7	Sweden	3
Mauritania	4			Russia	71	Ukraine	3
Morocco	2	**Antarctica**		Sri Lanka	1	United Kingdom	1
Mozambique	9	Antarctica	1	Turkey	3		
Namibia	27			United Arab Emirates	3	**Oceanic Islands**	
Somalia	1			Uzbekistan	1	Canary Islands	2
South Africa	22			Vietnam	1	Cape Verdes	5
Sudan	1			Yemen	1	Kerguelen	1
Tanzania	21						
Uganda	12			**Australasia**			
Zambia	7			Australia	10		
Zimbabwe	7			New Zealand	1		

Excel™ file (a) [Carbonatite.xls] they are quoted in decimal degree form, as was used for the digital plotting of the maps.

States, Provinces, and Territories

For a number of the larger countries (e.g. Canada, United States, Russia, and China), the province, state, or territory in which the occurrence lies is given.

Occurrence Names and Alternative Names

The generally accepted name, as far as we were able to determine, is given for each occurrence. However, a remarkably large number of occurrences have been referred to in the literature under alternative names or spellings. All the variants that we have been able to trace are given in the descriptions in the Word™ master file.

Carbonatite Type

This section includes both the rock name, or names, and a list of the minerals of which it is comprised, when available. Although the carbonatite name is generally rendered as calcite, dolomite, ankerite carbonatite, etc., it is sometimes given as sövite, rauhaugite, alvikite, or beforsite if these are used predominantly in the cited publication. The mineral lists are not always comprehensive. If little information is available then in general all the minerals known to occur in the rock will be given. For some localities, however, the data are very numerous and then a proportion of them, usually the commoner ones, are culled. The more rare and unusual minerals are invariably quoted.

Magmatic Style

Here information on the form of the carbonatite intrusion, assuming it is an intrusive occurrence, are given and its general context, for example “within a complex of silicate rocks” or “as a dyke swarm”. For extrusive occurrences the appropriate forms, when known, such as lava flow or tuff sheet, are noted. Often some idea of the size of the occurrence is given.

Associated Silicate Rocks

The igneous silicate rocks that, with the carbonatite, comprise an occurrence are listed. These may be separate intrusions within a complex or petrologically distinctive dykes in a multiple swarm. The same applies to extrusive occurrences; any associated silicate extrusive rocks are cited. Fenite, if present, is usually also listed. Excel™ file (b) [SilicateRocks.xls] lists the silicate rock types associated with each carbonatite locality .

Ages of Carbonatite Occurrences

All age determinations that have been traced in the literature are given. Although preference is given to ages obtained from the carbonatite itself, very often it is the associated igneous silicate rocks that have been dated. Although such dates will give an overall age for the occurrence they do not necessarily indicate the relative age of the carbonatite and silicate rocks. However, in very few complexes and multiple occurrences has dating been extensive and accurate enough to provide a comprehensive suite of ages, although the field relationships in many complexes indicate the relative ages of the constituent parts. If more than one age has been published, the single ages quoted in the tables on the world distribution map and in the Excel file (a) [Carbonatite.xls] listing all carbonatite occurrences have been 'selected' by the authors. Often there is a range of ages determined by different dating techniques. We generally prefer U-Pb ages, followed by Rb-Sr, Ar-Ar, and then to K-Ar ages, if ages from multiple techniques are available, but other considerations sometimes apply.

Dating Method and Age References

The dating methods used for all the ages cited, together with the references, are given.

Mineralization

There is a wide variety of different minerals that are currently (or have historically been) beneficiated from carbonatite, including bastnäsite, monazite, apatite, pyrochlore, magnetite, fluorite, vermiculite, calcite, chalcopyrite, baddeleyite, thorite, and uraninite. The commodities extracted from these minerals include the rare earth elements (REE), phosphate, niobium, iron ore, lime, Cu, Zr, Th, U, fluorine and fluorite, and vermiculite. A variety of byproducts or coproducts are also beneficiated, including Ta, Au, Ag, and PGE. In parts of the world, carbonatitic limestone is utilized in the cement industry or for agricultural purposes (e.g. van Straaten, 2002). In this section it is noted if the carbonatite hosts an active mine, is a past-producer, or is considered a "deposit" (i.e. there is a known mineral resource) along with the specific type of mineralization, e.g., niobium hosted by pyrochlore. Excel™ file (c) [EconomicCarbonatite.xls] lists the most important carbonatite-hosted mineral deposits. Cited references to published reserve or resource data and mineralization style for the deposits of economic interest in Excel™ file (c) are in tabulated Word™ file (e) [EconomicCarbonatiteReferences.doc].

Woolley Volume Reference

The majority of carbonatite occurrences in the Americas, the former USSR, and Africa are described in Woolley (1987, 2001) and Kogarko et al. (1995), and to facilitate the easy finding of these descriptions, the numbers used in those volumes are cited.

General References Cited

With each carbonatite description a single 'general reference' is cited for reasons of economy, rather than a fuller list of references. This reference is often the fullest available account of the occurrence, but in many instances a later reference will be given because this affords access to the more recent literature and will invariably cite the earlier work. For the age data, reference(s) are given for the quoted age determination(s).

A BRIEF DISCUSSION OF THE DATA

Number of Carbonatite Occurrences

As discussed earlier, there has been a steady increase in the known number of carbonatite occurrences over the last 100 years. This database has now reached a total of 527 (Table 2) and will certainly continue to increase. Although some degree of geological exploration has been undertaken over the whole of the Earth's surface above sea level, there are still vast areas that have only been explored cursorily, while the relatively small size of many carbonatite occurrences means they may be easily missed. Further, particularly in older, deformed terranes, it may be very difficult to distinguish carbonatite from metamorphosed sedimentary limestone and, indeed, even detailed sophisticated work may not afford an unambiguous confirmation. In many areas of high latitude, the bedrock is obscured by moraine or surficial deposits, while the deep lateritic weathering of many tropical areas similarly cloaks the underlying geology. In such areas, geophysical and sometimes geochemical techniques will reveal the presence of potential occurrences. In Canada, for instance, many complexes have been discovered in this way.

Although it might not be expected that new carbonatite occurrences would be forthcoming from the highly populated areas of, for instance, Europe, which has long been geologically mapped at high scales, in fact the first carbonatite discoveries in France, Spain, and the United Kingdom have only been made in

Table 2. The number of carbonatite occurrences by continent.

	Number of Known Occurrences	Percentage of Total Known Occurrences
Africa	171	35%
America North	112	22%
America South	29	5%
Antarctica	1	
Asia	160	30%
Australasia	11	2%
Europe	35	6%
Oceanic Islands	8	1%
Total	**527**	

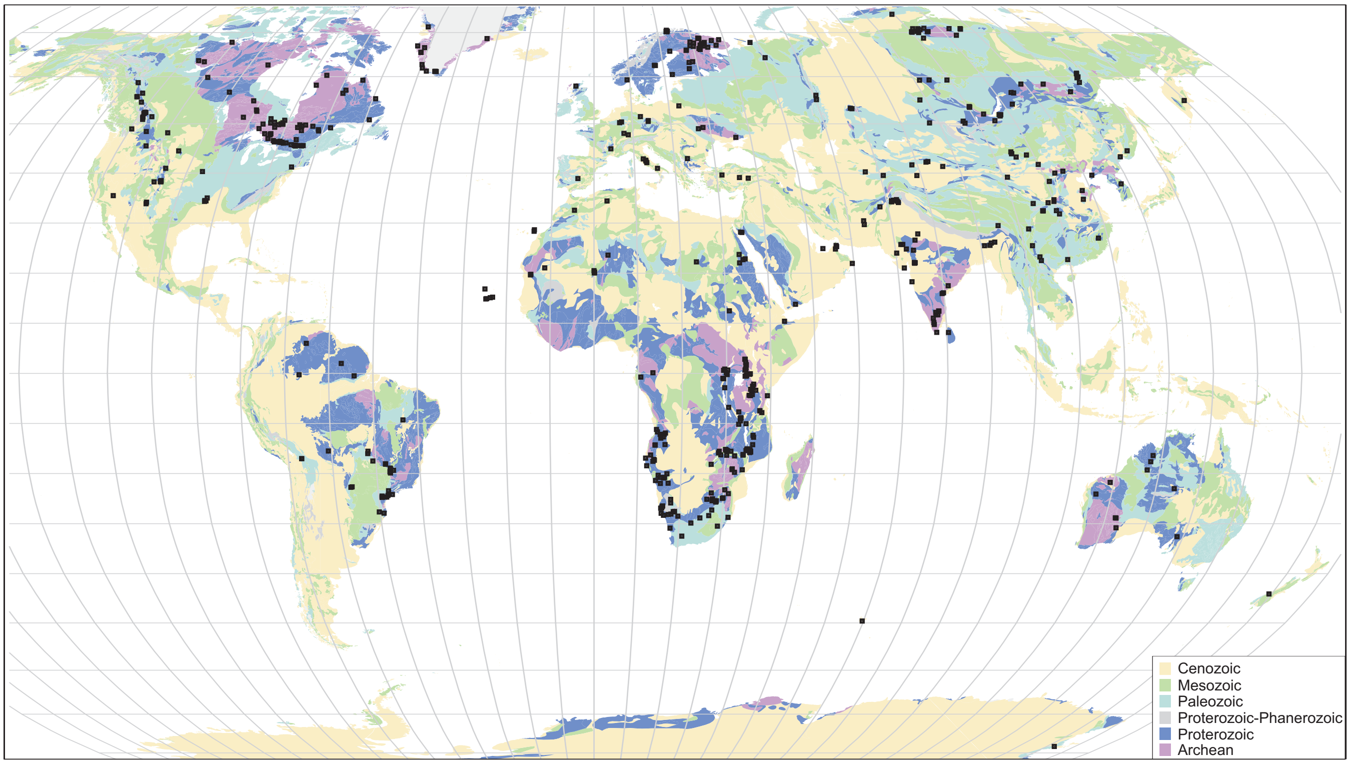

Figure 1. World map showing all known carbonatite localities.

recent years and the five examples known in Italy have all been discovered in the last 15 years. Thus, we suggest that there may be several hundred more carbonatite occurrences to be discovered.

World Distribution of Carbonatite

The maps of the world carbonatite distribution, which are an integral part of this report, are, we believe, the most comprehensive available. The spatial distribution of carbonatite was discussed in an earlier paper (Woolley, 1989), which was based on the 330 occurrences then compiled. The only region significantly underrepresented in that compilation was China, which has since been the subject of a brief review by Yang and Woolley (2006).

Although the earlier discussion of the spatial distribution of carbonatite appears still to be valid, there is one striking feature that was not appreciated in 1989 but clearly stands out on the present hard-copy, coloured map (Fig. 1). This is the concentration of occurrences in areas of exposed Precambrian rocks. Whether considering Africa, the Americas, Australia, or Russia, the location of carbonatite occurrences in Precambrian cratonic areas is manifest. There are, of course, numerous exceptions but it should be noted that more than half of the dated carbonatite occurrences (164 of 274 occurrences) are younger than Precambrian in age (<545 Ma), indicating a 'preference' for emplacement in Precambrian cratonic areas. It is the opinion of the authors that this correlation is determined by such petrogenetic factors as metasomatism of the base of the lithosphere and the necessity of the long-term presence of a relatively impermeable 'lid' over areas of focussed metasomatism, and also ties in with the fact that there are many areas where there have been repetition of carbonatitic activity over extensive periods of geological time. However, such apparent features are more appropriately discussed elsewhere.

Associated Silicate Rocks

It has been known for a long time that carbonatite tends to be associated with certain types of igneous rocks, notably alkaline rocks. An attempt to quantify this relationship, using a database of approximately 450 occurrences, was made by Woolley (2003) who concluded that six series of associated silicate rocks could be identified. This exercise has been repeated utilizing the updated database of this study and is described in more detail elsewhere (Woolley and Kjarsgaard, 2008). A difference from the conclusions of the earlier paper of Woolley (2003) is that magmatic and carbohydrothermal carbonatite occurrencess can be distinguished (Fig. 2), while a seventh silicate rock association, 'lamprophyre', has been now identified. The associated silicate rock data are utilized to form eight groupings (seven distinct silicate rock associations, plus a carbonatite-only grouping) that are tabulated as a column in the Excel™ file (b) [SilicateRocks.xls] and these groupings are listed below.

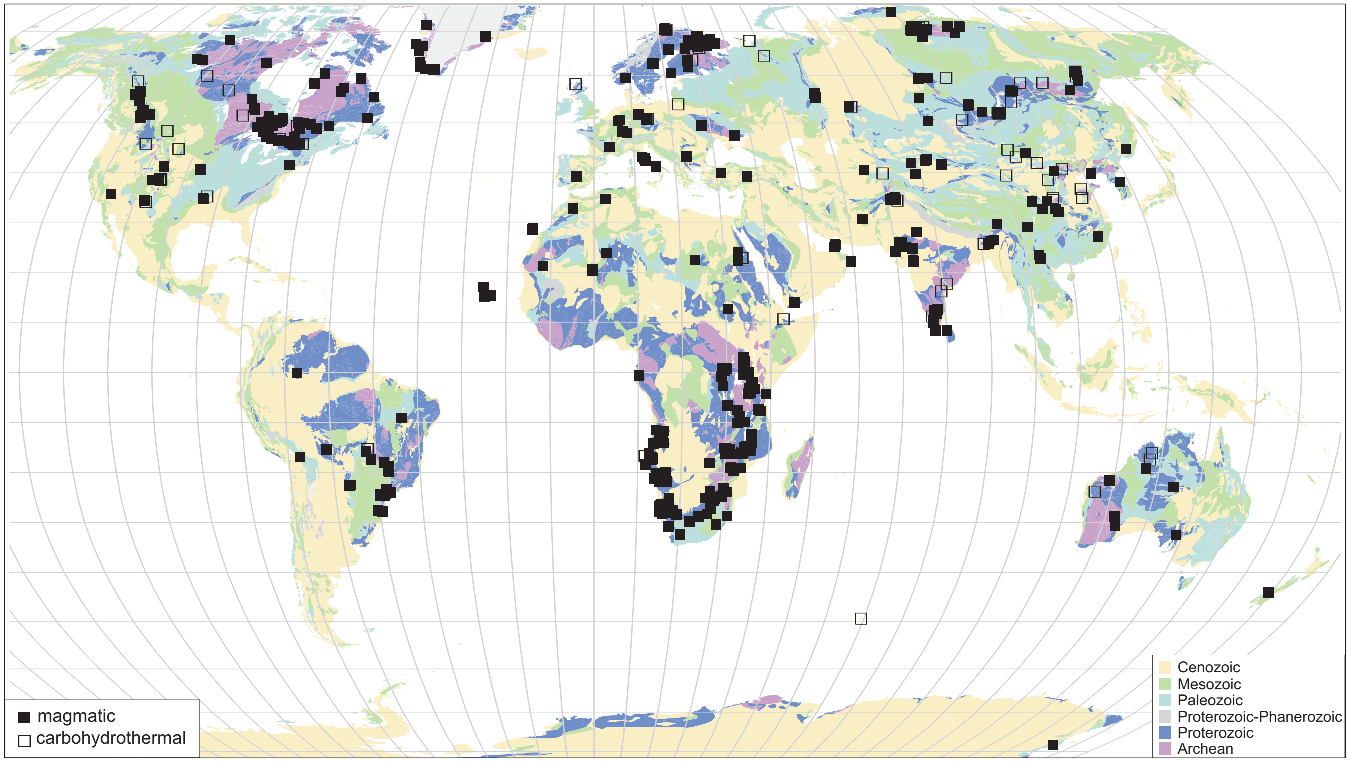

Figure 2. World map of magmatic versus carbohydrothermal carbonatite occurrences.

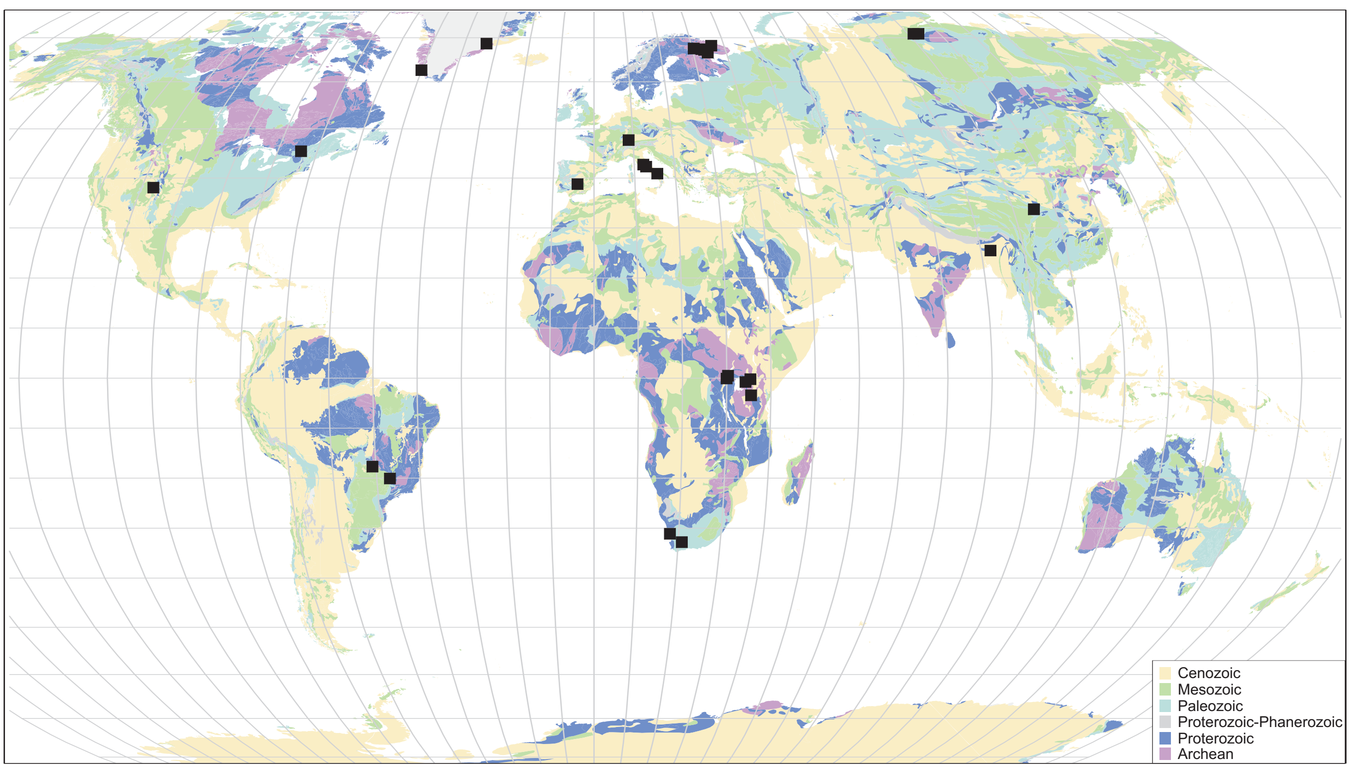

Figure 3. Localities of occurrences with melilitite (melilitolite) - carbonatite association.

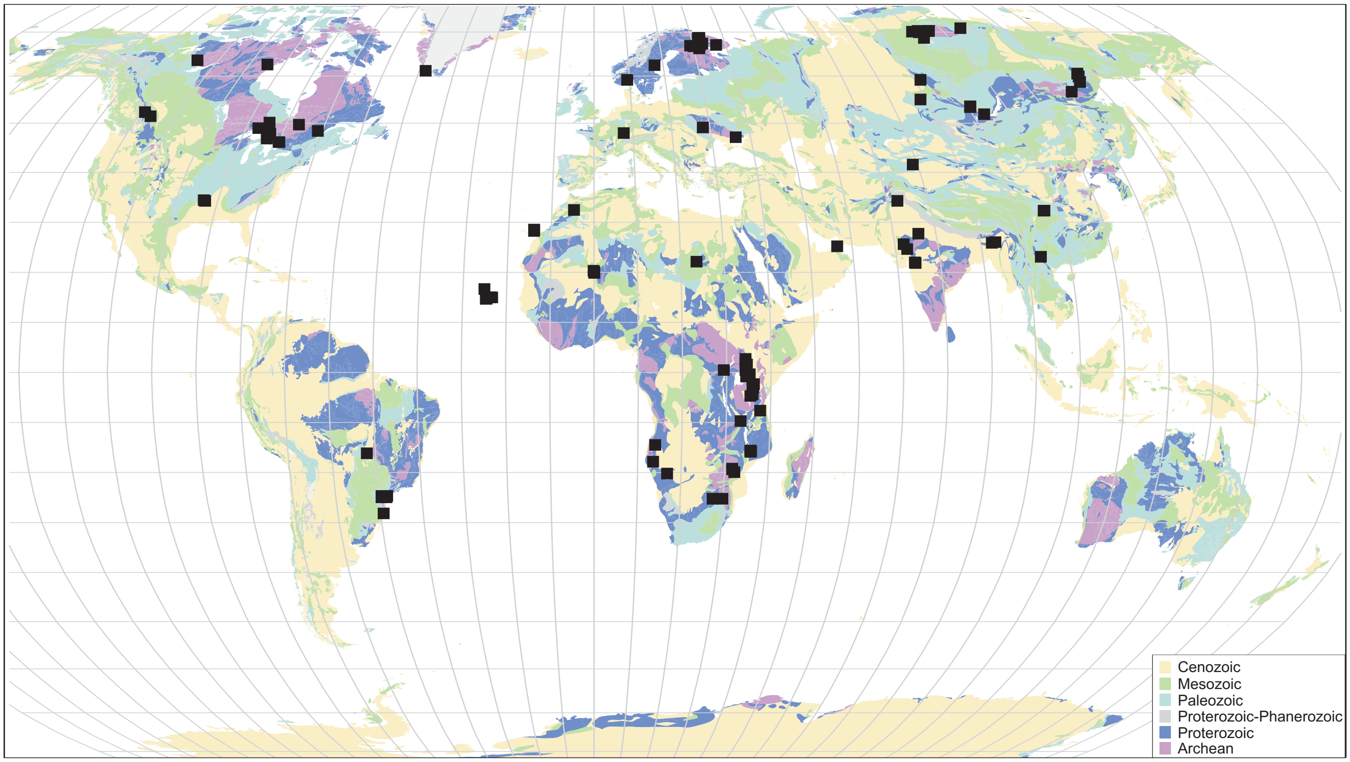

Figure 4. Localities of occurrences with nephelinite (ijolite) - carbonatite association.

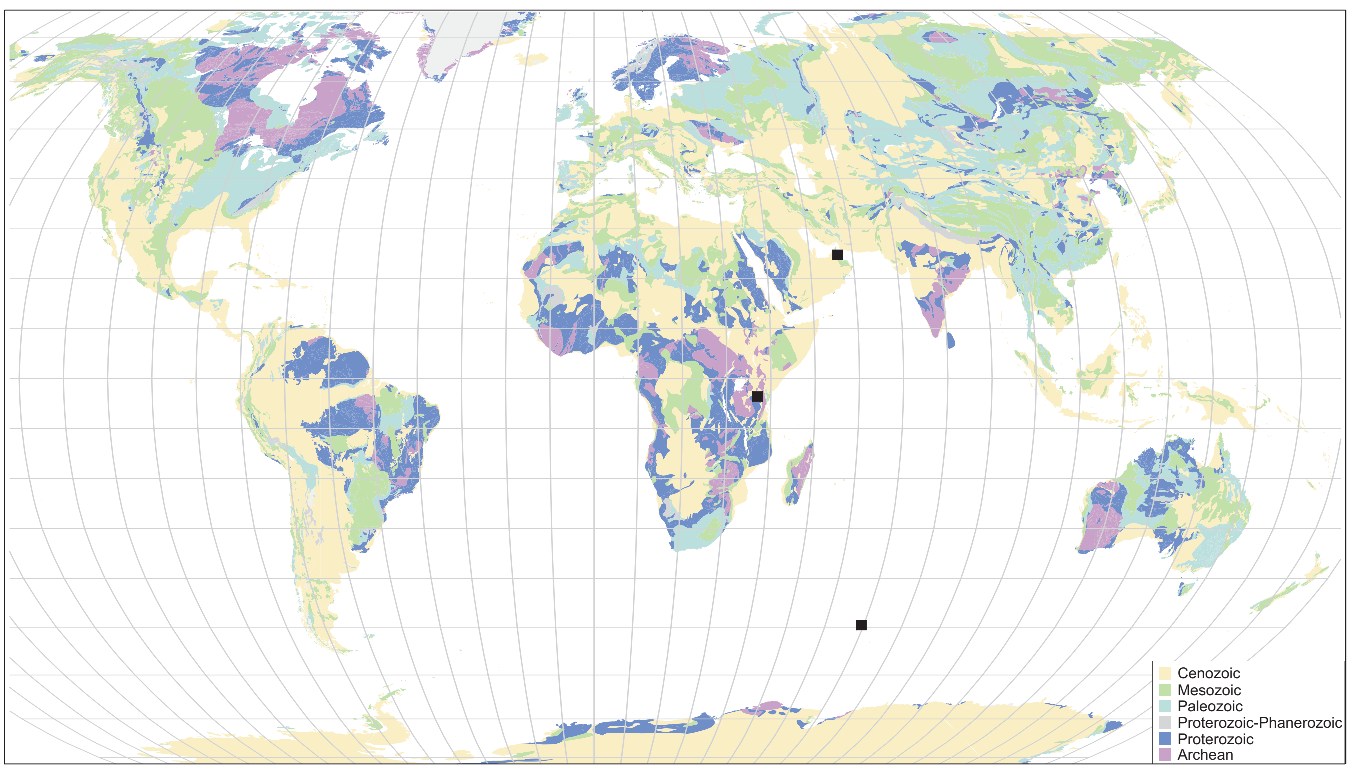

Figure 5. Localities of occurrences with basanite (alkali gabbro) - carbonatite association.

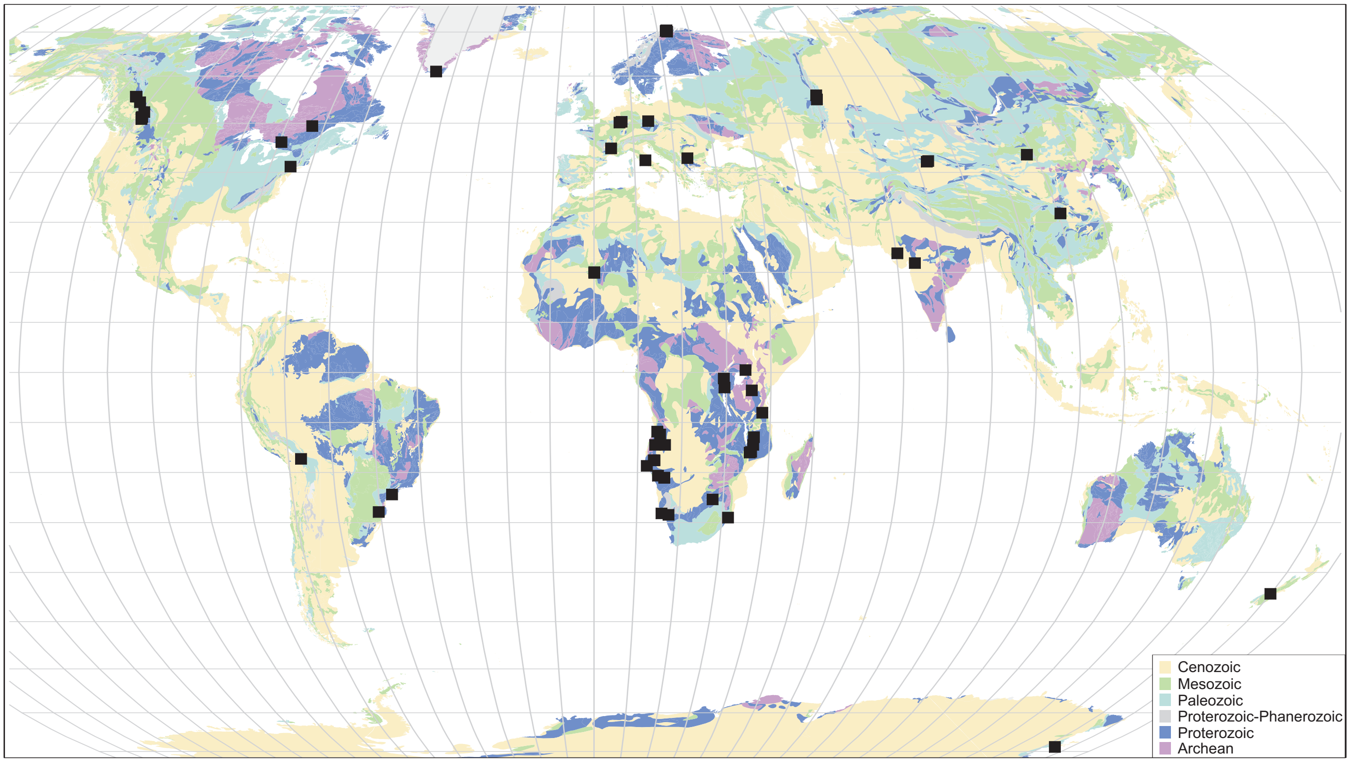

Figure 6. Localities of occurrences with phonolite (feldspathoidal syenite) - carbonatite association.

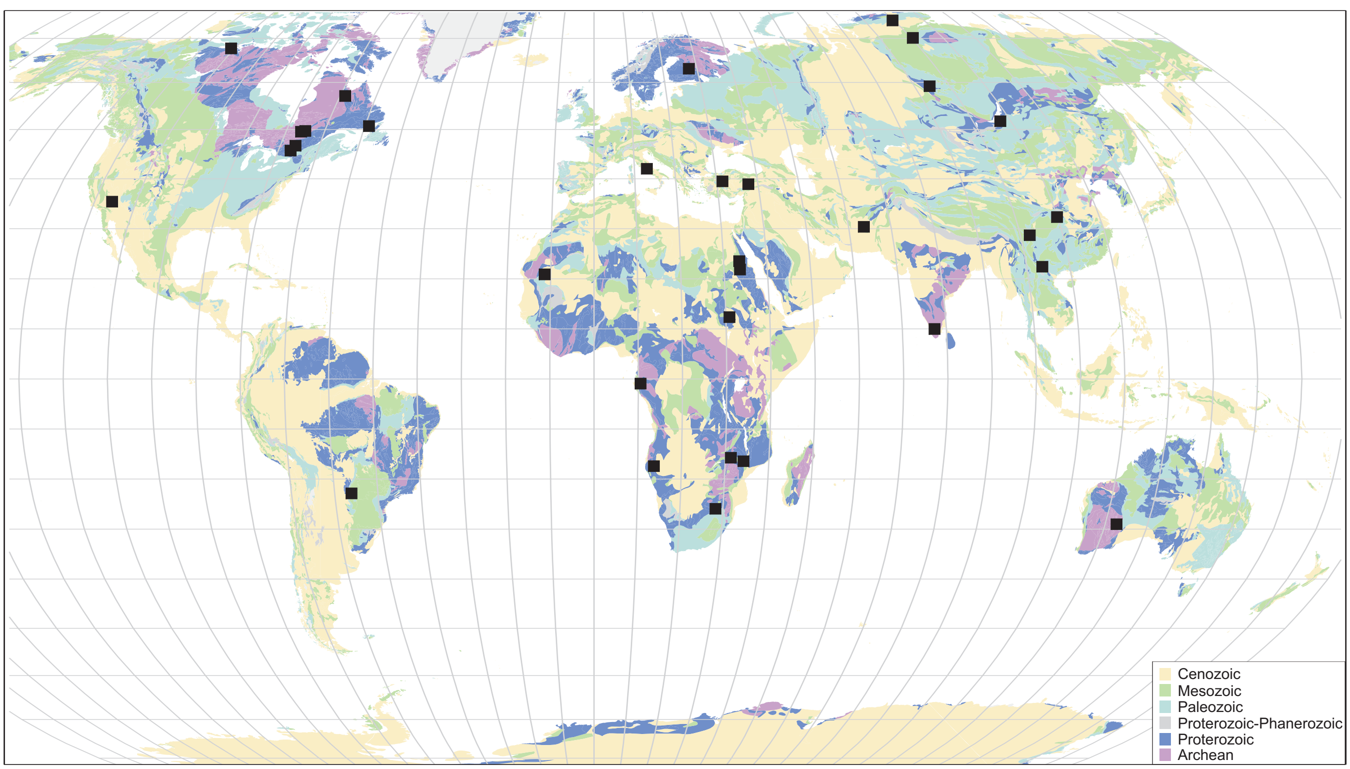

Figure 7. Localities of occurrences with trachyte (syenite) - carbonatite association.

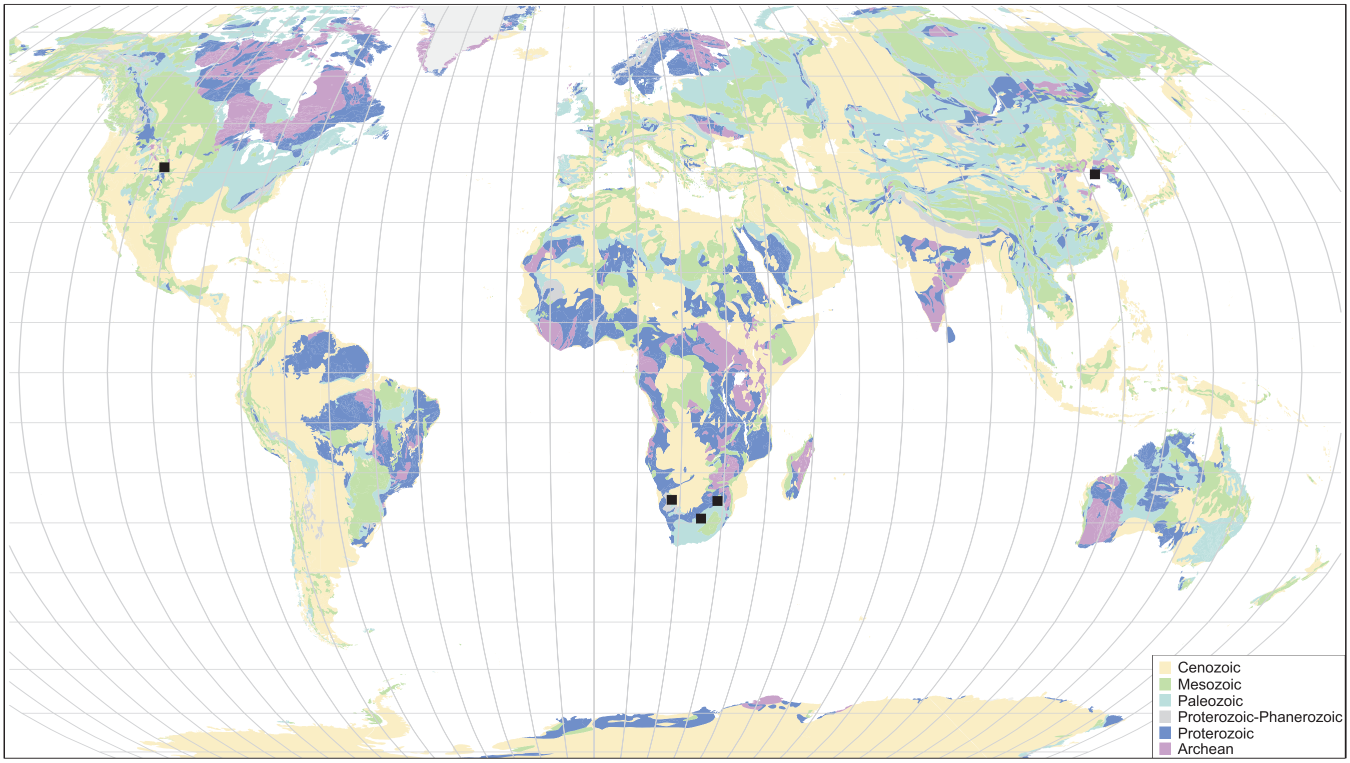

Figure 8. Localities of occurrences with kimberlite - carbonatite association.

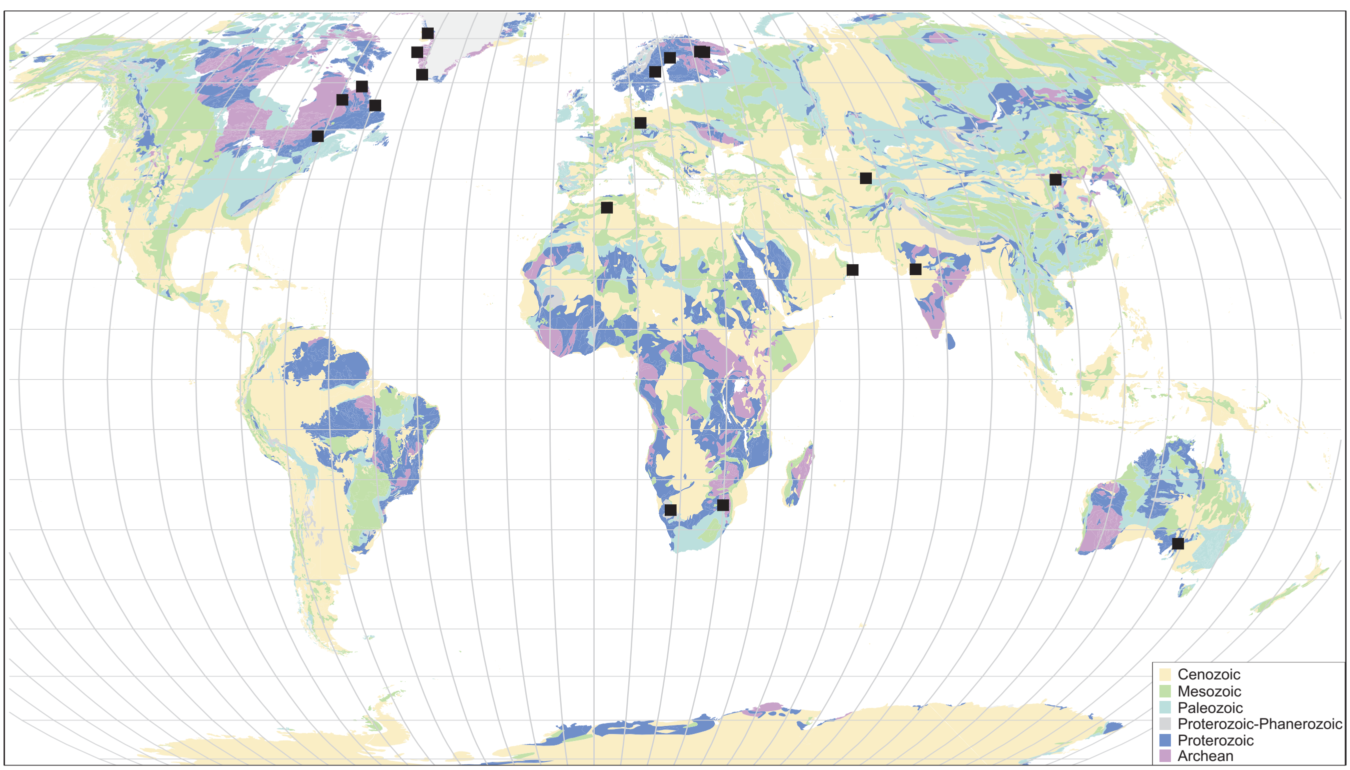

Figure 9. Localities of occurrences with lamprophyre - carbonatite association.

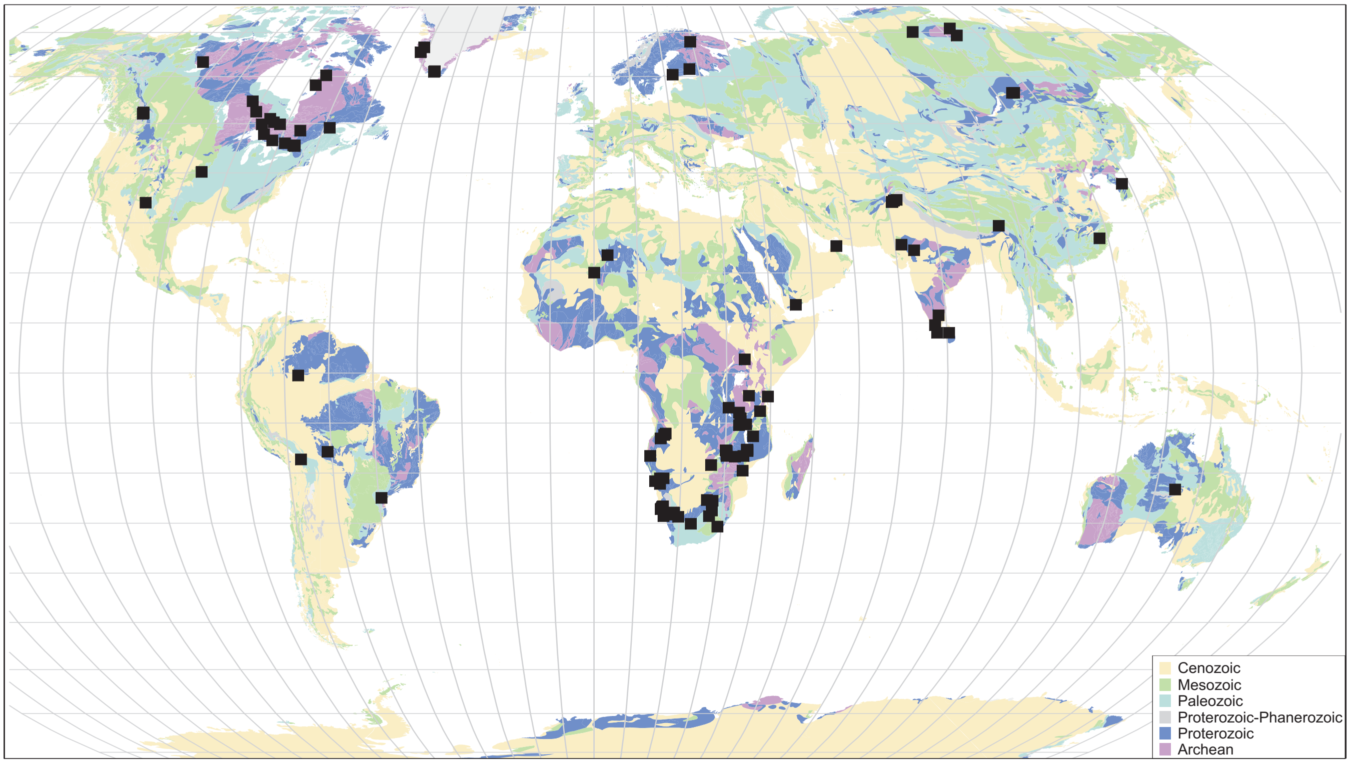

Figure 10. Carbonatite only localities.

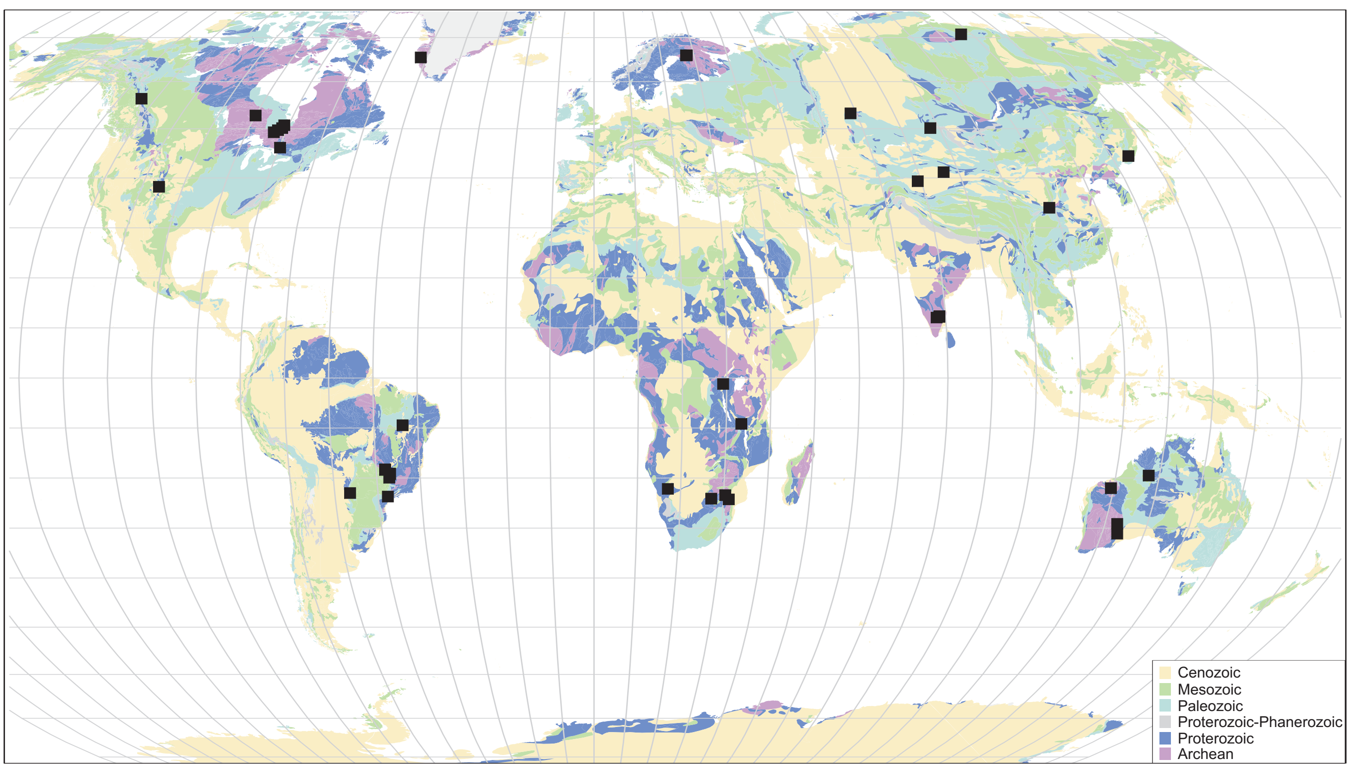

Figure 11. Localities of occurrences with carbonatite plus ultramafic cumulates.

1) Melilitite (melilitolite), Figure 3.
2) Nephelinite (ijolite), Figure 4.
3) Basanite (alkali gabbro), Figure 5.
4) Phonolite (feldspathoidal syenite), Figure 6.
5) Trachyte (syenite), Figure 7.
6) Kimberlite, Figure 8.
7) Lamprophyre (typically aillikite, alnöite), Figure 9.
8) Carbonatite only, Figure 10.

A suite of digital world maps showing the distribution of the localities for each of the eight groupings noted above is included with this package (see links, above). Peridotites and pyroxenites, commonly found associated with the nephelinite (ijolite) and melilitite (melilitolite) series, are considered most likely to be cumulates. Sometimes these ultramafic rock types occur as the only silicate rock associated with a carbonatite body (Fig. 11), but because they are not representative of a melt composition, this is not considered a distinct silicate rock association (Woolley and Kjarsgaard, 2008). It should be pointed out that Woolley (2003) and Woolley and Kjarsgaard (2008) believe that many (but not all) of the silicate rocks associated with the carbonatite are directly consanguineous. The reader should be aware that an alternative view point, entitled "Myth and reality in the carbonatite-silicate rock association", has been expressed by Gittins and Harmer (2003).

Carbonatite Ages

Woolley (1989, Fig. 2.9) utilized the 148 known age determinations available from the 330 carbonatite occurrences compiled at that time and generated a plot of carbonatite ages as a frequency histogram. The present database includes 264 age determinations from 527 occurrences listed in Excel™ file (a) [Carbonatite.xls] and these are plotted in an updated age-frequency histogram (Fig. 12). As might be expected, the graph takes exactly the same form as the earlier one (Woolley, 1989), with a temporal pattern, in general, indicating an exponential increase in abundance with decreasing age and subsidiary peaks reflecting concentrations in certain geographic areas and/or generally corresponding to tectonic or magmatic events, as discussed briefly in the earlier paper. The ages of carbonatite occurrences are plotted on the world map in Figure 13. The carbonatite occurrences are subdivided into eleven distinct age groups following natural breaks on a cumulative frequency plot (not shown), which correspond to global eon, era, period, or epoch time-scale breaks. Individual maps for ages of carbonatite in specific continents or regions clearly illustrate the notion of carbonatite 'events' in specific geographic regions (Figs. 14-19).

In the earlier paper (Woolley, 1989), it was simply concluded that (i) the conditions necessary for the production of carbonatite were established by the Neoarchean and (ii) that these conditions became more widespread with time, as reflected by their increasing abundance. However, this interpretation has been challenged by Veizer et al. (1992) who suggest "the observed trend may be viewed as an artifact of preservation, because the probability of preservation decreases exponentially with increasing age of the crustal segments". The present authors adhere to the earlier view, however, believing that the graph reflects continuing metasomatism of the lithosphere since the Archean and hence its increasing suitability for the generation of carbonatite under appropriate thermal and tectonic conditions. We also suggest that the concentration of carbonatite in Precambrian areas, as referred to earlier, supports this interpretation.

Economic Mineralization

There are a number of papers summarizing economic mineralization in carbonatite. These are the classic papers of Deans (1966, 1976), with more recent overviews written by Mariano (1989), Notholt et al. (1990), Pell (1996), and Richardson and Birkett (1996a,b). Since the studies of Deans (1966, 1976), papers have also been written on mineralization in carbonatite in specific regions, e.g., Brazil (Rodriques and Lima, 1984; Biondi, 2005), southern Africa (Verwoerd, 1986; van Straaten, 2002), and the Kola Peninsula area of Russia (Petrov, 2004). The worldwide distribution of carbonatite occurrences of economic interest, including active mines, past producers, and deposits (i.e. those with

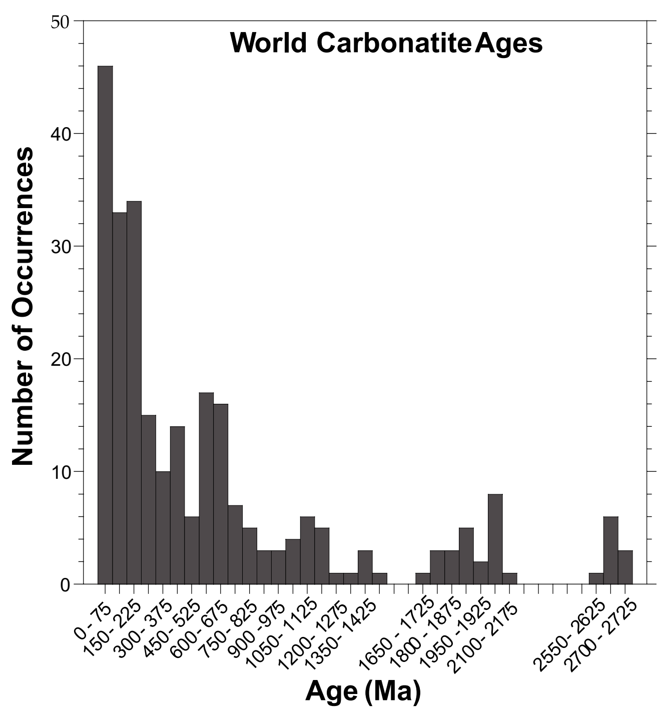

Figure 12. Carbonatite age histogram (using 75 million year bins).

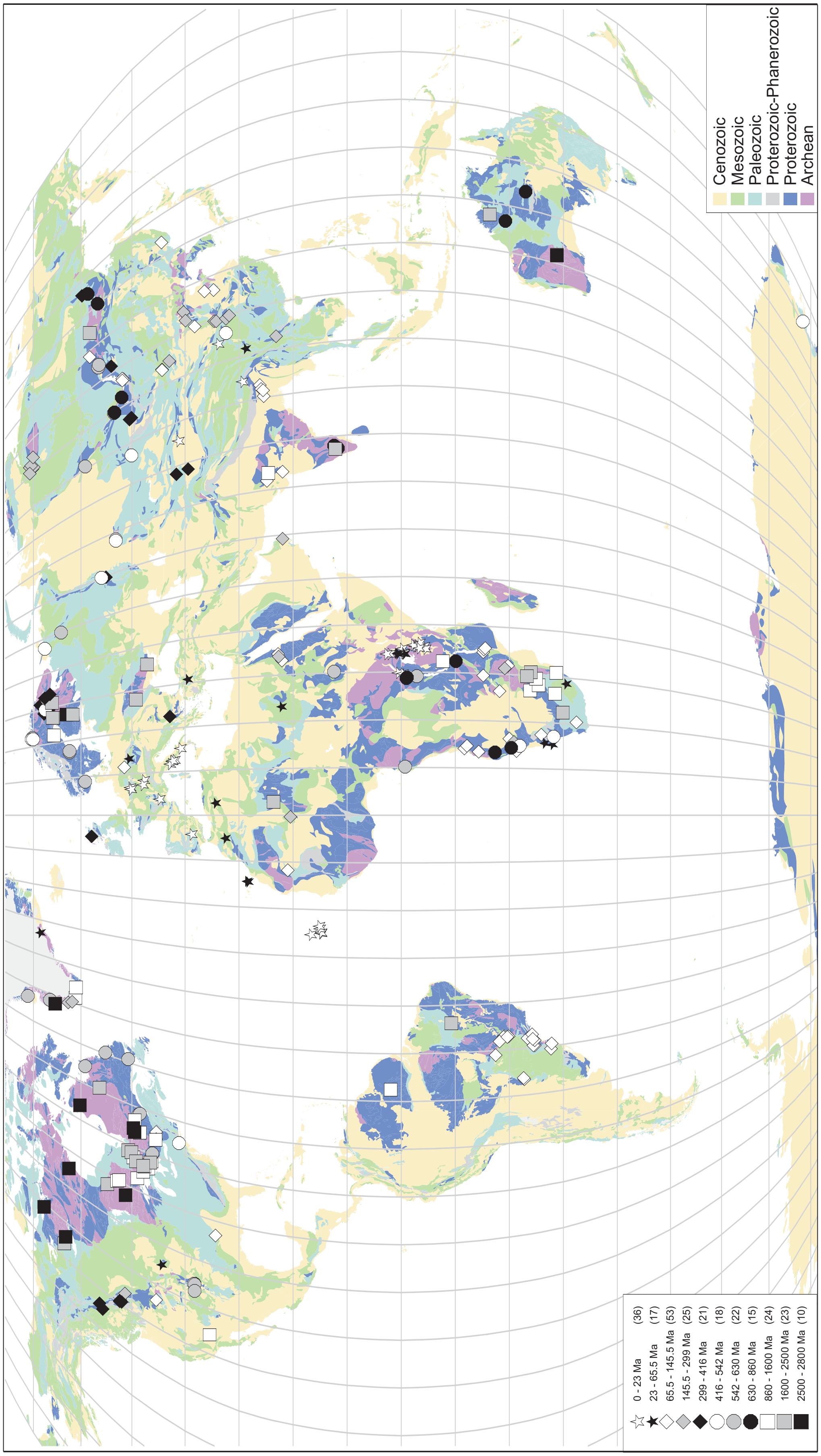

Figure 13. Carbonatite ages plotted on the world map and subdivided into eleven age groupings.

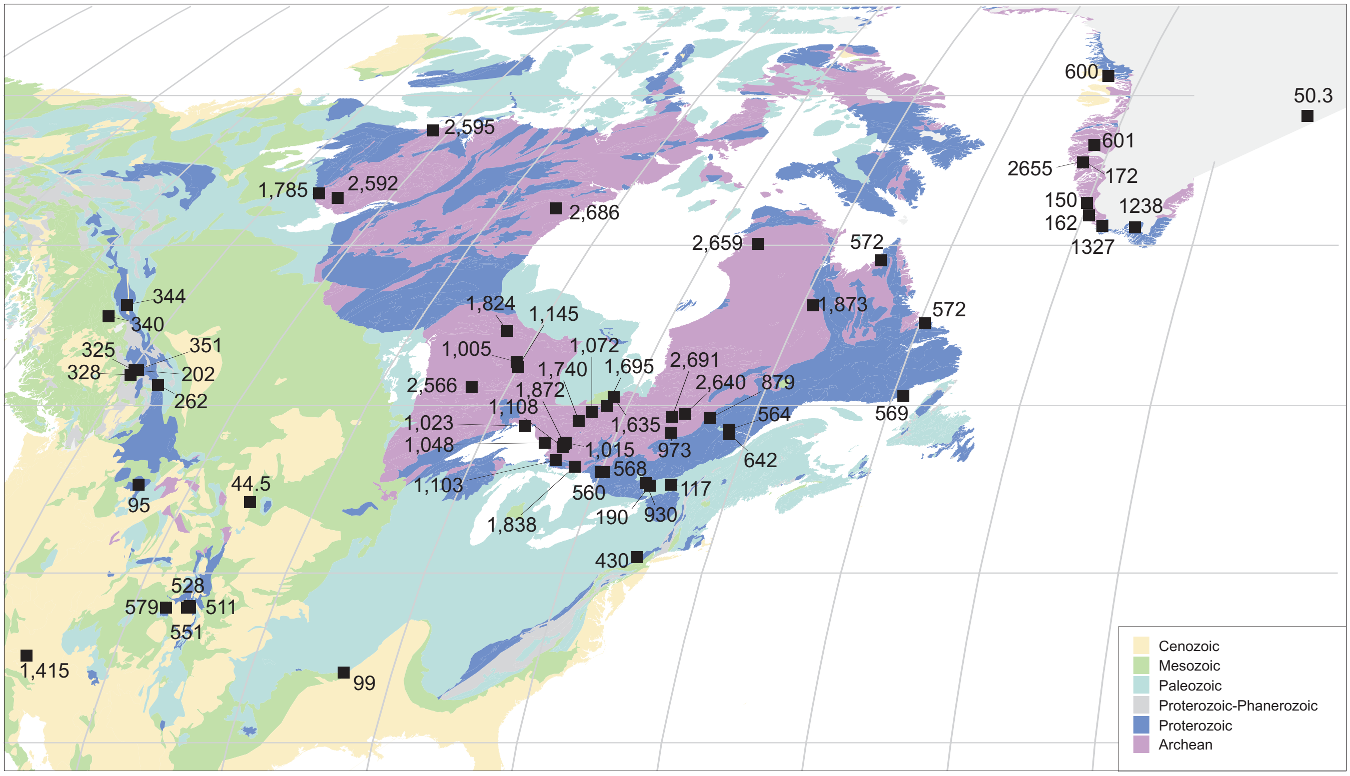

Figure 14. Ages of carbonatite occurrences for North America and Greenland.

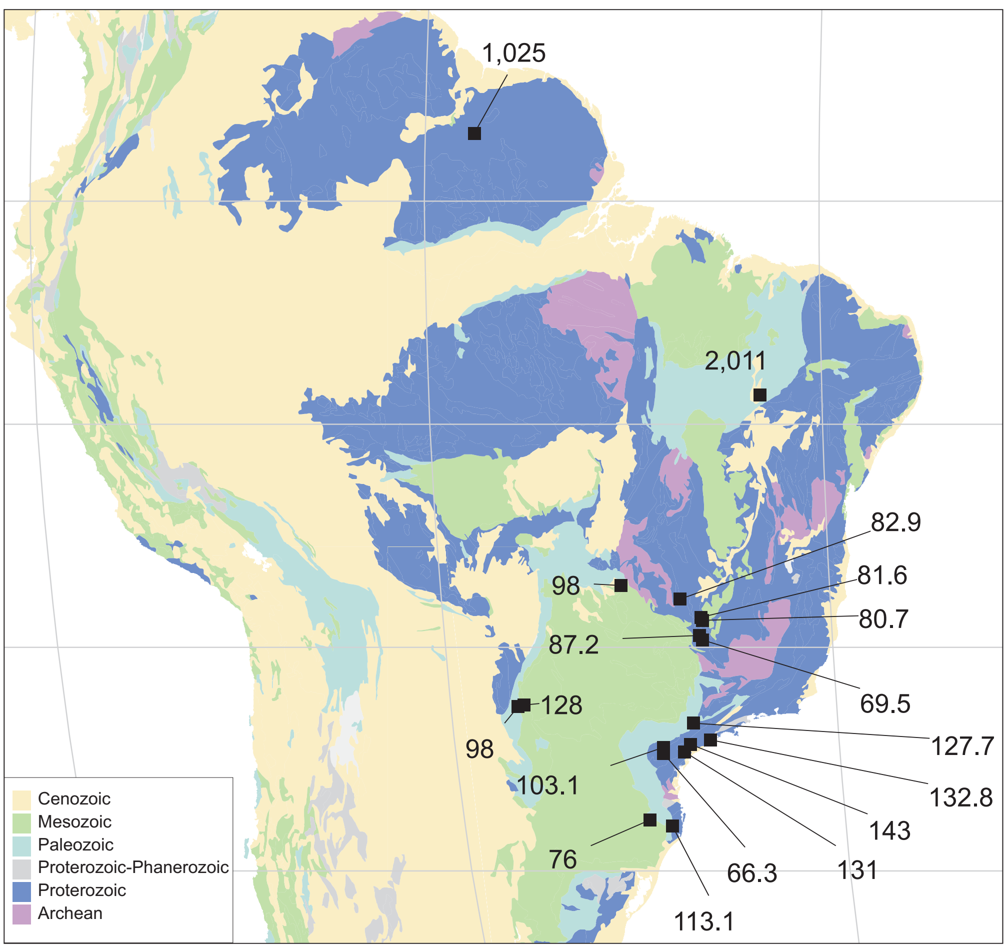

Figure 15. Ages of carbonatite occurrences in South America.

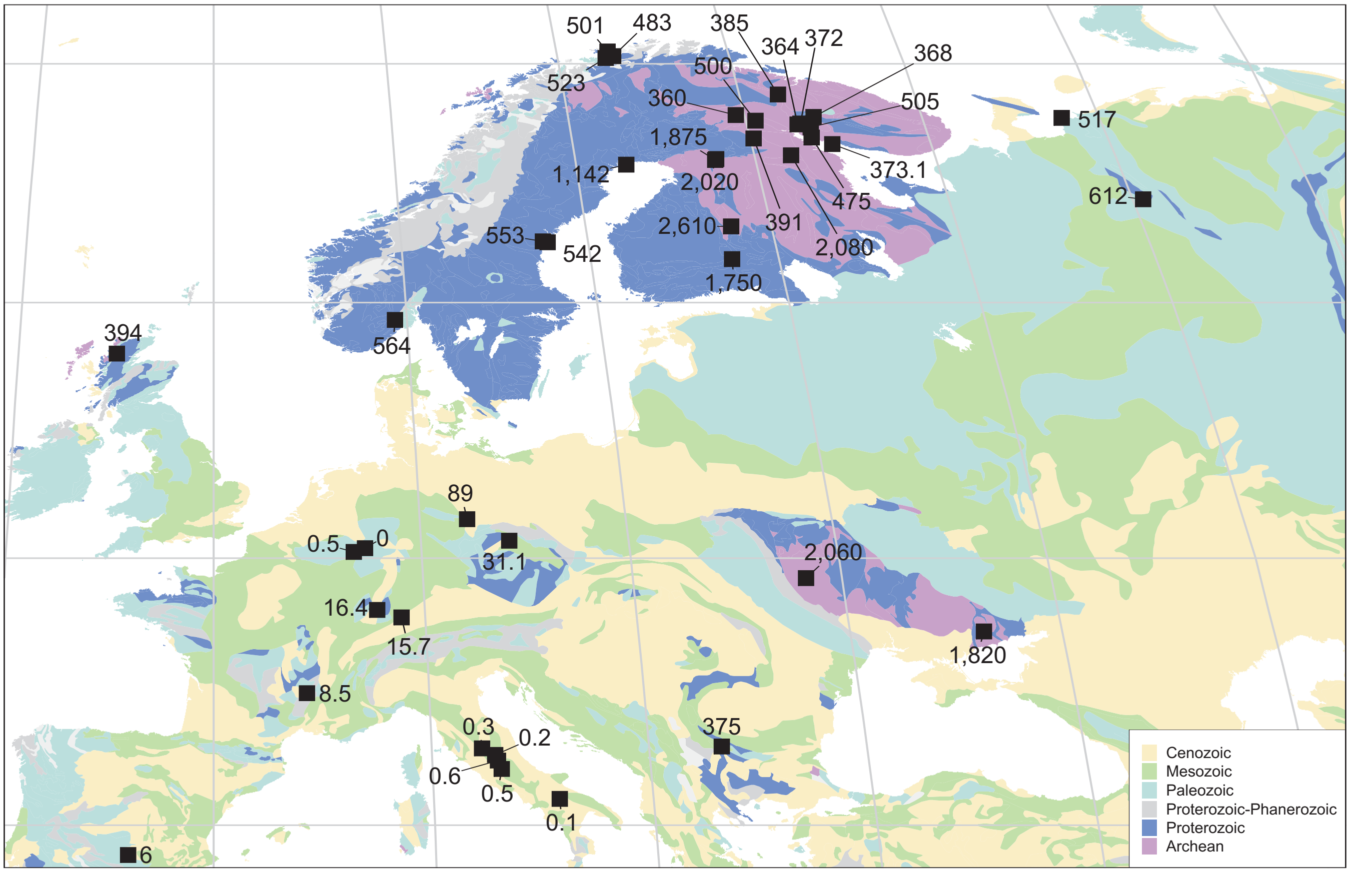

Figure 16. Ages of carbonatite occurrences in Europe and Russia west of Ural Mountains.

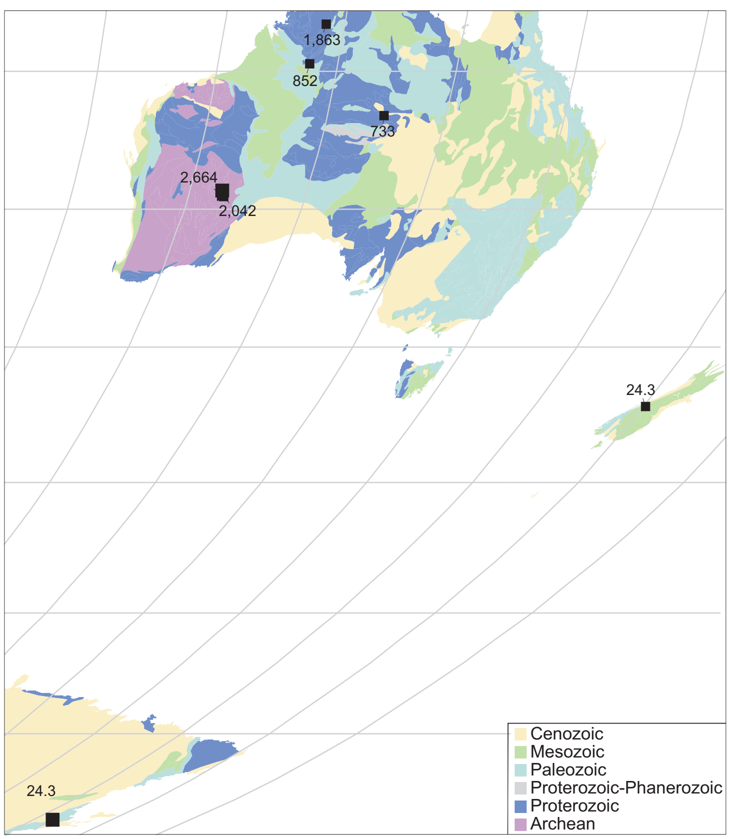

Figure 17. Ages of carbonatite occurrences in Australasia and Antarctica.

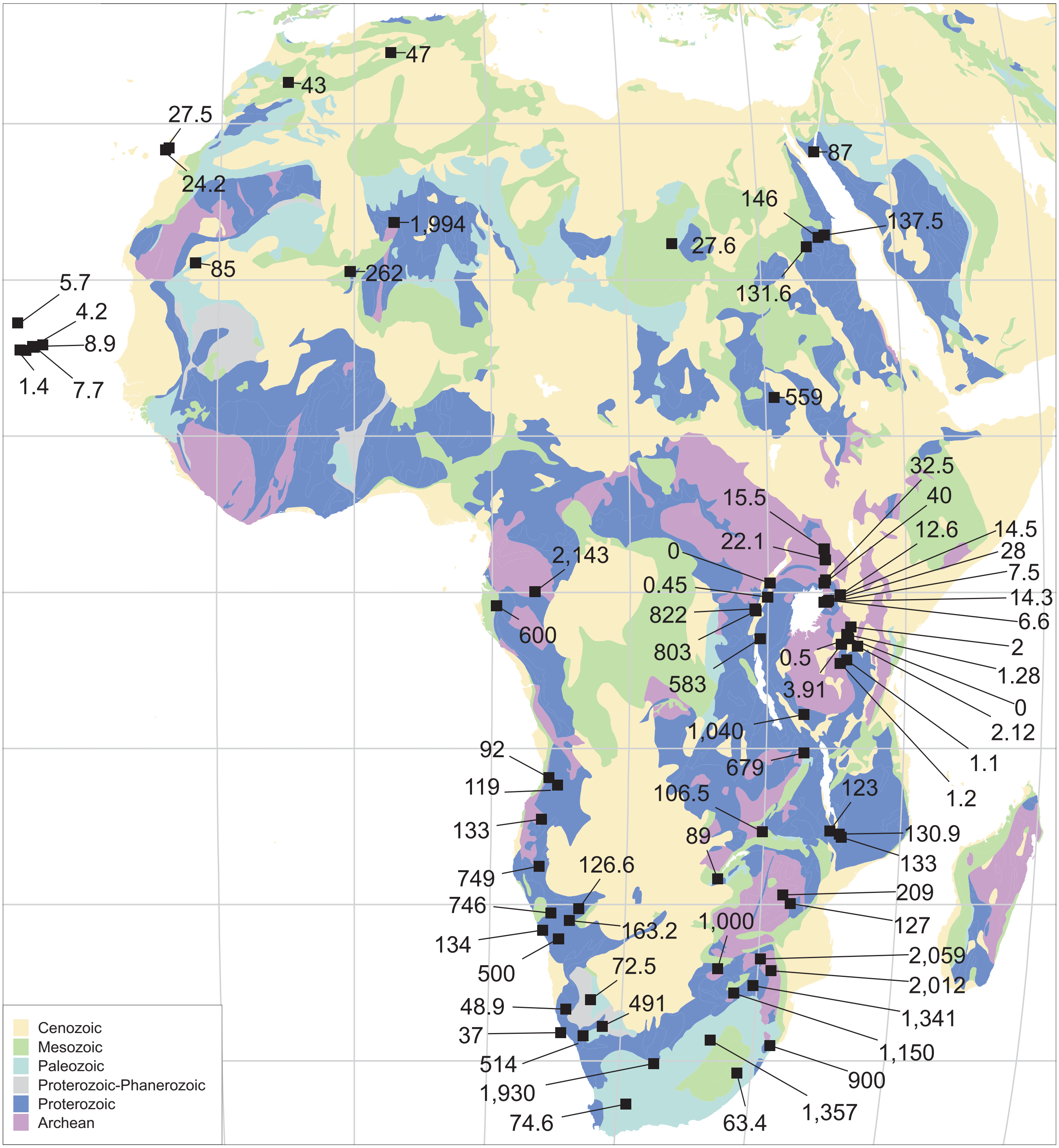

Figure 18. Ages of carbonatite occurrences in Africa.

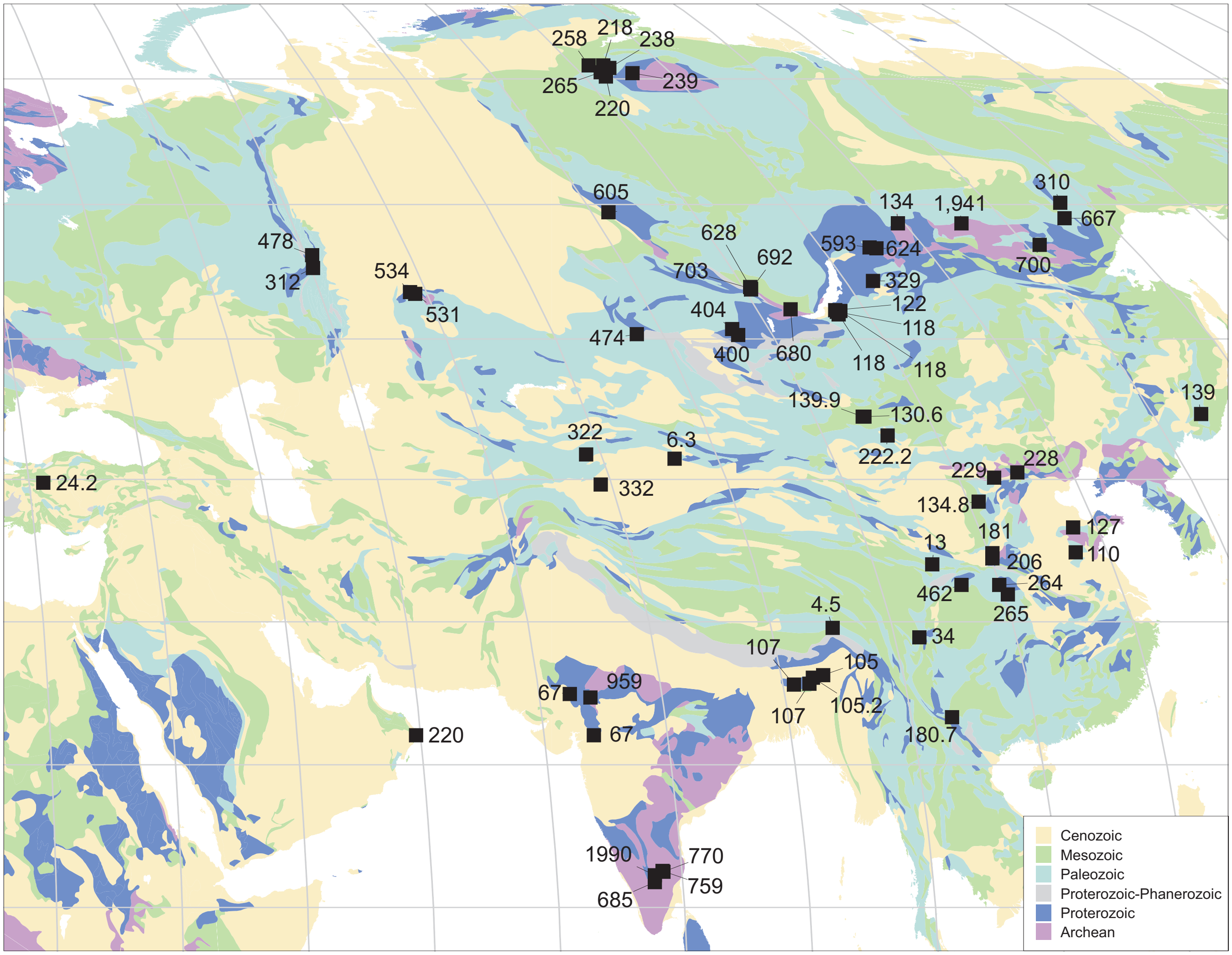

Figure 19. Ages of carbonatite occurrences in Asia and Russia, east of the Ural Mountains.

a mineral resource), is shown on the world map in Figure 20. For carbonatite occurrences that host active mines or hosted past producing mines, these localities are plotted on the world map by commodity type in Figure 21. Similarly, for carbonatite occurrences of economic interest, i.e., termed deposits (deposits are defined here as having grade and tonnage data), these localities are plotted on the world map by commodity type in Figure 22. The subdivision by commodity type, e.g., copper, iron, phosphate, lime, niobium, niobium-tantalum, fluorite, vermiculite, rare earth elements, titanium, zirconia, noble metals, and uranium-thorium, is further documented in Excel™ file (c) [EconomicCarbonatite.xls], with the economic minerals associated with the each specific commodity type being listed. Although it is not the purpose of this report to describe the different styles of mineralization (magmatic, carbohydrothermal, residual weathering/lateritic) or the link between mineralization and carbonatite-silicate rock associations, there are certainly what appear to be key relationships. For example, the vast majority of the active mines for phosphate, niobium, lime, and iron, as well as past producers and deposits for these commodities, are dominantly hosted in carbonatite associated with nephelinite-ijolite and/or ultrabasic cumulate rock types.

Mantle Materials Occurring in Carbonatite

Material of mantle derivation, both xenoliths and xenocrysts, has been identified in 20 carbonatite occurrences, 17 of which are dominated by extrusive carbonatite, with three (the last three localities) comprising carbonatite diatremes (consisting of fragmental carbonatite), at which there is now no extrusive rocks, although there may have been formerly. These occurrences are listed in Excel™ file (d) [ExtrusiveCarbonatiteMantle.xls]; this table includes brief details of mantle xenolith and xenocryst types, and mineralogy. Woolley and Church (2005) noted that since mantle material is only found in extrusive carbonatite and diatremes, and that none has been recognized so far in large carbonatite intrusions, this must reflect a more energetic environment of emplacement

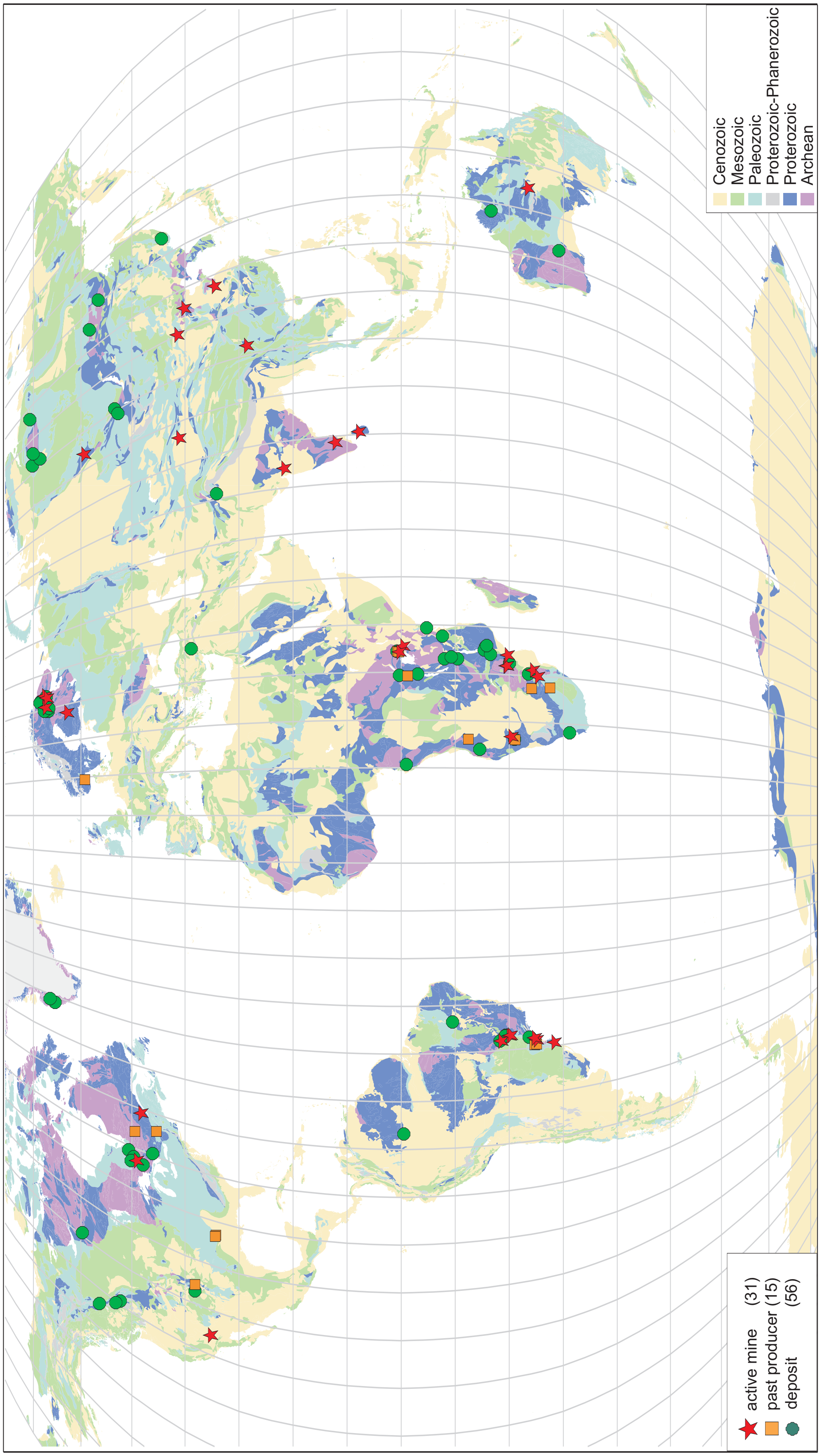

Figure 20. Carbonatite localities of economic interest, subdivided by active mine, past producer, and deposit.

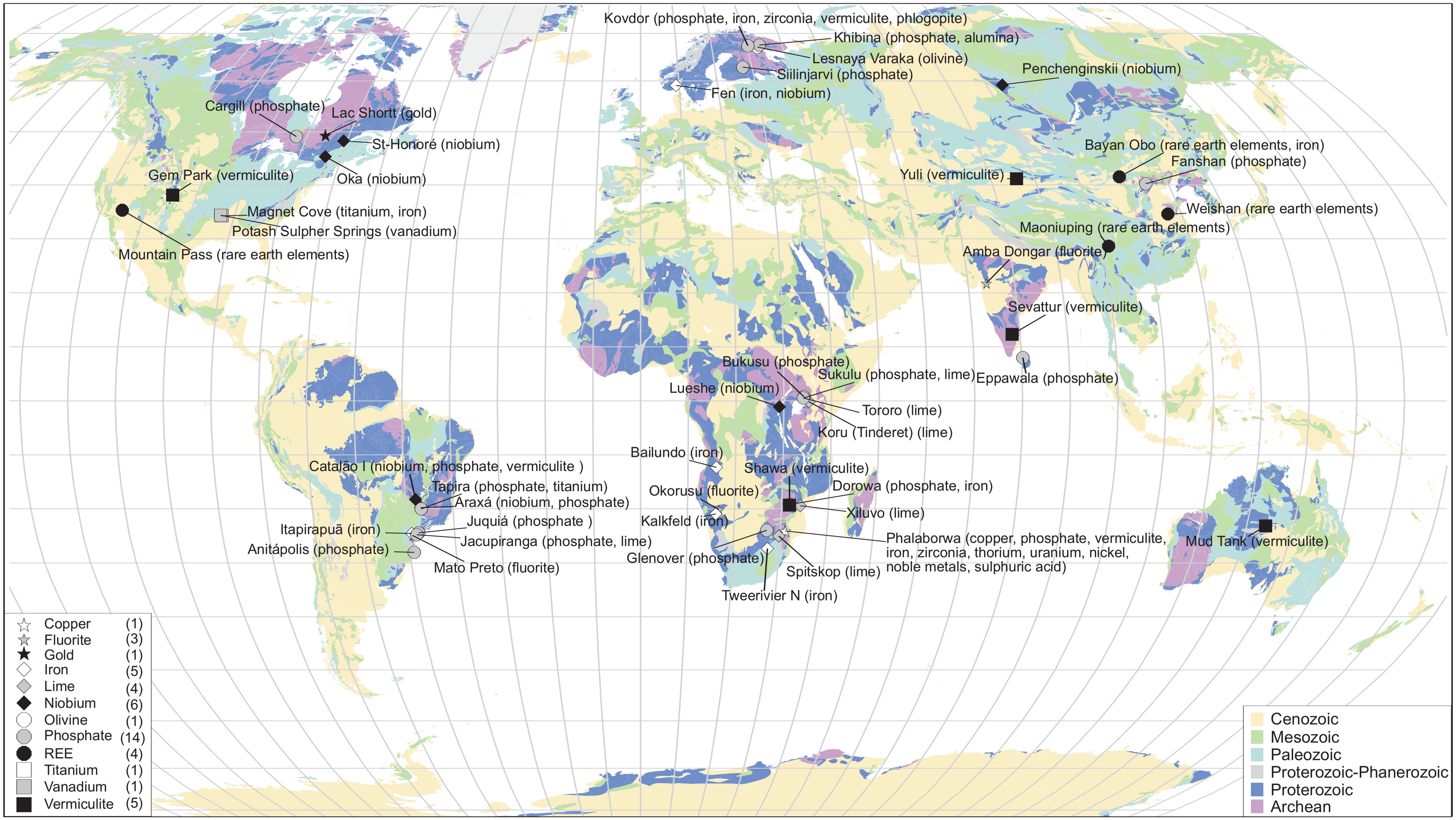

Figure 21. Carbonatite localities of economic interest that are active mines or past producers, sudivided by commodity type.

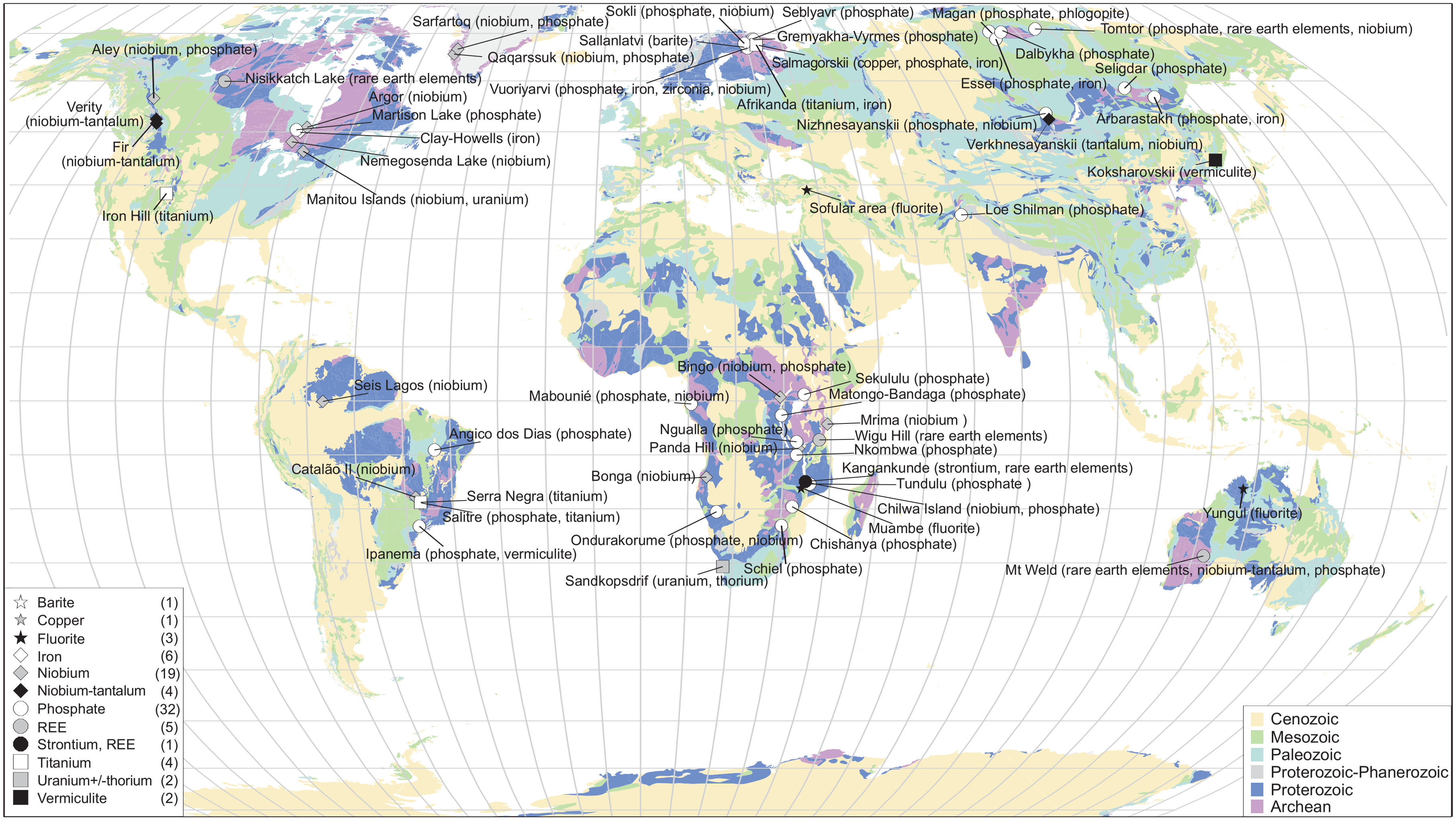

Figure 22. Carbonatite localities of economic interest that are deposits, sudivided by commodity type.

of the extrusives. Such high-density materials are likely to sink in a low-density, turbulent carbonatitic melt in, for example, a high-level magma chamber.

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REFERENCES

Biondi, J.C., 2005. Brazilian mineral deposits associated with alkaline and alkaline-carbonatite complexes, *in* Mesozoic to Cenozoic Alkaline Magmatism in the Brazilian Platform, (ed.) P. Comin-Chiaramonti and C.B. Gomes; Editora da Universidade de Sao Paulo: Fapesp, Sao Paulo, p. 707-750.

Bowen, N.L., 1924. The Fen area in Telemark, Norway; American Journal of Science, v. 8, p. 1-11.

Brögger, W.C., 1921. Die Eruptivgesteine des Kristianiagebietes. IV. Das Fengebiet in Telemark, Norwegen; Videnskapsselskapets Skrifter, 1. Mat.-Naturv, Klasse, 1920, No 9, p. 1-408.

Deans, T., 1966. Economic geology of African carbonatites, *in* Carbonatites, (eds.) O.F. Tuttle and J. Gittins; Wiley, New York, p. 385-413.

Deans, T., 1976. Mineral production from carbonatite complexes: A world review, *in* Proceedings of the First International Symposium on Carbonatites, (ed.) J.C. Braga; Ministério das Minas e Energia, Poços de Caldas, Brasilia, p. 123-133.

Dixey, F., Smith, W.C., and Bisset, C.B., 1937. The Chilwa Series of southern Nyasaland; Geological Survey of Nyasaland, Bulletin,v. 5: p. 1-85 (revised 1955).

Gittins, J., 1966. Summaries and bibliographies of carbonatite complexes *in* Carbonatites, (ed.) O.F. Tuttle and J. Gittins; John Wiley, New York, p. 417-570.

Gittins, J. and Harmer, R.E., 2003. Myth and reality in the carbonatite – silicate rock "association"; Periodico di Mineralogia, v. 72, p. 19-26.

Heinrich, E.W., 1966. The Geology of Carbonatites. Rand McNally, Chicago, 608 p.

Högbom, A.G., 1895. Uber das Nephelinsyenitgebiet auf der Insel Alnö; Geologiska Föreningens i Stockholm Förhandlingar, v. 98, p. 100-160 and p. 214-256.

Kogarko, L.N., Kononova, V.A., Orlova, M.P., and Woolley, A.R., 1995. Alkaline Rocks and Carbonatites of the world. Part 2: Former USSR; Chapman and Hall, London, 226 p.

Mahfoud, R.F. and Beck, J.N., 1995. Composition, origin, and classification of extrusive carbonatites in rifted southern Syria; International Geology Review, v. 37, p. 361-378.

Mariano, A.N., 1989. Nature of economic mineralization in carbonatites and related rocks, *in* Carbonatites, (ed.) K. Bell; Unwin Hyman, London, p. 149-176.

Notholt, A.J.G., Highley, D.E., and Deans, T. 1990. Economic minerals in carbonatites and associated alskine igneous rocks; Transactions of the Institution of Mining and Metallurgy, v. 99, p. B59-B80.

Pecora, W.T., 1956. Carbonatites, a review; Bulletin of the Geological Society of America, v. 67, p. 1537-1556.

Pell, J., 1996. Mineral deposits associated with carbonatites and related alkaline igneous rocks, *in* Undersaturated Alkaline Igneous Rocks: Mineralogy, Petrogenesis and Economic Potential, (ed.) R.H. Mitchell; Mineralogical Association of Canada, Short Course Volume 24, p. 271-310.

Petrov, S.V., 2004. Economic deposits associated with the alkaline and ultrabasic complexes of the Kola Peninsula, *in* Phoscorites and Carbonatites from Mantle to Mine, (eds.) F. Wall and A.N. Zaitsev; Mineralogical Society, London, p. 469-490

Richardson, D.G. and Birkett, T.C., 1996a. Carbonatite-associated deposits, *in* Geology of Canadian Mineral Deposit Types, (eds.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Decade of North American Geology, Geology of Canada, no. 8 p. 557-566.

Richardson, D.G. and Birkett, T.C., 1996b. Residual carbonatite-associated deposits, *in* Geology of Canadian Mineral Deposit Types, (eds.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Decade of North American Geology, Geology of Canada, no. 8, p. 108-119.

Rodriques, C.S. and Lima, P.R.A. dos S., 1984. Carbonatite Complexes of Brazil: Geology; Companhia Brasileira Metalurgia Mineração, Sao Paulo, 44 p.

Soellner, J., 1927. Zur Petrographie und Geologie des Kaiserstuhlgebirges im Breisgau; Neues Jahrbuch für Mineralogie,Geologie und Paläontologie, Beilage-bänd. Abt. A., v. 55, p. 299-318.

Sukheswala, R.N. and Viladkar, S.G., 1978. Carbonatites of India , *in* Proceedings of the First International Symposium on Carbonatites, (ed.) J.C. Braga; Ministério das Minas e Energia, Poços de Caldas, Brasilia, p. 277-293.

Tilton, G.R., Bryce, J.G., and Mateen, A., 1998. Pb-Sr-Nd isotope data from 30 and 300 Ma collision zone carbonatites in northwest Pakistan; Journal of Petrology, v. 39, p. 1865-1874.

van Straaten, P., 2002. Rocks for Crops: Agrominerals of sub-Saharan Africa; University of Guelph, Guelph, Ontario, 338 p.

Veizer, J., Bell, K., and Jansen, S.L., 1992. Temporal distribution of carbonatites; Geology, v. 20, p. 1147-1149.

Verwoerd, W.J., 1986. Mineral deposits associated with carbonatites and alkaline rocks, *in* Mineral Deposits of Southern Africa, Volumes I and II, (ed.) C.R. Anhaeusser, and S. Mansker; Geological Society of South Africa, Johannesburg, p. 2173-2191.

Viladkar, S.G., 2001. Carbonatites of India: An overview, *in* Alkaline Magmatism and the Problems of Mantle Sources, (ed.) N.V. Vladykin; Russian Academy of Sciences, Siberian Branch, Irkutsk, p. 257-271.

Yang, Z. and Woolley, A.R., 2006. Carbonatites in China: A review; Journal of Asian Earth Sciences, v. 27 p. 559-575.

Woolley, A.R., 1987. The Alkaline Rocks and Carbonatites of the World. Part 1: North and South America; British Museum (Natural History) and University of Texas Press, 216 p.

Woolley, A.R.M., 1989. The spatial and temporal distribution of carbonatites, *in* Carbonatites: Genesis and Evolution, (ed.) K. Bell; Unwin Hyman, London, p. 15-37.

Woolley, A.R., 2001. Alkaline Rocks and Carbonatites of the World. Part 3: Africa; Geological Society, London, 372 p.

Woolley, A.R., 2003. Igneous silicate rocks associated with carbonatites: Their diversity, relative abundances and implications for carbonatite genesis; Periodico di Mineralogia, v. 72, p. 9-17.

Woolley, A.R. and Church, A.A., 2005. Extrusive carbonatites: A brief review; Lithos, v. 85: p. 1-14.

Woolley, A.R. and Kjarsgaard, B., 2004. Carbonatites of the world: Map and database; 32nd International Geological Congress, Firenze, Italy, v. 1, p. 509 (106-5).

Woolley, A.R. and Kjarsgaard, B.A., 2008. Paragenetic types of carbonatite as indicated by the diversity and relative abundances of associated silicate rocks: Evidence from a global database; The Canadian Mineralogist, in press.