Revision 2

BERYLLIUM MINERAL EVOLUTION

Edward S. GREW
School of Earth and Climate Sciences, University of Maine, Orono, ME 04469,
Robert M. HAZEN
Geophysical Laboratory, Carnegie Institution of Washington, Washington DC, 20015

ABSTRACT

Beryllium is a quintessential upper crustal element, being enriched in the upper crust by a factor of 30 relative to primitive mantle, 2.1 ppm vs. 0.07 ppm. Most of the 112 minerals with Be as an essential element are found in granitic pegmatites and alkalic rocks or in hydrothermal deposits associated with volcanic and shallow-level plutonic rocks and skarns. Because of the extensive differentiation needed to enrich rocks sufficiently in beryllium for beryllium minerals to form, these minerals are relative late comers in the geologic record: the oldest known is beryl in pegmatites associated with the Sinceni pluton, Swaziland (3000 Ma). In general beryllium mineral diversity reflects the diversity in the chemical elements available for incorporation in the minerals and increases with the passage of geologic time. Furthermore, the increase is episodic; that is, steep increases at specific times are separated by longer time intervals with little or no increase in diversity. Nonetheless, a closer examination of the record suggests that at about 1700 Ma, the rate of increase in diversity decreases and eventually levels off at ~35species formed in a given 50 Ma time interval between 1125 and 475 Ma, then increases to 39 species at 125 Ma (except for four spikes), before dropping off to ~30 species for the last 100 Ma. These features appear to reflect several trends at work: (1) diversifications at 2475 Ma, 1775 Ma, and 525 Ma, which are associated with highly fractionated rare-element granitic pegmatites and with skarns at

Långban and similar deposits in the Bergslagen ore region of central Sweden, and which are inferred to correspond to the collisional phases of the supercontinents Kenorland, Nuna, and Gondwana, respectively; (2) diversification at 1175 Ma due to the rich assemblage of beryllium minerals in the Ilímaussaq peralkaline complex, Gardar Province, West Greenland in an extensional environment; (3) diversification at 275 Ma, which is largely attributable to granitic pegmatites (Appalachian Mountains, USA and Urals, Russia) and the Larvik alkalic complex, Norway, but nonetheless related to continental collision and (4) limited exhumation of environments where beryllium minerals could have formed in the last 100 Ma. That the maximum diversity of Be minerals in any one geologic environment could be finite is suggested by the marked slowing of the increase in the number of species formed in a given 50 Ma time interval, whereas the drop off at 100 Ma could be due to 100 Myr being too short a time interval to exhume the deep-seated occurrences where many Be minerals had formed. The relative roles of chance versus necessity in complex evolving systems has been a matter of considerable debate, one equally applicable to what extent the temporal distribution of beryllium minerals is a matter of contingency. On the one hand, the appearance of the most abundant Be minerals, such as beryl and phenakite, early in the history of Be mineralization appears to be a deterministic aspect since these minerals only require the abundant cations Al and Si and crystallize at relatively low concentrations of Be in aqueous solution or granitic magmas. On the other hand, it could be argued that the very existence of most other Be minerals, as well as the temporal sequence of their appearance, is a matter of chance since 55 of the 112 approved Be minerals are known from a single locality and many of these phases require an unusual combination of relatively rare elements. Consequently, we cannot exclude the possibility that other equally rare and thus contingent potential Be minerals await discovery in as yet unexposed subsurface

deposits on Earth, and we suggest that details of Be mineral evolution on other Earth-like planets could differ significantly from those on Earth.

Keywords: mineral age, beryllium, mineral evolution, granitic pegmatites, peralkaline complexes, supercontinent cycle, crystal structure, beryl

INTRODUCTION

Minerals are conventionally thought to be time-independent – it has been tacitly assumed that the minerals found on Earth and other planetary bodies or meteorites could have formed at any time in the history of the solar system. Mineral evolution challenges this assumption: it cannot be taken for granted that the minerals found today have always been present. This approach to mineralogy is concerned with the first appearance of minerals in the geological record and the relationship between the first appearances and events such as the assembly and break-up of supercontinents, major changes in the composition of the atmosphere, and colonization of dry land. Although Hazen et al. (2008, 2011, 2012) have developed and quantified the mineral evolution paradigm to a far greater extent than before, and Krivovichev (2013) has extended it to the complexity of crystal structures, several important concepts in mineral evolution were anticipated up to nearly 50 years earlier. Compiling data from all over the world, Gastil (1960) found a pronounced cyclicity in mineral dates. Zhabin (1979, 1981) articulated the concept of stages of mineral evolution and duration of a mineral's presence, contrasting common rock-forming minerals like quartz and zircon that have been present throughout geologic time beginning with meteorites with rarities such as welshite (Fig. 1), which has been reported only from a single locality. Yushkin (1982) discussed the increasing mineralogical complexity, which he related to increasing entropy through geologic time, emphasizing that these changes were concentrated in the upper parts of Earth's crust and on its

surface. Mineral evolution was also anticipated in the ore geology literature (Nash et al. 1981; Meyer 1981, 1985; Rundkvist 1982; Stowe 1994; see also Krivovichev 2013 for a history of mineral evolution).

Minerals containing Be as an essential constituent appear to be relatively late comers on Earth, none having been reported in extraterrestrial rocks (Shearer 2002) or in terrestrial rocks older than ca. 3000 Ma (Grew and Hazen 2009, 2010b, 2013), after 1500 Ma years of Earth's existence. This delayed appearance of Be minerals is no accident, as Be is the least abundant element lighter than Fe in the solar system (Lodders 2010; Lauretta 2011). Beryllium is highly enriched in the upper continental crust compared to other reservoirs, i.e., 2.1 parts per million vs. 1.4 parts per million in the lower crust and 0.07 parts per million in primitive mantle (Rudnick and Gao 2005; Palme and O'Neill 2004). However, less than 10 parts per million are rarely sufficient to stabilize a mineral of which Be is an essential constituent (e.g., Grew 2002b). Normally, further enrichment by at least an order of magnitude is necessary for the more common Be minerals, notably beryl, to appear, for example, 70 parts per million in granitic pegmatites (Evensen and London 2002; London and Evensen 2002).

The minerals of Be can add a different perspective on mineral evolution from the minerals of mercury, the first element to be treated in detail (Hazen et al. 2012). Both elements are rare, but their cosmochemical behavior differs because Hg has a much lower 50% condensation temperature for a solar-system composition gas: 252 °C for Hg in troilite vs. 1179 °C for Be in melilite (Lauretta and Lodders 1997; Lodders 2003). Their geochemical behavior also is markedly different, as Be is a lithophile elements showing only one valence (2+) in geologic systems, whereas Hg is chalcophile and shows three valence states (0, 1+, and 2+), so that the redox conditions that play a large role in Hg mineral evolution would have had relatively little

impact on Be mineral evolution. Another major distinction is that mercury mineralization was enhanced by interactions with organic matter (Hazen et al. 2012), whereas organic materials played a minimal role in the diversification of Be minerals.

In the present paper, we review the occurrences of the 112 species containing essential beryllium, with particular emphasis on the first and last reports in the geologic record and the frequency with which the minerals have been reported over geologic time. Broadly speaking there is an increase in mineral diversity with time. As reported by Hazen et al. (2012) for mercury minerals, spurts in species diversification of beryllium minerals appear to be related to the supercontinent cycle. However, the tendency for increased diversification with time does not give the full story of Be mineral evolution, and so our paper will also discuss influences that could have constrained increases in mineral diversity.

THE MINERALS OF BERYLLIUM – OUR DATABASE

Table 1 lists in alphabetical order the 112 minerals containing essential Be that are considered valid by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (CNMNC IMA), together with their formulae, which are largely taken from the 2012 CNMNC IMA list (the list can be downloaded from the CNMNC IMA website, http://pubsites.uws.edu.au/ima-cnmnc/IMA_Master_List_%282013-08%29.pdf, or the RRUFF website, http://rruff.info/ima/). Group assignment is based largely on Back and Mandarino (2008) and Mills et al. (2009); other relationships are taken from Hawthorne and Huminicki (2002) and Grice (2010).

We question the validity of two of the approved species, and thus we have not included them in our count. Bohseite, $Ca_4Be_3AlSi_9O_{25}(OH)_3$, may not be distinct from bavenite, $Ca_4Be_2Al_2Si_9O_{26}(OH)_2$, given the results reported by Lussier and Hawthorne (2011).

Krivovichev et al. (2004) found that clinobarylite could be considered the 1*O*-polytype of $BaBe_2Si_2O_7$, for which barylite is the 2*O*-polytype, in which case these minerals are not distinct species, but polytypes of a single species. Vinogradovite had also been listed by the CNMNC IMA as a valid mineral containing essential Be, $(Na,Ca,K)_5(Ti,Nb)_4(Si_6BeAl)O_{26}\cdot 3H_2O$. However, Be is not an essential constituent of vinogradovite, because there is no evidence for significant Be in the type material (Semenov et al. 1956). Significant Be substitutes for Si and Al at the Si(2) site in several samples of vinogradovite from the Ilímaussaq complex (Greenland), but it is not dominant at this site, i.e., Si ≈ 6, Al ≈ 1.2, and Be ≈ 0.8 out of 8 atoms total at the Si(2) site (Kalsbeek and Rønsbo 1992), and thus the Ilímaussaq vinogradovite would not qualify as a mineral species distinct from type vinogradovite. Consequently, vinogradovite is no longer listed as a Be mineral in the CNMNC IMA list.

A third controversial species, the gadolinite-datolite group mineral calcybeborosilite-(Y), $(Y,REE,Ca)(B,Be)_2(SiO_4)_2(OH,O)_2$ (e.g., Pekov et al. 2000), could be a valid species although listed as "questionable" in the list at the CNMNC IMA website. Our question is whether Be is an essential constituent. Strunz and Nickel (2001) gave the end-member formula as $(CaY)\square(BBe)[OH|SiO_4]_2$, but this is not a proper end member because there are two cations at two sites (Hawthorne 2002). Grew (2002a) gave the end member as $Y_2\square(Si_2O_8)O_2$, i.e., natural calcybeborosilite-(Y) could be a solid solution of $Y_2\square B_2(Si_2O_8)O_2$ with $Ca_2\square B_2(Si_2O_8)(OH)_2$ (datolite), $Y_2FeBe_2(Si_2O_8)O_2$ (gadolinite-(Y)) and $Y_2\square Be_2(Si_2O_8)(OH)_2$ (hingganite-(Y)). Further discussion of the status of calcybeborosilite-(Y) is beyond the scope of this paper; sufficient for our purposes is the absence of evidence that Be is an essential constituent of calcybeborosilite-(Y), and thus we have not included it as a Be mineral (Table 1).

None of the valid unnamed minerals (Smith and Nickel 2007) in their list updated in 2011, which is also available at the CNMNC IMA website, appears to be distinct from an approved mineral. However, there are two additional minerals included in Table 1, bringing the total to 112 valid Be minerals. Pršek et al. (2010) reported a hingganite in which Nd is dominant among the rare earth elements + yttrium, which is potentially a new species, hingganite-(Nd). Hawthorne (2002) suggested that yttrian milarite approaching the end-member $K(CaY)Be_3Si_{12}O_{30}$ in composition (Černý et al. 1991; Nysten 1996) could be a distinct mineral.

Even for valid species, not all reported occurrences are well documented. For example, minasgeraisite-(Y) has been reported from the Krenn quarry, Matzensdorf/Tittling, Germany (Habel and Habel 2009) and Vlastějovice region, Czech Republic (Novák et al. 2013), but in neither case does the reported composition correspond to the ideal minasgeraisite-(Y) end-member $CaY_2Be_2Si_2O_{10}$, and other data such as powder X-ray diffraction are either not given or only mentioned without specifics. Consequently, we have not accepted such reports, and minasgeraisite-(Y) is listed as a mineral occurring only at the type locality.

Complex solid solutions, most notably the roscherite group, required special attention; we accepted as valid only those reports of a given mineral species in which the identification was substantiated by chemical analysis, and, if necessary, symmetry. Rhodizite and its Cs-dominant analogue londonite posed a particular problem. “Rhodizite” has been reported from several localities in the Urals and Madagascar and from one locality in Wisconsin and the United Kingdom, but K-dominant material, i.e. rhodizite sensu stricto, has been confirmed only from two localities in Madagascar (Pring et al. 1986; Simmons et al. 2001). Re-examination of “rhodizite” specimens from the Urals turned up londonite (Pekov et al. 2010), whereas the single published analysis of “rhodizite” from the Animikie Red Ace pegmatite in Wisconsin,

characterized as a "representative" analysis, gave K 0.393 and Cs 0.407 per formula unit (Falster et al. 2001a), i.e., londonite. No analysis is available for rhodizite reported by A.W.R. Kingsbury from Meldon, Devon, U.K. (Embrey 1978); indeed the report needs confirmation (A. Tindle, 2008, http://www.mindat.org/mesg-7-92300.html; cf. Ryback et al. 1998, 2001 for other minerals). Consequently, rhodizite is considered to be found at one locality (as defined below), whereas londonite has been verified from 3 localities by this definition.

In terms of mineral class (Strunz and Nickel 2001), the Be minerals that we consider valid include 66 silicates (e.g., Fig. 1a,c,d,e,i), 28 phosphates (e.g., Fig. 1b), 1 arsenite, 2 arsenates, 11 oxides (Fig.1h) and hydroxides, 1 carbonate (Fig. 1g), and 4 borates (e.g., Fig. 1c).

DETERMINING THE AGES FOR CRYSTALLIZATION OF BERYLLIUM MINERALS

The database for determining the evolution of Be minerals is presented in Tables 2 and 3, which are compilations of the earliest and latest reported occurrences of Be minerals in the geologic record, respectively, together with the reported number of localities. The first column of references in each table gives the best source for information of the occurrence of the mineral at the specified locality. The second column of references in each table gives the best source of information for dating the crystallization of the mineral, which is the same reference in some cases. The listed references either give all the necessary information or cite other work that we consulted for compiling the table. The age assignments range widely in quality – in some cases, the age is well constrained, in many others, much less so because we must infer that the rock containing a Be mineral is coeval with the dated rock, and this date could be problematic (see below). We also checked whenever feasible the ages of other localities in order to be sure that we had found the earliest and latest reported occurrences.

The number of localities worldwide for a given mineral is specified only if the number does not exceed 10. Closely spaced localities having identical ages, e.g., pegmatites associated with Larvik plutonic complex in the Langesundsfjord area south of Oslo, Norway (Larsen 2010), are considered to constitute a single locality in Table 3. We made extensive use of the compilations in Grew (2000a, b) and at http://www.mindat.org. However, we verified the occurrences listed at http://www.mindat.org for minerals reported from <10 localities to be sure that the cited occurrences were sufficiently substantiated to be considered valid, e.g., minasgeraisite-(Y) above. Of the 112 species of Be minerals, 55 are reported from only one locality – i.e., "monochronous" (Zhabin 1979, 1981). In contrast, only 23 minerals have been reported from more than 10 localities worldwide. In terms of Zhabin's (1979, 1981) classification, these minerals can be considered either "panchronous", i.e., formed continuously from the beginning until the present time (bertrandite, beryl, helvite, and phenakite come closest to meeting these criteria, Table 3) or "polychronous", i.e., formed many times (e.g., genthelvite, leucophanite, and moraesite, Table 3). Beryl is the most widespread Be mineral by far; the locality list at http://www.mindat.org includes 4776 items as of October 18, 2013, but this list is undoubtedly incomplete. In compiling and interpreting our dataset, we had to take into account the deficiencies in the geologic record and the difficulties in dating beryllium minerals.

Imperfections in the geologic record

The geologic record is incomplete. A significant proportion of the upper continental crust, which hosts all the Be minerals discovered to date, has been lost to subduction, erosion, and metamorphism, or is covered by sedimentary or volcanic rocks, by ice, or by water. As pointed out by Barton and Young (2002), some deposits of Be minerals formed on or near Earth's surface and could be lost to erosion; possible examples are the four minerals (e.g., almarudite,

Table 2) reported in Pliocene and Pleistocene volcanic rocks in the Eifel district, Germany (Schminke 2007) and the Roman comagmatic region, Italy (Della Ventura et al. 1992). These four Be minerals might have appeared earlier in the geologic record, but did not survive.

Mineral investigations are not evenly distributed over the planet, but are largely limited to bedrock or sediments on or near Earth's surface, and are concentrated in areas that have received the most attention from geologists, mineralogists, and collectors. For example, the presence of numerous centers of mineralogical research and mining activity in Scandinavia undoubtedly played a role in stimulating the many discoveries of Be minerals in the Långban-type deposits, granite pegmatites of the Svecofennian province and northern Norway, Neoproterozoic pegmatites in Norway, and alkalic pegmatites in the Oslo rift (e.g., Magnussan 1930; Holtstam and Langhof 2007; Nysten and Gustafsson 1993; Langhof et al. 2000; Husdal 2008, 2011; Bergstøl and Juve 1988; Larsen 2010). Similarly it is no accident that the pegmatites in the Superior Province of North America are reported to be the oldest occurrences of a fair number of species given the proximity to the University of Manitoba, which is famous for its mineralogists (e.g., Černý 2005).

The ambiguities of dating crystallization of beryllium minerals

Dating the formation of Be minerals can be problematic, and not only because geochronological data themselves are associated with significant uncertainties. Emerald is the only Be mineral that has been dated directly, namely by the Rb–Sr method (Vidal et al. 1992); an attempt with the $^{40}Ar/^{39}Ar$ method gave a meaningless age of 6665 Ma due to excess argon (Cheillitz et al. 1993). In principle, any Be mineral containing K could be dated by the K–Ar and $^{40}Ar/^{39}Ar$ methods (e.g., rhodizite, Giuliani et al. 1995) as could gadolinite containing Th and U, such as the gadolinite-(Y) from Vico Lake in the Roman comagmatic province, Italy (Cámara et

al. 2008). In the great majority of cases, ages of Be minerals must be inferred from ages obtained on associated minerals, i.e., $^{40}Ar/^{39}Ar$ method on biotite and muscovite with emerald (Cheilletz et al. 1993) and U-Pb method on columbite-tantalite associated with Be minerals in pegmatite (e.g., Romer and Smeds 1994; Breaks et al. 2005), or from circumstantial evidence such as an age for the deposit in which the minerals are found. Not uncommonly, Be minerals appear to be younger than the host rocks, e.g., metamorphic or in veins and fracture fillings, introducing even more ambiguity into their ages.

The Tip Top pegmatite associated with Harney Peak granite in the Black Hills, South Dakota (Norton and Redden 1990) is a good example for which a fairly reliable age is possible because both the mineralogy and the geochronology have been well studied. The unique suite of secondary Be phosphates in the Tip Top pegmatite formed from the hydrothermal alteration of triphylite and beryl by meteoric water or residual aqueous fluid at temperatures between 300 and 25 °C (Campbell and Roberts 1986; Loomis and Campbell 2002). Emplacement of the Harney Peak granite is dated at 1715 ± 3 Ma (U-Pb monazite age, Redden et al., 1990). On the basis of mica $^{40}Ar/^{39}Ar$ cooling ages, Dahl et al. (2005) calculated that the Harney Peak granite was not uplifted until ca. 1480–1330 Ma, at which point it had cooled to ca. 300–350 °C, i.e., it is doubtful the Be minerals would be older than 1300 Ma. However, another approach would give an age of ~1700 Ma. On the basis of fluid inclusions from the Tin Mountain pegmatite, which is also associated with the Harney Peak granite, Sirbescu and Nabelek (2003) estimated a crystallization temperature of 340 °C (at 2.7 kbar) for this pegmatite, which is dated at 1702.4 ± 2.5 Ma (U-Pb apatite age, Krogstad and Walker 1994). Assuming a comparable temperature for the Tip Top pegmatite and a residual, rather than meteoric, origin of the hydrothermal fluids, we

think that a formation age of ca. 1700 Ma is a more reasonable estimate for the secondary Be minerals in the Tip Top pegmatite.

There are no proper constraints on the ages of bearsite and glucine. Both are supergene minerals, i.e., bearsite formed in the oxidized zone of an arsenic-bearing deposit at a depth of 15 m below Earth's surface (Kopchenova and Sidorenko 1962), whereas glucine formed in greisens subjected to weathering along faults at depths up to 40 m, e.g., 34 m in one deposit (Pokrovskaya et al. 1965; Ginzberg and Shatskaya 1966). The glucine reported from Mount Mica, Paris, Maine (King and Foord 1994; A. Falster, in preparation) could also have a supergene origin, and consequently, it is unlikely that ages of the deposits in which bearsite and glucine occur would give even an approximate age of formation of these two Be minerals.

Significance of the diversity diagrams

Figures 2a and 2b present two complementary aspects of the increase of Be mineral diversity with time. Cumulative diversity (Fig. 2a) shows the increase in the total number of species that are reported to have formed by a given time in Earth's history, and is based on the reported first occurrences in the geological record. At the present time, the cumulative diversity is 112 species, i.e., the totality of species that have appeared on Earth at one time or another, that have been preserved in the geologic record, and that have been discovered. However, this number is *not* the number of species that could be forming now or within the last 50-100 Ma, which Figure 2b gives as about 30 species. More generally, Figure 2b shows our estimate of the diversity of Be minerals at a given time in Earth's history, i.e., the number of species inferred to have formed during a given 50 Ma interval. The number of species in these intervals was estimated from three types of information: (1) reported first occurrences, (2) reported last occurrences and (3) frequency of reported occurrences in the geologic record. That is, Figure 2b

277 is based on a larger dataset than Figure 2a, but still one that is relatively small, comprising 110
278 species and a few hundred localities. It is three orders of magnitude smaller than the number of
279 dated detrital zircon grains (Fig. 2c). Thus, interpretation of the variations in the number of
280 species from one 50-Ma interval to the next must be mindful of the poor statistics; differences of
281 5 species or less are probably not statistically significant.

282 **Supercontinent cycles**

283 In our discussion relating mineral diversity to supercontinental cycles, we have adopted the
284 names for supercontinents proposed by Hoffman (1997), rather than the alternatives
285 Superia/Sclavia (Bleeker 2003; Cawood et al. 2013) and Columbia (Rogers and Santosh 2002)
286 for the two oldest supercontinents, respectively, and Pannotia in lieu of Gondwana (cf. Hazen et
287 al. 2012). The names of the older continents are not interchangeable, because each implies a
288 different interpretation of the extent to which continental fragments had aggregated, i.e.,
289 Kenorland is viewed as single supercontinent comprising most of the cratons, including Slave
290 (Sclavia) and Superior (Superia). Nuna comprised North America (including Greenland) and
291 Baltica, but Hoffman (1997) considered connections of Nuna to Siberia and Australia to be
292 tenuous. In contrast, Rogers and Santosh (2002, Fig. 1) showed Nuna and Siberia to constitute
293 one fragment of Columbia; other fragments comprised Australia and the other continents which
294 eventually regrouped to form Gondwana. Our choice of Kenorland and Nuna makes sense for
295 considering Be minerals, because Be minerals have been found in the Archean Eon in several
296 cratons other than Superia and Sclavia, whereas Paleoproterozoic Be minerals are found only in
297 North America and Baltica (Table 2; Fig. 2a).

298

299 **BERYLLIUM IN METEORITES AND THE SOLAR SYSTEM**

Reeves et al. (1970) formulated the hypothesis that Be formed by high-energy processes involving cosmic rays acting on the interstellar medium, a hypothesis that explains the cosmic abundance of ^{9}Be (e.g., Reeves 1994; Ramaty et al. 1996, 1997). Because of the small electric charge (+ 4) and small binding energy of its nucleus, Be is a "fragile" element that is destroyed by the heat in stellar interiors (Reeves 1994; Lodders 2010). For these reasons Be has a much lower abundance than C, N, and O in the solar system. Beryllium abundance in chondrites, achondrites, stony irons, and irons is reported to range from 0 to 400 ppb Be, but reaches 560 ppb in calcium-aluminum-rich inclusions (CAIs), with the maximum concentration in melilite and alteration phases in the CAIs, 649 ppb and ~1 ppm, respectively (Lauretta and Lodders 1997; Shearer 2002; Paque et al. 2003). The affinity of Be for melilite is attributed to its being isostructural with gugaite, $Ca_2BeSi_2O_7$.

BERYLLIUM MINERALS IN THE ARCHEAN EON (4000 TO 2500 MILLION YEARS)

Pegmatites are the primary sources of Be minerals found in Archean rocks. The oldest differentiated pegmatites, ca. 3100 Ma, are reported from the Barberton Mountain Land, South Africa (Tkachev 2011); these deposits include the 3040 Ma New Consort pegmatites (Harris et al. 1995). Although sufficiently differentiated to contain spodumene and up to 39 ppm Be, these pegmatites are reported to be devoid of Be minerals. The two oldest reported Be minerals are beryl and phenakite from southern Africa. Beryl is reported in pegmatites coeval with the Sinceni pluton, Swaziland, and thus dated at 3000 ± 100 Ma using Rb-Sr isotopes (Trumbull 1993); a more precise date for the Sinceni Pluton is given by a 3074 ± 4 Ma ^{207}Pb/^{206}Pb zircon evaporation age (Maphalala and Kröner 1993), but its accuracy needs confirmation (Trumbull 1993).

Emerald (Fig 1a) and phenakite occur in biotite schist associated with "albitite pegmatoid" and phenakite is found in the pegmatoid in the Gravelotte emerald deposit, Murchison greenstone belt, South Africa (Robb and Robb 1986; Grundmann and Morteani 1989), for which the zircon age of 2969 ± 17 Ma on the Discovery Granite (Poujol 2001) probably best dates crystallization of this "pegmatoid." Granitic pegmatites ranging in age from 2850 to 2550 million years associated with greenstone belts in the Pilbara (Fig. 2a) and Yilgarn Cratons, Western Australia (e.g., Sweetapple and Collins 2002; Jacobson et al. 2007) and the Superior Province, Ontario and Manitoba, Canada (e.g., Breaks et al. 2005; Černý 2005) contain 7 silicate and 3 phosphate Be minerals – evidence that the differentiation of granitic melts was more than sufficient to enrich resulting pegmatites in Be (e.g. 170 ppm, Tanco pegmatite, Manitoba, Canada, Stilling 2006) and give a diverse suite of Be minerals in Archean orogenic belts. The increase of diversity is coeval with the two peaks in the number of zircon grains associated with the assembly of Kenorland (Superia/Sclavia, Cawood et al. 2013; Fig. 2c).

Peralkaline rocks are very rare in Archean complexes, and there are only two reports of Be minerals in peralkaline rocks of that era – meliphanite and behoite as metasomatic minerals associated with nepheline syenite of the Sakharjok complex, Keivy Alkaline Field, Kola Peninsula, Russia (Bel'kov and Denisov 1968; Batiyeva and Bel'kov 1984; Lyalina et al. 2009), which was dated at 2682 ± 10 Ma (Zozulya et al. 2005).

Metamorphic Be minerals are also reported from just one locality in strictly Archean rocks: chrysoberyl in a granulite-facies plagioclase-biotite-quartz gneiss 2640 - 2649 million years in age, Yilgarn craton, Australia (Downes and Bevan 2002). However, two Be silicates and one Be oxide are found in granulite-facies anatectic veins of earliest Paleoproterozoic age (2485 million

344 years) in the Archean Napier complex: khmaralite, surinamite, and magnesiotaaffeite-6*N*'3*S*
345 (Grew et al. 2000, 2006).

346 Based on reported occurrences, by the earliest Paleoproterozoic Era there were 18 Be
347 minerals (Figs. 2a,b), representing 16% of the total known.

348 **BERYLLIUM MINERALS IN THE PROTEROZOIC EON (2500 TO 542 MILLION YEARS)**

349 **Paleoproterozoic (2500 Ma to 1600 Ma).**

350 During the second half of the Paleoproterozoic, i.e., beginning in 2050 Ma after a 435 m.y.
351 period during which no new species have been documented, there was a marked increase Be
352 mineral diversity (Fig. 2a,b) in both metamorphic and pegmatitic environments, which is coeval
353 with the peaks in number of zircon grains coincident with assembly of the supercontinent Nuna
354 (Fig. 2c). A remarkable diversity is found at Långban and similar deposits in the Bergslagen ore
355 region of central Sweden (Magnusson 1930; Holtstam and Langhof 1999; Jonsson 2004): 10 Be
356 species, mostly as skarn minerals at the peak of metamorphism or in related cavities and vugs at
357 ca. 1825 Ma (periods B and C of Magnusson 1930). The history of the Långban-type deposits
358 began with submarine volcanic-hydrothermal exhalation and precipitation in a back-arc setting at
359 1890 Ma followed first by regional amphibolite-facies metamorphism and vein formation
360 through remobilization at about 1850-1800 Ma (Svecofennian event) and then by brittle
361 deformation possibly at about 1000 Ma (period D of Magnusson 1930). Multiple reworking of an
362 unusual mix of constituents in an oxidizing environment where the chalcophile elements Pb, Sb,
363 As, and Sn combined with Be in oxides and silicates resulted in 10 minerals, e.g., welshite (Fig.
364 1e), swedenborgite, and the amphibole joesmithite, which are "monochronous" minerals (Zhabin
365 1979, 1981) unique to Långban and similar deposits – not yet reported outside the Bergslagen
366 ore region.

Granite pegmatites were the other major contributor of mineral diversity during the second half of the Paleoproterozoic, but over a narrower time span: between ca. 1850 Ma and 1700 Ma. Four areas yielded 17 of the 28 species of Be minerals reported to first appear in the geologic record at this time: (1) pegmatites approximately coeval with metamorphism of Långban-type deposits between ~ 1800 and ~1850 Ma in age (Lahti 1989; Lindroos et al. 1996; Romer and Smeds 1994; 1996; 1997) in the Svecofennian province of Sweden and Finland; (2) pegmatites associated with the Tysfjord granite, 1742 ± 46 Ma, Nordland, Norway (Andresen and Tull 1986; Husdal 2008); (3) pegmatites associated with Harney granite, Black Hills, South Dakota, USA, ca. 1700 Ma (see above); and (4) the Animikie Red Ace pegmatite, Penokean Orogen, Wisconsin, USA, 1760 Ma (e.g., Falster et al. 2001a,b; Sirbescu et al. 2008). Many of these pegmatitic minerals are "monochronous" – one-time occurrences (Zhabin 1979, 1981), which contribute to two spikes that stand out against an overall increase in diversity between 1875 Ma and 1675 Ma (Fig. 2b). Even more of these minerals are secondary phases, which are derived from the alteration of primary Be minerals, in most cases, beryl, i.e. 4 of the new Be minerals from Sweden (Nysten & Gustafsson 1993; Langhof et al. 2000) and all 8 new Be minerals from the Black Hills, South Dakota (Campbell and Roberts 1986; Loomis and Campbell 1992). Diversity could be the result not just of mixing of constituents from different sources by late, low-temperature hydrothermal fluids, e.g., triphylite for phosphate and beryl for Be in the Tip Top pegmatite (Campbell and Roberts 1986; Loomis and Campbell 1992). At low temperatures, hydroxyl and molecular water are incorporated in minerals, resulting in complex crystal structures, which increase the potential for diversity.

Mesoproterozoic and Neoproterozoic (1600 Ma to 542 Ma).

389 The second half of the Proterozoic Eon is marked by a continuation of the overall increase in
390 diversity up until about 950 Ma, e.g., the two Be minerals in the 1538 Ma skarns of the
391 Pitkaranta ore field, Karelia, Russia (Amelin et al. 1997; Sviridenko and Ivashchenko 2000;
392 Stein et al. 2003; Ramo 2005). The latter part of the increase overlaps assembly of the
393 supercontinent Rodinia (1300-950 Ma, Cawood et al. 2013), but not all the Be occurrences
394 during this time can be related to the phase of supercontinent assembly, for example, the 1267
395 Ma Igaliko and 1160 Ma Ilímaussaq peralkaline complexes (see below). Other contributors to the
396 increase in diversity are granitic pegmatites, a zinc deposit, metamorphic rocks and skarns, and
397 hydrothermal supergene alteration. Minerals in granitic pegmatites include secondary Sc-Be
398 minerals bazzite and oftedalite from the Heftetjern pegmatite, renowned for its diversity in Sc
399 minerals (e.g., Raade et al. 2004; Bergstøl and Juve 1988; Juve and Bergstøl 1990). The
400 Heftejern pegmatite is related to the Tørdal granite (Bergstøl and Juve 1988; Cooper et al. 2006),
401 which is coeval with 967±4 Ma (U-Pb zircon) post-orogenic Vrådal granite in Telemark, Norway
402 (Bergstøl and Juve 1988; Andersen et al. 2007). Bergstøl and Juve (1988) attributed most of the
403 Sc enrichment of the pegmatite to contamination with mafic volcanogenic rocks through which
404 the pegmatites passed, i.e., mineral diversity (new Be-Sc minerals) resulted from mixing of
405 constituents from two different sources. Metamorphic, skarn, hydrothermal, and supergene
406 minerals include two minerals from ca. 1000 Ma rocks in the zinc deposits of the Franklin
407 Marble, New Jersey in the Grenville Province of North America. Aminoffite (Hurlbut 1937) is
408 the only mineral containing either B or Be that could belong to the fissure mineralization at
409 Långban, Sweden (period D of Magnusson 1930), which is attributed to hydrothermal activity at
410 1000 Ma, over 800 Ma later than the skarn and vug minerals of periods B and C (Jonsson 2004;
411 personal communication, 2009).

412 The large spike at 1160 Ma is due to the Ilímaussaq peralkaline complex, in the Gardar
413 Province, southwest Greenland (e.g., Peterson and Secher 1993; Krumrei et al. 2006; McCreath
414 et al. 2012). Together with the nearby Igaliko complex, it constitutes one of the world's premier
415 localities for Be minerals, both in species appearing for the first time in the geologic record (9
416 minerals in the Ilímaussaq complex, e.g., sørensenite, Fig. 1c, Table 4) and in overall diversity
417 (Engell 1971; Markl 2001). However, in contrast to the mineral species found in the Långban-
418 type deposits, few of the minerals in the Igaliko and Ilímaussaq complexes are "monochronous"
419 (Zhabin 1979, 1981), such as sørensenite; many of these unusual minerals, e.g., tugtupite, are
420 also found in younger peralkaline complexes (Table 4), notably Khibiny and Lovozero on the
421 Kola Peninsula, Russia (362 Ma, Pekov 2000; Yakovenchuk et al. 1999; Arzamastsev et al.
422 2007); Larvik complex, Norway (294 Ma, Larsen 2010); Mont Saint-Hilaire, Quebec, Canada
423 (124 Ma, Eby 1984; Currie et al 1986; Gilbert and Foland 1986); and Zomba-Malosa, Malawi
424 (113 Ma, Eby et al. 1995).

425 The overall increase in diversity until about 950 Ma was followed first by a leveling off at
426 35-38 species per 50-Ma interval (Fig. 2b), and then a spike of 41-42 species at 575-525 Ma.
427 This spike in Be mineral diversification extends beyond the Proterozoic Eon into the Cambrian
428 Period, coeval with the assembly of the supercontinent Gondwana (700-500 Ma, Cawood et al.
429 2013). Of the nine Be minerals new to the geologic record between 585 and 500 Ma, six are
430 secondary, including four phosphates of the roscherite group, in pegmatites associated with the
431 Late Neoproteroterozoic-Cambrian Brasiliano orogeny, Minas Gerais, Brazil, 585-500 Ma (e.g.,
432 Atencio 2000; Morteani et al 2000; Pedrosa-Soares et al. 2011).

433 In summary, we see a recurring theme – the major contributions to Be mineral diversity are
434 suites of secondary, low-temperature minerals containing components generally not occurring

435 together in great abundance. These minerals have complex crystal structures incorporating
436 significant amounts of OH and H_2O, which can add considerably to structural complexity in
437 some cases (Table 1 and Krivovichev 2013).

438 **BERYLLIUM MINERALS IN THE PHANEROZOIC EON (542 MILLION YEARS TO THE PRESENT)**

439 The most salient feature in the Paleozoic is a prominent spike of 54 species at 275 Ma
440 superimposed on a modest increase from 35 at 475 Ma to 39 species at 125 Ma. An example of
441 increased diversity in the early Paleozoic is formation of høgtuvaite during Caledonian
442 metamorphism (414 Ma) of an 1800 Ma Be deposit (Grauch et al. 1994; Skår 2002). Granitic
443 pegmatites in the Urals (e.g., makarochkinite at 265 Ma, roggianite at 250 Ma, Table 2) and
444 Appalachians (e.g., gainesite at 293 Ma, Table 2; also Bradley et al. 2013), together with alkalic
445 pegmatites associated with Larvik plutonic complex at 294 Ma in the Oslo rift, Norway (Larsen
446 2010) contributed to the 275 Ma spike, which is coeval with one of the peaks in the number of
447 zircon grains and assembly of Pangea (Fig. 2b,c).

448 The youngest feature in Figure 2b is a drop off from 39 to about 30 species during the last
449 100 Ma, despite the appearance of four beryllium minerals in the Pleistocene volcanic rocks in
450 the Eifel district, Germany (Schminke 2007) and the Plio-Pleistocene Roman comagmatic region
451 or Roman perpotassic province (e.g., Della Ventura et al. 1992), e.g., almarudite and stoppaniite,
452 respectively. Other examples of very young volcanic occurrences are behoite at Honeycomb
453 Hills, Juab County, Utah (Table 3), as well as beryl and bertrandite at Spor Mountain, about 35
454 km distant (younger than 21 Ma, possibly younger than 6-7 Ma, Lindsey 1977).

455 **DISCUSSION**

456 Figures 2a and 2b show that very broadly beryllium mineral diversity increases with the
457 passage of geologic time and the increase is episodic, i.e., spikes of markedly increased diversity

458 separated by longer time intervals with much less increase; indeed none between 2450 and 1950
459 Ma. After 1700 Ma, the rate of overall diversity increase slackens and eventually tops off at ~40
460 species present in a given 50 Ma time interval except for a prominent spike at 275 Ma, before
461 dropping off to ~30 species for the last 100 Ma. These features appear to reflect several trends at
462 work: (1) episodic and uneven diversification related to overall evolution of the continental crust,
463 (2) finiteness in the maximum mineralogical diversity in a given geological environment, and (3)
464 limited exposure of environments where beryllium minerals could be forming now, geologically
465 speaking (last 5-10 Ma).

466 **Beryllium minerals and supercontinent cycles**

467 The spikes in diversity shown in Figure 2b, namely, 2475 Ma (break in the steady diversity
468 increase), 1775 Ma (paired spikes), 1175 Ma, 550 Ma (paired spikes), and 275 Ma, overlap peaks
469 in numbers of dated detrital zircon grains in the compilation of Voice et al. (2011), which was
470 used by Cawood et al. (2013), and is reproduced as Figure 2c. That is, these diversity spikes
471 could correspond to the collisional phases of the supercontinental cycles of Kenorland, Nuna,
472 Rodinia, Gondwana, and Pangea, respectively. Cawood et al. (2013) emphasized that the peak in
473 zircon numbers probably does not represent episodic spurts of continental growth, but rather the
474 greater potential for preservation of rocks formed during the later stages of ocean closure and
475 continental collision, a similar conclusion was reached by Condie et al. (2011). The
476 correspondences are noteworthy in that preservation plays a different role. The zircons are
477 detrital grains from metasedimentary and sedimentary rocks ranging in age from Archean to
478 Recent (Voice et al. 2011), and thus could have been preserved in many cases without their
479 source rocks in the continental crust being preserved, whereas the beryllium minerals were found

in situ, i.e., the segment of continental crust containing the beryllium minerals must be preserved in order for the beryllium minerals to be preserved.

Nonetheless, there are several complications in relating the diversity spikes to supercontinent cycles. The spikes in species diversity relate to three distinct geologic environments: (1) metamorphic and metasomatic complexes, (2) granitic pegmatites, and (3) alkalic and peralkaline intrusive complexes. Regional metamorphic rocks and most granitic pegmatites (the main exception being pegmatites in the NYF family, e.g., Černýand Ercit 2005) are characteristic of collisional orogeny (e.g., rare-element pegmatites, Bradley et al. 2012, 2013) and thus relating the spikes resulting from diversification in these two environments, i.e., 2475 Ma, 1775 Ma and 525 Ma, could correspond to the collisional phases of Kenorland, Nuna, and Gondwana, respectively, as suggested above. The last correspondence is not surprising as all the reported species are found in Brazil (plus one in Madagascar). In addition, minerals formed in the zinc deposit at Franklin, New Jersey during the Grenville orogeny at ca. 1000 Ma could be related to assembly of Rodinia.

Granitic pegmatites and related rocks in the Urals and Appalachians, together with pegmatites associated with the Larvik plutonic complex, contribute to the large spike in diversity at 275 Ma. This spike is roughly coeval with a late phase of collision of Pangea (Appalachians, Bradley et al. 2013), whereas the Larvik pegmatites are associated with passive rifting in the Oslo Graben, possibly related to the rotation of the Pangea supercontinent during a late stage of the Hercynian/Variscan orogeny (Heersemans et al. 1996; 2004; Larsen et al. 2008).

Linking mineral diversification to supercontinent evolution is less obvious for the spike centered at 1175 Ma and the diversity increase beginning at about 1300 Ma (Figs. 2a, b). These increases in diversity are due to minerals found in the peralkalic Igaliko and Ilímaussaq

503 complexes of the Gardar Province in West Greenland. Upton et al. (2003) associated rifting in
504 the province with the break-up of the supercontinent Paleopangea, but only stated this
505 association in the abstract and did not explore or develop it further in the paper. We are not
506 aware of another paper in which rifting in the Gardar Province is tied to supercontinent breakup.
507 For example, J.D.A. Piper (e.g., Piper 1982, 2010), who developed the concept of a Paleopangea
508 supercontinent that lasted from at least 1300 Ma to its breakup extending from 600 to 500 Ma,
509 did not mention such a relationship. Goodenough et al. (2002) suggested that magmas in the
510 Gardar Province originated in subcontinental lithospheric mantle metasomatized by subduction-
511 related fluids or melts during the Ketilidian orogeny at about 1800 Ma, an interpretation
512 extended by Goodenough et al. (2013) to include enrichment of rare earth elements, Nb and Ta.
513 Taken a step further, we suggest that Be was also introduced with these elements, but this leaves
514 unanswered the question concerning the relationship to supercontinent assembly and break up.
515 One might conjecture that rifting in the Gardar Province bears a relationship to the older events
516 recorded in accreted terranes (1140-1250 Ma, Rivers 2008) in the Grenville belt analogous to
517 that of far field rifting in the Oslo Graben to the Variscan/Hercynian orogeny.

518 **Structural and chemical complexity of beryllium minerals**

519 Krivovichev (2013) summarized mineral evolution as involving both increasing diversity of
520 mineral species and increasing crystal structural complexity, which is a measure of both size-
521 and symmetry-sensitive aspects and can be calculated according to a modified Shannon formula.
522 On the basis of 3949 structure reports on minerals extracted from the Inorganic Crystal Structure
523 Database, Krivovichev (2013) classified structures in terms of total structural information
524 content (bits per unit cell) into very simple (0-20 bits), simple (20-100 bits), intermediate (100-
525 500 bits), complex (500-1000 bits), and very complex (> 1000 bits), respectively, 15%, 28%,

526 46%, 8% and 3%, and the proportions reported for 92 beryllium mineral structures in
527 Krivovichev's (2013) database are not very different (Table 1; Fig. 3).

528 There is little, if any, increase in complexity of Be mineral structures with time. Although
529 none of the minerals reported to first appear in the Archean (>2500 Ma) have complex structures,
530 their absence could simply be due to the proportion of complex and very complex structures
531 being only 14% among beryllium minerals.

532 Chemical composition played a more important role in the diversification of beryllium
533 minerals than crystal structure. For example, minerals in the beryl and gadolinite-datolite group
534 illustrate the limitations of relying on structural complexity as a measure of mineral evolution.
535 Beryl, bazzite, and stoppaniite give total structural complexities of 133-146 bits; only the Cs-Li
536 beryl-group mineral pezzottaite is significantly higher at 941 bits (Table 1). These numbers belie
537 the complexity of beryl composition, which incorporates significant Li, Na, and Cs in the most
538 differentiated granitic pegmatites (Černý 2002). Mixing with Sc-bearing fluids resulted in the Sc-
539 dominant analogue, bazzite (Bergstøl and Juve 1988), whereas a combination of unusually
540 oxidizing conditions and peralkalinity might explain the high Fe^{3+}-and low Al content in
541 stoppaniite (Černý 2002). Moreover, the rarer beryl-group species appear later in the geologic
542 record than beryl (Table 2). Similarly, structural complexity of gadolinite and hingganite has a
543 narrow range (107-114 bits, Table 1), yet the solid solutions of these minerals are highly
544 complex with substitutions involving both light and heavy REE, Ca, and Fe at the the larger
545 sites, Be and B at tetrahedral sites, and hydroxyl at O sites, all of which have confounded
546 classification of this mineral group (e.g., Grew 2002a). Only gadolinite-(Y) is reported from
547 Archean rocks, whereas two of the four hingganite species have not been found in Precambrian
548 rocks (Table 2). In summary, the chemical variables that define mineral species in these two

549 groups constitute a more sensitive measure of increasing diversity with time than does structural
550 complexity.

551 **Are there limits to beryllium mineral diversity?**

552 Figure 2a suggests that there is no limit to Be mineral diversity. However, this diagram gives
553 cumulative diversity, which would correspond to actual diversity at any given time only if
554 species formed earlier in Earth's history continued to form up until the time in question, e.g., all
555 112 Be minerals found in the geologic record were forming now. Figure 2b shows that this is not
556 the case, and that there could be a limit to beryllium mineral diversity, at least in the more
557 widespread geologic environments in the upper continental crust, e.g., granitic pegmatites,
558 alkaline and peralkaline pegmatites, metamorphic rocks and skarns. Discounting the spikes
559 discussed above, Figure 2b shows that between 1700 Ma and 100 Ma the number of species
560 likely to have formed during a given 50 Ma time interval increases more slowly and eventually
561 levels out at ~40 species. The spikes result from addition of up to 15 more species to a given
562 time interval; many of these species are found only in one deposit ("monochronous" of Zhabin
563 1979), e.g., six minerals at Långban, Sweden (1825 Ma). This unique diversity must reflect a
564 one-time convergence of circumstances such as a unique mixing of constituents not generally
565 enriched together. In other cases, the "monochronous" minerals are secondary phases, e.g., five
566 of the secondary hydrated phosphates at the Tip Top mine, South Dakota (1702 Ma).

567 Table 4 is also suggestive of an upper limit to diversity in alkalic pegmatites. Although the
568 overall diversity of the Phanerozoic Larvik and Mont Saint-Hilaire alkalic complexes rivals or
569 exceeds that of the Proterozoic Ilímaussaq complex, neither introduces as many minerals new to
570 the geologic record as does Ilímaussaq. The proportion of Be minerals in any one of the 8
571 complexes that are not found in the other 7 complexes does not exceed 20%; i.e., the beryllium

572 mineral assemblages among the 8 complexes differ much less than one might expect given the
573 availability of a wide variety of rare elements, several of which are essential constituents of Be
574 minerals (Table 4).

575 A third example comprises 16 minerals reported in granitic pegmatites and alpine fissures in
576 the Alpine-Himalayan belt (5-33 Ma, Table 3). None of these minerals is new to the geologic
577 record; rather they are reported from granitic pegmatites as old as 3000 Ma (e.g., beryl Table 2).
578 This situation suggests that even in an environment as conducive to extreme mineralogical
579 diversity as a granitic pegmatite, there are limits to diversity; the exceptional diversity in
580 secondary beryllium minerals at the Tip Top mine, Black Hills, S.D., is the exception, not the
581 rule in granitic pegmatites.

582 **Why is there a decrease in diversity in the Upper Cretaceous and Cenozoic?**

583 The drop off in diversity from ~40 species to ~30 species in the last 100 Ma is unexpected,
584 particularly as another five species were first reported in the geologic record in this time period,
585 including four species in Pleistocene volcanic rocks at Earth's surface (Eifel, Germany and
586 Roman Comagmatic Province, Italy). This drop-off contrasts with the marked increase in
587 diversity of Hg, Br, I, and B minerals in the last 100 million years, which Hazen et al. (2012) and
588 Grew and Hazen (2010a) attributed to many of the minerals being soluble in aqueous fluids (e.g.,
589 halides and many borates) or volatile (e.g., native Hg), and thus ephemeral. None of the 110 Be
590 minerals can be considered ephemeral in this sense, and thus preservation of Be mineral diversity
591 is relatively little affected by stability of minerals at Earth's surface. Thus, once a Be mineral
592 forms it is more likely to be preserved unless it erodes away. Conversely, only a few Be
593 minerals, such as bearsite, glucine, uralolite, and moraesite, are supergene, i.e., formed by

oxidation or weathering close to Earth's surface (Kopchenova and Sidorenko 1962; Pokrovskaya et al. 1965; Ginzberg and Shatskaya 1966).

The situation for Be minerals could be analogous to that for economically significant orogenic gold deposits, none of which are younger than 50 Ma (Goldfarb et al. 2001). Since such deposits typically formed at mid-crustal levels, Goldfarb et al. (2001) concluded that they are still being unroofed. Beryllium minerals might also be sensitive indicators of the rates of deep rock exposure and erosion. Even in geologic terms, 100 Myr is a relatively short time interval, one that could be insufficient for formation and exhumation of rocks containing a diverse assemblage of Be minerals. Herein lies a possible explanation for this paradox: perhaps additional Be mineral species have been forming at depth over the past 100 Ma, but there has not been sufficient time for certain geologic environments to be exhumed. For example, there are no Be-enriched plutonic alkalic complexes younger than 100 Ma, so the youngest ages reported for minerals characteristic of this environment exceed 100 Ma. Another example is surinamite, a metamorphic mineral restricted to relatively deep-seated rocks (typically $P \geq 8$ kbar, $T \geq 800$ °C, e.g., Grew 2002b) no younger than 1050 Ma (Chimwala, Chipata district, Zambia, de Roever and Vrána 1985; Johnson et al. 2006). Younger analogues of Precambrian upper-amphibolite to granulite-facies rocks are not often exhumed, and given the scarcity of surinamite (5 localities, worldwide, 7 if the 3 Antarctic localities are counted separately, Grew 2002b), the chances of finding surinamite in an exhumed terrane are slim indeed. In contrast, the more common Be minerals such as beryl and bertrandite have been found in relatively deep-seated complexes exhumed in the Alpine-Himalaya orogenic belt (e.g., Pakistan, Fig. 4), as well as in Neogene and Quaternary volcanic deposits.

Mineral evolution: An accident of historical contingency?

The relative role of chance versus necessity in complex evolving systems has been a matter of considerable debate. For example, a dominant role for contingency was advanced for biological evolution by Stephen J. Gould, who "confronted our traditional view about progress and predictability in the history of life with the historian's challenge of contingency—the 'pageant' of evolution as a staggeringly improbable series of events, sensible enough in retrospect and subject to rigorous explanation, but utterly unpredictable and quite unrepeatable" (Gould 1989, p. 14; see also Gould 2002). This conclusion arose in part from Gould's interpretation of the "weird wonders" from the Middle Cambrian Burgess Shale of British Columbia—a soft-bodied fauna that features many unusual, if not unique, invertebrate morphologies. However, Conway-Morris (1998) challenged Gould's conclusions and countered that virtually all of the seemingly strange Burgess Shale fossils represent well-established arthropod anatomies, and thus do not support the hypothesis of contingency-dominated evolution. Mahler et al. (2013) also challenged Gould's view of biological evolution, finding that many anatomical features in the speciation of Caribbean lizards are predictable.

An analogous debate can inform studies of the evolution of Be minerals. To what extent is the temporal distribution of beryllium minerals a matter of chance versus necessity? On the one hand, the appearance of the most abundant Be minerals, including beryl, phenakite, and chrysoberyl, early in the history of Be mineralization appears to be a deterministic aspect of any Earth-like planet. These phases only require the abundant cations Al and Si, and they crystallize at relatively low concentrations of Be in aqueous solution or granitic magmas. Therefore, if a Be concentration mechanism exists on a terrestrial planet or moon, then these phases are likely to be among the first Be minerals to form. The likelihood that these phases would form and not others

639 in widespread geologic environments is also suggested by the limit to beryllium mineral
640 diversity implicit in Figure 2b.

641 On the other hand, it could be argued that the very existence of most other Be minerals, as
642 well as the temporal sequence of their appearance, is a matter of chance. The fact that 55 of the
643 112 approved Be minerals are known from only 1 locality (Table 1) points to the significant role
644 of contingency in diversification. Most of these phases require an unusual combination of
645 relatively rare elements (Be combined with Sc, Zn, Zr, or Sn, for example, Table 5). Several of
646 these odd combinations yield different minerals in different environments, e.g., Be-Sn gives
647 sørensenite in the alkalic Ilimaussaq complex, Greenland, but sverigite in the skarn complex at
648 Långban, Sweden. Furthermore, these unusual chemical concatenations must be exposed at or
649 near Earth's surface and then must be recognized as sufficiently different from other minerals to
650 warrant study. This realization, that chance plays a significant role in Earth's mineral evolution
651 and in our discovering the diversity resulting from this evolution, has important implications not
652 only for the present paper, but also for other papers on mineral evolution (e.g., Zhabin 1979;
653 Hazen et al. 2008, 2012).

654 To what extent, therefore, does chance play a significant role in the evolution of Earth's near-
655 surface environment? Would any planetary body of the same size and composition, the same
656 location relative to a star similar in size to our Sun, and subjected to comparable meteoritic and
657 cometary bombardment end up grossly similar to Earth? A full consideration of these questions
658 is beyond the scope of the present paper, but some basic principles are worth exploring in the
659 context of Be mineral evolution.

660 First, we expect that the concentration of Be in such a planet as a whole would be comparable
661 to that of Earth since Be is one of the sparsest elements in the cosmos due to its destruction in

662 stellar interiors (Reeves 1994; Lodders 2010); a planet enriched in Be such as Isaac Asimov's
663 (1954) fictional "Junior" in the novella "Sucker Bait" is not likely. Second, the volumetric
664 distribution of major rock-forming minerals will certainly be similar to Earth. Basalt will
665 dominate the crust, while derivative igneous rocks will also be abundant. Complex pegmatites
666 and alkali rocks with suites of Be minerals will form as widespread, if volumetrically minor,
667 deposits. Beryllium phases will also occur in hydrothermal zones associated with volcanic and
668 shallow-level plutonic rocks and skarns. These types of deposits, which are volumetrically minor
669 but widespread on Earth today, thus appear to be deterministic aspects of any Earth-like planet.
670 Furthermore, the episodic appearance and relative timing of many Be minerals may also be
671 deterministic. Morra et al. (2013) found regulatities in the size distributions of tectonic plates
672 over the last 200 Ma, with the implication that timing of supercontinent assembly and break-up
673 might not be a matter of chance, but rather is governed by the dynamics of the Earth system and
674 thus in principle is predictable. To the extent that mineral formation and preservation is linked to
675 the supercontinent cycle, Be mineral episodicity and sequence may be constrained. With
676 increasing sophistication and quantification in studies such as Morra et al. (2013), it may be
677 possible to evaluate the extent to which determinism is a dominant factor in the large-scale
678 sweep of Earth history.
679 On the other hand, many details of Earth's Be mineral evolution story must be contingent on
680 improbable events. The occurrence of many unique minerals with Be plus other rare elements
681 depends initially on the chance juxtaposition of elements rarely found together in significant
682 concentrations, coupled with the subsequent preservation and fortuitous exposure of the deposit.
683 It is likely that the 55 approved Be minerals known from a single occurrence, as well as many of

684 the 10 Be minerals reported from two or three occurrences, i.e., 49-58% of the 112 Be minerals,
685 represent chance finds that might well be absent on other similar planets.

686 By this reasoning, we also cannot exclude the possibility that other equally rare and thus
687 contingent potential Be minerals await discovery in as yet unexposed subsurface deposits,
688 despite the apparent limit on mineral diversity implicit in Figure 2b. Furthermore, other plausible
689 Be minerals, i.e., phases with a distinct composition and crystal structure that meet criteria of the
690 the correspondence principle of Lewis acidity – Lewis basicity (Hawthorne 2013 and in
691 preparation) and with a plausible pressure-temperature-composition stability range, may have
692 never formed on Earth because such rare contingent events did not occur. Consider the
693 distribution of minerals of Be and coexisting elements in Table 5. Geochemical affinity could
694 play a role in predicting which rare combinations are more likely, for example, 2 of 16 known
695 minerals of the lithophile element Sc and 4 of 17 known minerals of the lithophile element Cs
696 contain essential Be; all 6 minerals are from granitic or alkalic pegmatites, while there are no
697 known Be minerals that incorporate the chalcophile element Cu or the siderophile elements Co
698 and Ni—all relatively common mineral-forming elements, but ones that do not enjoy
699 geochemical affinities with Be. Thus, it is not surprising that there are no Be minerals
700 incorporating the less abundant chalcophile (e.g., Se, Ag, Te, Hg, Bi) or siderophile (Mo)
701 elements. Nonetheless, there are counter examples to the influence of geochemical affinity, i.e.,
702 the presence of 15 Be minerals with the chalcophile elements S, Zn, As and Sb, and absence of
703 Be minerals incorporating the lithophile elements Nb, Ta, Th and U, which, like Be, are
704 commonly enriched in granitic or alkalic pegmatites.

705 The recent discoveries of new species in the roscherite group, ferrochiavennite and of
706 mariinskite, the Cr analogue of chrysoberyl, point to the possibility of discovering other

707 analogues of known Be minerals, particularly those analogues that have already been
708 synthesized, at least as a subordinate constituent:

709 1. $Mn^{2+} \Leftrightarrow Fe^{2+} \Leftrightarrow Mg^{2+}$. Most plausible are Fe^{2+} analogues of Mn^{2+} phases such as
710 väyrynenite and trimerite;
711 2. Cr^{3+}, V^{3+}, Mn^{3+}, $Fe^{3+} \Leftrightarrow Al^{3+}$. Possibilities include analogues of chrysoberyl and beryl,
712 e.g. $BeFe_2O_4$ (up to about 45% in synthetic chrysoberyl; Gjessing et al. 1943; Gusarov and
713 Semin 1992) and BeV_2O_4 (up to 70% in synthetic chrysoberyl, Sarazin and Forestier
714 1959). Up to a few percent $Be_3V_2Si_6O_{18}$ or $Be_3Cr_2Si_6O_{18}$ have been reported in synthetic
715 beryls (e.g., Franz and Morteani 2002). Frondel and Ito (1968) synthesized V-, Cr- and
716 Mn-bearing bazzite from mixtures containing up to 50% $Be_3V_2Si_6O_{18}$, $Be_3Cr_2Si_6O_{18}$ and
717 $Be_3Mn_2Si_6O_{18}$ in $Be_3Sc_2Si_6O_{18}$, but were unable to quantify the proportion of the V, Cr
718 and Mn end members as the run products contained other phases.
719 3. OH $\Leftrightarrow$ F substitution. A natural F-dominant analogue of hambergite has been reported
720 (53.7% of the F end member, Novák et al. 1998), but the F compound, $Be_2(BO_3)F$, is not
721 isostructural with hambergite (Baidina et al. 1978; Burns et al. 1995).

722 The great majority of the rare Be minerals are chemically complex silicates or phosphates,
723 whereas other anionic complexes are much subordinant. Except for tugtupite, halogens occur
724 only as substituants for hydroxyl. Nonetheless, the known 11 oxides and hydroxides, plus the
725 single carbonate, have by no means exhausted the potential for Be minerals other than silicates,
726 borates and phosphates. Examples of relatively simple compounds reported as synthetics include
727 a carbonate $BeCO_3 \cdot 4H_2O$; sulfates of which the tetrahydrate $BeSO_4 \cdot 4H_2O$ is most commonly
728 encountered; halides BeF_2 and $BeCl_2$ and a sulfide, BeS (Ross 1964; Bell 1972; Everest 1973
729 and references cited therein). Several of these compounds correspond in stoichiometry to well

known minerals of other elements in Group IIB, but differ markedly in crystal structure, e.g. BeS is isostructural with sphalerite; α-BeF_2 and γ-BeF_2 have the structures of β-cristobalite and quartz, respectively; and α-$BeSO_4$ has the structure of low cristobalite. In general, the Be compounds are less stable than corresponding compounds of other Group IIB elements, e.g., the sulfate and carbonate break down at lower temperatures than other alkaline earth sulfates and carbonates, respectively, mainly due to the stronger polarizability of Be^{2+} (Everest 1973). The compounds discussed above by no means exhaust the possibilities for Be minerals, given the large number of other synthetic compounds, e.g., the oxides $Be_3Al_2O_6$ and $BeAl_6O_{10}$ (Franz and Morteani 2002 and references cited therein), complex beryllium fluorides (e.g., Hahn 1953; Ross 1964; Bell 1972) and alkali boratoberyllates such as $NaBe_2(BO_3)F_2$ (Baidina et al. 1975) and $NaBeB_3O_6$ (Wang et al. 2010). Many of these synthetic compounds are highly soluble in water, so it is not surprising that they would not have been preserved except conceivably as yet undiscovered daughter crystals in fluid or melt inclusions.

Implications

The relative roles of determinism and contingency, together with the potential of other Be minerals implicit in the diversity of synthetic beryllium compounds, have implications regarding Earth's potentially "missing" Be minerals, including the extinction of phases that once existed but are now eroded or dissolved away. It is, of course, more difficult to analyze what is missing from Earth's complex historical record than what is present. Nevertheless, a fuller consideration of what we do not find, but conceivably could find, would add insight to the story of Earth's evolution. And, given the number of potential rare and as yet unknown Be minerals, we suggest that details of Be mineral evolution on other Earth-like planets may differ significantly from those on Earth as a consequence of contingent events.

753

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References:

Agakhanov, A.A., Pautov, L.A., Belakovskiy, D.I., Sokolova, E.V. and Hawthorne, F.C. (2003): Telyushenkoite, $CsNa_6[Be_2(Si,Al,Zn)1_8O_{39}F_2]$ – a new cesium mineral of the leifite group. New Data on Minerals 38, 5-8.

Allen, R.L., Lundstrom, I., Ripa, M. and Christofferson, H. (1996) Facies analysis of a 1.9 Ga, continental margin, back-arc, felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe oxide deposits, Bergslagen region, Sweden. Economic Geology, 91, 979-1008.

Amelin, Yu.V., Larin, A.M. and Tucker, R.D. (1997) Chronology of multiphase emplacement of the Salmi rapakivi granite-anorthosite complex, Baltic Shield: implications for magmatic evolution. Contributions to Mineralogy and Petrology, 127, 353-368.

Andersen, T., Andresen, A. and Sylvester, A.G. (2002) Sveconorwegian crustal underplating in southwestern Fennoscandia: LAM-ICPMS U–Pb and Lu–Hf isotope evidence from granites and gneisses in Telemark, southern Norway. Lithos, 93, 273-287.

Andersen, T., Griffin, W.L. and Sylvester, A.G. (2007) Timing of late- to post-tectonic Sveconorwegian granitic magmatism in South Norway. Norges Geologiske Undersekelse Bulletin, 440,5-18.

Andresen, A. and Tull, J.F. (1986). Age and tectonic setting of the Tysfjord gneiss granite, Efjord, North Norway. Norsk Geologisk Tidsskrift, 66, 69-80.

Arzamastsev, A.A., Arzamastseva, L.V., Travin, A.V., Belyatsky, B.V., Shamatrina, A.M., and Antonov, A.V., Larionov, A.N., Rodionov, N.V. and Sergeev, S.A. (2007) Duration of formation of magmatic system of polyphase Paleozoic alkaline complexes of the Central Kola:U–Pb, Rb–Sr, Ar–Ar data. Doklady Earth Sciences, 413A, 432–436.

Asimov, I. (1954) Sucker Bait. Astounding Science Fiction, 52(6), 8-56; 53(1), 111-139.

Atencio, D. (2000) Type Mineralogy of Brazil. Universidade de Sao Paulo, Instituto de Geociencias: Sao Paulo, Brazil

Atencio, D., Coutinho, J.M.V. and Menezes Filho, L.A.D. (2005) Roscherite-group minerals from Brazil. Axis, 1, Number 6 http://www.mineralogicalrecord.com/journal.asp

Atencio, D., Chukanov, N.V., Coutinho, J.M.V., Menezes Filho, L.A.D., Dubinchuk, V.T. and Möckel, S. (2007) Ruifrancoite, a new Fe^{3+}-dominant monoclinic member of the roscherite group from Galiléia, Minas Gerais, Brazil. Canadian Mineralogist, 45, 1263-1273.

Atencio, D., Matioli, P.A., Smith, J.B., Chukanov, N.V., Coutinho, J.M.V., Rastsvetaeva, R.K. and Möckel, Steffen (2008) Footemineite, the Mn-analog of atencioite, from the Foote Mine, Kings Mountain, Cleveland County, North Carolina, U.S.A., and its relationship with other roscherite-group minerals. American Mineralogist, 93, 1-6.

Aurisicchio, C., De Vito, C., Ferrini, V. and Orlandi, P. (2002) Nb and Ta oxide minerals in the Fonte del Prete granitic pegmatite dike, Island of Elba, Italy. Canadian Mineralogist, 40, 799-814.

Back, M.E & Mandarino, J.A. (2008): Fleischer's Glossary of Mineral Species 2008. The Mineralogical Record Inc., Tucson, Arizona.

Baidina, I.A., Bakakin, V.V., Batsanova, L.R., Pal'chik, N.A. Podberezskaya, N.V. and Solov'eva, L.P. (1975) X-ray structural study of borato-fluoroberyllates with the composition $MBe_2(BO_3)F_2$ (M = Na, K , Rb, Cs). Journal of Structural Chemistry, 15(6), 963-965.

Baidina, I.A., Bakakin, V.V., Podberezskaya, N.V., Alekseev, V.I., Batsanova, L.R. and Pavlyuchenko (1978) Crystal structure of beryllium fluoride borate $Be_2(BO_3)F$. Journal of Structural Chemistry, 19(1), 105-108.

Barbier, J., Grew, E.S., Moore, P.B. and Su, S.-C. (1999) Khmaralite, a new beryllium-bearing mineral related to sapphirine: A superstructure resulting from partial ordering of Be, Al and Si on tetrahedral sites. American Mineralogist, 84, 1650-1660.

Barton, M.D. and Young, S. (2002): Non-pegmatitic deposits of beryllium: mineralogy, geology, phase equilibria and origin. Reviews in Mineralogy and Geochemistry, 50, 591-691.

Batiyeva, I.D. and Bel'kov, I.V. (1984) Sakharyok Alkalic Massif and its rocks and minerals. Kola Filial of the USSR Academy of Sciences, Apatity, Russia [in Russian]

Bayanova, T. and Voloshin, A. (1999) U-Pb Dating of Zircon Megacrysts (8cm) from Amazonite Rand-Pegmatite of Mt. Ploskaya, Baltic Shield. Journal of Conference Abstracts, European Union of Geosciences 10, 4(1), 153.

Bel'kov, I.V. and Denisov, A.P. (1968) Meliphane of the Sakharyok alkalic massif. Materialy po Mineralogii Kol'skogo Poluostrova, 6, 221-224 [in Russian].

Bell, N.A. (1972) Beryllium halides and pseudohalides. Advances in Inorganic Chemistry and Radiochemistry, 14, 255-332.

Belolipetskii, A.P. and Voloshin, A.V. (1996) Yttrium and rare earth element minerals of the Kola Peninsula, Russia. In Jones, J.P., Wall, F. and Williams, C. T. (eds.) Rare Earth Minerals Chemistry, Origin and Ore Deposits, The Mineralogical Society Series 7, 311-326.

Bergstøl, S. and Juve, G. (1988) Scandian ixiolite, pyrochlore and bazzite in granite pegmatite in Tørdal, Telemark, Norway. A contribution to the mineralogy and geochemistry of scandium and tin. Mineralogy and Petrology, 38, 229-243.

Bernhard, F., Hauzenberger, C. and Walter, F. (2008) Pseudosinhalite, magnesiotaaffeite-6*N*'3*S* and magnesiotaaffeite-2*N*'2*S* as replacement products of spinel in dolomite marble from Stubenberg, Styria, Austria. Canadian Mineralogist, 46, 1195-1205.

Birch, W.D., Pring, A. and Foord, E.E. (1995) Selwynite, $NaK(Be,Al)Zr_2(PO_4)_4 .2H_2O$, a new gainesite-like mineral from Wycheproof, Victoria, Australia. Canadian Mineralogist 33, 55-58.

Bleeker, W. (2003) The late Archean record: a puzzle in ca. 35 pieces. Lithos, 71, 99-134.

Bradley, D.C. (2011) Secular trends in the geologic record and the supercontinent cycle, Earth-Science Reviews, 108, 16-33.

Bradley, D.C., McCauley, A., Buchwaldt, R., Shea, E.K. and Bowring, S. (2012) Lithium-cesian-tantalum pegmatites through time, their orogenic context, and relationships to the supercontinent cycle. Geological Society of America Abstracts with Programs. 44(7), 294.

Bradley, D.C., Buchwaldt, R., Shea, E.K., Bowring, S., O'Sullivan, P., Benowitz, J., McCauley, A. and Bradley, L. (2013) Geochronology and orogenic context of northern Appalachian lithium-cesium tantalum pegmatites. Geological Society of America Abstracts with Programs. 45(1), 108.

Breaks, F.W., Selway, J.B. and Tindle A,C. (2005) Fertile peraluminous granites and related rare-element pegmatites, Superior Province of Ontario. Short Course Notes – Geological Association of Canada, 17, 87-125.

Brugger, J. & Gieré, R. (1999): As, Sb, Be and Ce enrichment in minerals from a metamorphosed Fe-Mn deposit, Val Ferrera, eastern Swiss Alps. Canadian Mineralogist **37**, 37-52.

Bulnaev, K.B. (2006) Fluorine–beryllium deposits of the Vitim Highland, western Transbaikal Region: Mineral types, localization conditions, magmatism, and age. Geology of Ore Deposits, 48, 277–289.

Burke, E.A.J. and Lustenhouwer, W.J. (1981) Pehrmanite, a new beryllium mineral from Rosendal pegmatite, Kemiö Island, southwestern Finland. Canadian Mineralogist 19:311-314.

Burns, P.C. Novák, M. and Hawthorne, F.C. (1998) Fluorine-hydroxyl variation in hambergite: a crystal-structure study. Canadian Mineralogist, 33, 1205-1213.

Cámara, F., Oberti, R., Ottolini, L., Della Ventura, G. and Bellatreccia, F. (2008) The crystal chemistry of Li in gadolinite. American Mineralogist, 93, 996-1004.

Campbell, T.J. and Roberts, W.L. (1986): Phosphate minerals from the Tip Top Mine, Black Hills, South Dakota. Mineralogical Record, 17, 237-254.

Cawood, P.A., Hawkesworth, C.J, and Dhuime, B. (2013) The continental record and the generation of continental crust. Geological Society of America Bulletin. 125, 14-32.

Ceciliato, L. (2007) Phenacite and fluorite in Elba pegmatites. Rivista Mineralogica Italiana, 3, 162-164 (in Italian)

Černá, I., Selway, J.B. and Chapman, R. (2002) Paragenesis and origin of secondary beryllophosphates; beryllonite and hydroxylherderite from the BEP granitic pegmatite, southeastern Manitoba, Canada. Canadian Mineralogist, 40, 1339-1345.

Černý, P. (2002) Mineralogy of beryllium in granitic pegmatites. Reviews in Mineralogy and Geochemistry, 50, 405-444.

Černý, P. (2005) The Tanco rare-element pegmatite deposit, Manitoba; regional context, internal anatomy, and global comparisons. Short Course Notes – Geological Association of Canada **17**, 127-158.

Černý, P. and Ercit, T.S. (2005) The classification of granitic pegmatites revisited. Canadian Mineralogist, 43, 2005-2026.

Černý, P., Hawthorne, F.C., Jambor, J.L. and Grice, J.D. (1991) Yttrian milarite. Canadian Mineralogist, 29, 533-541.

Chao, C.-L. (1964) Liberite (Li2BeSiO4), a new lithium-beryllium silicate mineral from the Nanling Ranges,South China. Acta Geol Sinica 44(3):334-342 (in Chinese with English abstract)[Am Mineral 50: 519]

Cheilletz, A., Feraud, G., Giuliani, G. and Ruffet, G. (1993) Emerald dating through $^{40}Ar/^{39}Ar$ step-heating and laser spot analysis of syngenetic phlogopite. Earth and Planetary Science Letters, 120, 473-485.

Chukanov, N.V., Möckel, S., Rastsvetaeva, R.K. and Zadov, A.E. (2003) Greifensteinit aus Sachsen, Österreich, Cornwall, USA, Brasilien and Kasachstan. Lapis, 28(4), 39.

Chukanov, N.V., Rastsvetaeva, R.K., Möckel, S., Zadov, A.E., and Levitskaya, L.A. (2006) The roscherite group and its new representative member atencioite, $Ca_2Fe^{2+}\square Mg_2Fe^{2+}{}_2Be_4(PO_4)_6(OH)_4 \bullet 6H_2O$. New Data on Minerals, 41, 18-25.

Chukanov, N.V., Atencio, D., Zadov, A.E., Menezes Filho, L.A.D., and Coutinho, J.M.V. (2007) Guimarãesite, a new Zn-dominant monoclinic roscherite-group mineral, from Itinga, Minas Gerais, Brazil. New Data on Minerals, 42, 11-15.

Collins, R.F. (1949) Volcanic rocks of northeastern New Mexico. Bulletin of the Geological Society of America, 60, 1017-1040.

Condie, K.C., Bickford, M.E., Aster, R.C., Belousova, E. and Scholl, D.W. (2011) Episodic zircon ages, Hf isotopic composition, and the preservation rate of continental crust. Geological Society of America Bulletin, 123, 951–957.

Conway-Morris, S. (1998) The Crucible of Creation: The Burgess Shale and the Rise of Animals. Oxford: Oxford University Press.

Cooper, M.A., Hawthorne, F.C., Ball, N.A., Černý, P. and Kristiansen, R. (2006) Oftedalite, $(Sc,Ca,Mn^{2+})_2K(Be,Al)_3Si_{12}O_{30}$, a new member of the milarite group from the Heftetjern

914 Pegmatite, Tordal, Norway; description and crystal structure. Canadian Mineralogist, 44,
915 943-949.

916 Cox, D.E., Frazer, B.C., Newnham, R.E. and Santoro, R.P. (1969) Neutron diffraction
917 investigation of the spiral magnetic structure in Cr_2BeO_4. Journal of Applied Physics, 40,
918 1124-1125

919 Currie, K.L., Eby, G.N. & Gittins, J. (1986): The petrology of the Mont Saint Hilaire Complex,
920 southern Quebec; an alkaline gabbro-peralkaline syenite association. Lithos **19**, 65-81.

921 Dahl, P.S. and Foland, K.A.. (2008): Concentric slow cooling of a low-P–high-*T* terrane:
922 Evidence from 1600–1300 Ma mica dates in the 1780–1700 Ma Black Hills Orogen, South
923 Dakota, U.S.A. American Mineralogist, 93, 1215-1229.

924 Della Ventura, G., Di Lisa, G.A., Marcelli, M., Mottana, A. & Paris, E. (1992): Composition and
925 structural state of alkali feldspars from ejecta in the Roman potassic province, Italy ;
926 petrological implications. European Journal of Mineralogy 4, 411-424.

927 Della Ventura, G., Rossi, P., Parodi, G.C. Mottana, A., Raudsepp, M. and Prencipe, M. (2000)
928 Stoppaniite, $(Fe,Al,Mg)_4(Be_6Si_{12}O_{36})*(H_2O)_2(Na,\square)$ a new mineral of the beryl group from
929 Latium (Italy). European Journal of Mineralogy 12, 121-127.

930 Della Ventura, G., Bonazzi, P., Oberti, R. and Ottolini, L. (2002) Ciprianiite and mottanaite-
931 (Ce), two new minerals of the hellandite group from Latium (Italy). American Mineralogist,
932 87, 739-744.

933 DeMark, R.S. (1984) Minerals of Point of Rocks, New Mexico. Mineralogical Record, 15(3),
934 149-156.

935 DeMark, R.S. (1989) Micromounting in New Mexico. Mineralogical Record, 20(1), 57-64.

936 Demartin, F., Gramaccioli, C.M. and Pilati T (1992) A first occurrence of euclase in the Swiss
937 Alps: Discovery and refinement of the crystal structure. Schweizerische Mineralogische und
938 Petrographische Mitteilungen, 72, 159-165.

939 Demartin, F.; Guastoni, A., Pezzotta, F and Picciani (2003): Barylith, Niobophyllit &
940 yttriumreicher Milarit - Neufunde aus den Pegmatiten von Zomba─Malosa, Malawi. Lapis
941 28 (1), 18-21, 58.

942 De Rita, D., Funiciello, R. Rossi, U. and Sposato, A. (1983) Structure and evolution of the
943 Sacrofano-Baccano Caldera, Sabatini volcanic complex, Rome. Journal of Volcanology and
944 Geothermal Research, 17, 219—236.

945 de Roever, E.W.F. & Vrána, S. (1985): Surinamite in pseudomorphs after cordierite in
946 polymetamorphic granulites from Zambia. American Mineralogist **70**, 710-713.

947 Devouard, B. and Devidal, J.L. (2007) Pezzottaite from Myanmar, Gems & Gemology, 43(1),
948 70-72

Downes, P.J. and Bevan, A.W.R. (2002) Chrysoberyl, beryl and zincian spinel mineralization in granulite-facies Archaean rocks at Dowerin, Western Australia. Mineralogical Magazine, 66**,** 985-1002.

Downs, R. T. (2006) The RRUFF Project: an integrated study of the chemistry, crystallography, Raman and infrared spectroscopy of minerals. Program and Abstracts of the 19th General Meeting of the International Mineralogical Association in Kobe, Japan. O03-13.

Dunn, P.J. and Wight, W. (1976) Green gem herderite from Brazil. Journal of Gemmology, 15, 27-28.

Dunn, P.J., Peacor, D.R., Grice, J.D., Wicks, F.J. and Chi, P.H. (1990) Wawayandaite, a new calcium manganese beryllium boron silicate from Franklin, New Jersey. American Mineralogist, 75, 405-408.

Eby, G.N. (1984) Geochronology of the Monteregian Hills alkaline igneous province, Quebec. Geology, 12, 468-470.

Eby, G.N., Roden-Tice, M., Krueger, H.L., Ewing, W., Faxon, E.H. and Woolley (1995) Geochronology and cooling history of the northern part of the Chilwa Alkaline Province, Malawi. Journal of African Earth Sciences, 20, 275-288.

Embrey, P.G. (1978) Fourth supplementary list of British minerals. Mineralogical Magazine, 42, 170-177

Engell, J. (1971) Beryllium mineralization in the Ilímaussaq intrusion, South Greenland, with description of a field beryllometer and chemical methods. Grønlands Geologiske Undersøgelser Rapport, 33, 1-40.

Evensen, J.M. & London, D. (2002): Experimental silicate mineral/melt partition coefficients for beryllium, and the beryllium cycle from migmatite to pegmatite. Geochimica et Cosmochimica Acta **66,** 2239–2265.

Everest, D.A. (1973) 9. Beryllium. In: Bailar, J.C., Jr., Emeléus, H.J., Nyholm, R. and Trotman-Dickenson, A.F. (eds) Comprehensive Inorganic Chemistry, Volume 1 H, Noble Gases, Group IA, Group IIA, Group IIIB, C and Si, p. 531-590) Pergamon, Oxford.

Falster, A.U., Simmons, W.B. and Webber, K.L. (2001a): The mineralogy and geochemistry of the Animikie Red Ace pegmatite, Florence County, Wisconsin. Recent Research Developments in Mineralogy 1, 7-67.

Falster, A.U., Simmons, W.B. and Webber, K.L. (2001b): Unorthodox compositional trends in columbite-group minerals from the Animikie Red Ace pegmatite, Wisconsin, USA. Journal of the Czech Geological Society **46**, 69-79.

Fernandez, A., Schreurs, G., Villa, I.M., Huber, S. and Rakotondrazafy, M. (2003) Age constraints on the tectonic evolution of the Itremo region in Central Madagascar. Precambrian Research, 123, 87–110.

985 Fershtater, G.B. Krasnobaev, A.A., Bea, F., Montero, P. and Borodina, N.S. (2007) Geodynamic
986 settings and history of the Paleozoic intrusive magmatism of the central and southern Urals:
987 Results of zircon dating. Geotectonics, 41, 465-486.

988 Flink, G. (1917) Contribution to Swedish mineralogy. 105. Harstigite from Harstigsgrufvan.
989 Arkiv för Kemi, Mineralogi och Geologi, 6, 49-51 (in Swedish).

990 Foord, E.E., Gaines, R.V., Crock, J.G., Simmons, W.B., Jr. and Barbosa, C.P. (1986)
991 Minasgeraisite, a new member of the gadolinite group from Minas Gerais, Brazil. American
992 Mineralogist, 71, 603-607.

993 Foord, E.E., Brownfield, M.E., Lichte, F.E., Davis, A.M. and Sutley, S. J. (1994) Mccrillisite,
994 $NaCs(Be,Li)Zr_2(PO_4)_4.1\text{-}2H_2O$, a new mineral species from Mount Mica, Oxford County,
995 Maine, and new data for gainesite. Canadian Mineralogist, 32, 839-842.

996 Fornaseri, M. (1985) Geochronology of volcanic rocks from Latium (Italy) Rendiconti della
997 Società Italiana di Mineralogia e Petrologia, 40, 73-106.

998 Franz, G. and Morteani, G. (2002) Be-Minerals: Synthesis, Stability, and Occurrence in
999 Metamorphic Rocks. Reviews in Mineralogy and Geochemistry, 50, 551-589.

1000 Frondel, C. and Ito, J. (1968) Synthesis of the scandium analogue of beryl. American
1001 Mineralogist, 53, 943-953.

1002 Gastil, G. (1960) The distribution of mineral dates in time and space. American Journal of
1003 Science, 258, 1-35.

1004 Gatta, G.D., Rotiroti, N., McIntyre, G.J., Guastoni, A. and Nestola, F. (2008) New insights into
1005 the crystal chemistry of epididymite and eudidymite from Malosa, Malawi: A single-crystal
1006 neutron diffraction study. American Mineralogist, 93, 1158-1165.

1007 Gilbert, L.A. and Foland, K.A. (1986) The Mont Saint Hilaire plutonic complex; occurrence of
1008 excess (super 40) Ar and short intrusion history. Canadian Journal of Earth Sciences, 23,
1009 948-958.

1010 Ginzberg, A.I. and Shatskaya, V.T. (1966) Hypergene beryllium phosphates and conditions of
1011 their formation. In: Geology of Rare-Element Deposits, 30, 101-117. Nedra, Moscow (in
1012 Russian).

1013 Giuliani, G., Cheilletz, A. and Vidal, P. (1995) La datation isotopique des gemmes. Analusis
1014 Magazine, 23(1), 34-37.

1015 Giuseppetti, G., Mazzi, F. , Tandini, C. Larsen, A.O., Åsheim, A. and Raade, G. (1990)
1016 Berborite polytypes. Neues Jahrbuch für Mineralogie Abhandlungen, 162, 101-116.

1017 Gjessing, L., Larsson, T. and Major, H. (1943) Isomorphous substitute for $Al^{\cdots}$ in the compound
1018 Al_2BeO_4. Norsk Geologisk Tidskrift, 22, 92-99.

Goldfarb, R.J., Groves, D.I. and Gardoll, S. (2001) Orogenic gold and geologic time: a global synthesis. Ore Geology Reviews, 18, 1–75.

Goodenough, K.M., Upton, B.G.J. and Ellam, R.M. (2002) Long-term memory of subduction processes in the lithospheric mantle: evidence from the geochemistry of basic dykes in the Gardar Province of South Greenland. Journal of the Geological Society, London, 159, 705–714.

Goodenough, K.M., Krabbendam, M., Shaw, R.A. and Crowley, Q.G. (2013) Making and breaking Columbia (Nuna): formation of a critical metal province? A North Atlantic view. Building Strong Continents, 2-4 September 2013 University of Portsmouth, UK Programme and Abstracts, p. 44.

Gould, S.J. (1989) Wonderful Life. The Burgess Shale and the Nature of History. Norton, New York.

Gould, S.J. (2002) The Structure of Evolutionary Theory. Cambridge, Massachusetts: Belknap Press.

Grauch, R.I.; Lindahl, I., Evans, H.T., Jr., Burt, D.M., Fitzpatrick, J.J., Foord, E.E., Graff, P.R. & Hysingjord, J. (1994): Høgtuvaite, a new beryllium member of the aenigmatite group from Norway, with new X-ray data on aenigmatite. Canadian Mineralogist **32**, 439-448.

Grew, E. S. (2002a) Mineralogy, petrology and geochemistry of beryllium: An introduction and list of beryllium minerals. Reviews in Mineralogy and Geochemistry, 50, 487-549.

Grew, E. S. (2002b) Beryllium in metamorphic environments (emphasis on aluminous compositions). Reviews in Mineralogy and Geochemistry, 50, 487-549.

Grew, E., and Hazen, R. M. (2009): Evolution of the minerals of beryllium, a quintessential crustal element [Abstract]. Geological Society of America Abstracts with Programs, 41(7), 99.

Grew, E. and Hazen, R.M. (2010a) Evolution of boron minerals: Has early species diversity been lost from the geological record? Geological Society of America Abstracts with Programs, 42(5), 92.

Grew, E., and Hazen, R. M. (2010b): Evolution of the minerals of beryllium, and comparison with boron mineral evolution [Abstract]. Geological Society of America Abstracts with Programs, 42(5), 199.

Grew, E.S. and Hazen, R.M. (2013) Evolution of the minerals of beryllium. Stein Magasin for Populærgeologi. Særhefte 1 Roy Kristiansen 70 År, 4-19.

Grew, E. S., Belakovskiy, D. I., Fleet, M. E., Yates, M. G., McGee, J. J., and Marquez, N. (1993) Reedmergnerite and associated minerals from peralkaline pegmatite, Dara-i-Pioz, southern Tien Shan, Tajikistan. European Journal of Mineralogy, 5, 971-984.

Grew, E. S., Yates, M. G., Belakovskiy, D. I., Rouse, R. C., Su, S.-C, and Marquez, N. (1994) Hyalotekite from reedmergnerite-bearing alkali pegmatite, Dara-i-Pioz, Tajikistan and from Mn skarn, Långban, Värmland, Sweden: a new look at an old mineral. Mineralogical Magazine, 58, 285-297

Grew, E.S., Yates, M.G., Barbier, J., Shearer, C.K., Sheraton, J.W., Shiraishi, K. and Motoyoshi, Y. (2000): Granulite-facies beryllium pegmatites in the Napier Complex in Khmara and Amundsen Bays, western Enderby Land, East Antarctica. Polar Geoscience, 13, 1-40.

Grew, E.S., Barbier, J., Britten, J.F., Yates, M.G., Polyakov, V.O., Shcherbakova, E.P., Hålenius, U. and Shearer, C.K. (2005) Makarochkinite, $Ca_2Fe^{2+}{}_4Fe^{3+}TiSi_4BeAlO_{20}$, a new beryllosilicate member of the aenigmatite-sapphirine-surinamite group from the Il'men Mountains (southern Urals), Russia. American Mineralogist, 90, 1402-1412.

Grew, E.S., Yates, M.G., Shearer, C.K., Hagerty, J.J., Sheraton, J.W., and Sandiford, M. (2006) Beryllium and other trace elements in paragneisses and anatectic veins of the ultrahigh-temperature Napier Complex, Enderby Land, East Antarctica: The role of sapphirine. Journal of Petrology, 47, 859-882.

Grew, E.S., Barbier, J., Britten, J.F., Hålenius, U. and Shearer, C.K. (2007) The crystal chemistry of welshite, a non-centrosymmetric (*P*1) aenigmatite-sapphirine-surinamite group mineral. American Mineralogist, 92, 80-90.

Grice, J.D. (2010) The role of beryllium in beryllosilicate mineral structures and zeolite formation. Canadian Mineralogist, 48, 1493-1518.

Grice, J.D. and Kristiansen, R. (2013) Hydrogen in the gugiaite structure. Geological Association of Canada, Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, Manitoba.
http://gac.esd.mun.ca/gac_2013/search_abs/sub_program.asp?sess=98&form=10&abs_no=12

Grice, J.D. and Robinson, G.W. (1984) Jeffreyite, $(Ca,Na)_2(Be,Al)Si_2(O,OH)_7$, a new mineral species and its relation to the melilite group. Canadian Mineralogist, 22, 443-446.

Grice, J.D., Peacor, D. R., Robinson, G.W., van Velthuizen, J., Roberts, W.L., Campbell, T.J. and Dunn, P.J. (1985) Tiptopite $(Li,K,Na,Ca,)_8Be_6(PO_4)\ )_6(OH)_4$, a new mineral species from the Black Hills, South Dakota. Canadian Mineralogist, 23, 43-46.

Grice, J.D., Rowe, R., Poirier, G., Pratt, A. and Francis, J. (2009) Bussyite-(Ce), a new beryllium silicate mineral species from Mont Saint-Hilaire, Quebec. Canadian Mineralogist, 47, 193-204.

Grigor'yev, N.A. (1963) Glucine—a new beryllium mineral. Zapiski Vsesoyuznogo Mineralogicheskogo Obshchestva, 92, 691-696 (in Russian).

Grundmann, G., and Morteani, G. (1989) Emerald mineralization during regional metamorphism: the Habachtal (Austria) and Leydsdorp (Transvaal, South Africa) deposits. Economic Geology, 84, 1835-1849.

Guastoni, A., Demartin, F., and Pezzotta, F (2004): Mineralogische Neuigkeiten aus Zomba, Malawi (2003). Lapis 29 (1), 37-38, 58.

Guastoni, A., Diella, V. and Pezzotta, F. (2008) Vigezzite and associated oxides of Nb–Ta from emerald-bearing pegmatites of the Vigezzo Valley, western Alps. Italy. Canadian Mineralogist, 46, 619-633.

Gusarov, V.V. and Semin, Ye.G. (1992) A diagram of the state of the subsolidus domain of the $BeAl_2O_4$–$[BeFe_2O_4]$ quasi-binary system. Zhurnal Neorganicheskoy Khimii, 37, 2092-2096 (in Russian).

Habel, A. and Habel, M. (2009) Minasgeraisit-(Y) aus dem Krennbruch in Matzersdorf/Tittling. MineralienWelt, 20(5), 51-53.

Hahn, T. (1953) Modellbeziehungen zwischen Silikaten und Fluoberyllaten. Neues Jahrbuch für Mineralogie Abhandlungen, 86, 1-65.

Harlow, G.E. and Hawthorne, F.C. (2008) Herderite from Mogok, Myanmar, and comparison with hydroxyl-herderite from Ehrenfriedersdorf, Germany. American Mineralogist, 93, 1545–1549.

Harris, P.D., Robb, L.J. and Tompkinson, M.J. (1995) The nature and structural setting of rare-element pegmatites along the northern flank of the Barberton greenstone belt, South Africa. South African Journal of Geology, 98(1), 82-94.

Hawthorne, F.C. (2002) The use of end-member charge-arrangements in defining a new mineral species and heterovalent substitutions in complex minerals. Canadian Mineralogist, 40, 699-710.

Hawthorne, F.C. (2013) MSA Roebling Medal Lecture: Toward a basis for theoretical mineralogy. Geological Society of America Abstracts with Programs, 45(7), 625.

Hawthorne, F.C. and Huminicki, D.M.C. (2002) The crystal chemistry of beryllium. Reviews in Mineralogy and Geochemistry, 50, 333-403.

Hawthorne, F.C., Cooper, M.A., Simmons, W.B., Falster, S.U., Laurs, B.M., Armbruster, T., Rossman, G.R., Peretti, A., Günter, D., and Grobéty, B. (2004) Pezzottaite, $Cs(Be_2Li)Al_2Si_6O_{18}$, a spectacular new beryl-group mineral from the Sakavalana Pegmatite, Fianarantsoa Province, Madagascar. Mineralogical Record, 35, 369-378.

Hazen, R. M., and Eldredge, N. (2010): Themes and variations in complex systems. Elements **6**, 43-46.

Hazen, R. M., and Ferry, J. M. (2010): Mineral evolution: Mineralogy in the fourth dimension. Elements **6**, 9-12.

Hazen, R. M., Papineau, D., Bleeker, W., Downs, R. T., Ferry, J. M., McCoy, T. J., Sverjensky, D. A., and Yang, H. (2008): Mineral evolution: American Mineralogist **93**, 1693-1720.

Hazen, R. M., Ewing, R. C., & Sverjensky, D. A. (2009): Evolution of uranium and thorium minerals: American Mineralogist **94**, 1293-1311.

Hazen, R. M., Bekker, A., Bish, D. L., Bleeker, W., Downs, R. T., Farquhar, J., Ferry, J. M., Grew E. S., Knoll, A. H., Papineau, D. F., Ralph, J. P., Sverjensky, D. A., and Valley, J. W. (2011): Needs and opportunities in mineral evolution research: American Mineralogist, **96**, 953-963.

Hazen, R. M., Golden, J., Downs, R. T., Hystad, G., Grew, E. S., Azzolini, D., and Sverjensky, D. A. (2012) Mercury (Hg) mineral evolution: A mineralogical record of supercontinent assembly, changing ocean geochemistry, and the emerging terrestrial biosphere: American Mineralogist **97**, 1013-1042.

Heeremans, M., Larsen, B.T. and Stel, H. (1996) Paleostress reconstruction from kinematic indicators in the Oslo Graben, southern Norway: new constraints on the mode of rifting. Tectonophysics, 266, 55-79.

Heeremans, M., Faleide, J.I. and Larsen, B.T. (2004) Late Carboniferous–Permian of NW Europe: an introduction to a new regional map. In Wilson, M., Neumann, E.-R., Davies, G.R., Timmerman, M.J., Heeremans, M. and Larsen, B.T. (eds). Permian-Carboniferous Magmatism and Rifting in Europe. Geological Society of London, Special Publications, 223, 75-88..

Hoffman, P.F. (1997) Tectonic genealogy of North America. In van der Pluijm, B.A., and Marshak, S., eds., Earth Structure: An Introduction to Structural Geology and Tectonics: New York, McGraw-Hill, p. 459–464.

Hokada, T. and Harley, S.L. (2004) Zircon growth in UHT leucosome: constraints from zircon-garnet rare earth elements (REE) relations in Napier Complex, East Antarctica. Journal of Mineralogical and Petrological Sciences, 99, 180-190.

Holtstam, D. and Andersson, U.B. (2007) The REE minerals of the Bastnäs-type deposits, south-central Sweden. Canadian Mineralogist, 45, 1073-1114.

Holtstam, D. and Langhof, J., eds. (2007): Långban The Mines, their Minerals, Geology and Explorers. Swedish Museum of Natural History, Raster Förlag.

Horváth, L. and Horváth-Pfenninger, E. (2000) Die Mineralien des Mont Saint-Hilaire. Lapis, 25 (7-8), 23-61.

Huang, Y., Du, S. and Zhou, X. (1988) Hsianghualing rocks, mineral deposits and minerals. Beijing Science and Technology Publishing Bureau, Beijing (in Chinese with English summary)

Huminicki, D.M.C. and Hawthorne, F.C. (2000) Refinement of the crystal structure of väyrynenite. Canadian Mineralogist, 38, 1425-1432.

Hurlbut, C.S., Jr. (1937) Aminoffite, a new mineral from Långban. Geol Fören Förhandl 59, 290-292.

Husdal, T. (2008) The minerals of the pegmatites within the Tysfjord granite, northern Norway. Norsk Bergverksmuseum, Skrift, 38, 5-28.

Husdal, T. (2011): Tysfjordgranittens pegmatitter. Stein **38**(4), 4-35 (in Norwegian).

Jacobson, M.I., Calderwood, M.A. and Grguric, B.A. (2007) Guidebook to the Pegmatites of Western Australia. Hesperian Press, Carlisle, Western Australia.

Johnson, S.P., De Waele, B. & Liyungu, K.A. (2006): U/Pb sensitive high-resolution ion microprobe (SHRIMP) zircon geochronology of granitoid rocks in eastern Zambia; terrane subdivision of the Mesoproterozoic southern Irumide Belt. Tectonics 25, TC6004, DOI:10.1029/2006TC001977.

Jonsson, E. (2004): Fissure-hosted mineral formation and metallogenesis in the Långban Fe-Mn-(Ba-As-Pb-Sb…) deposit, Bergslagen, Sweden. Meddelanden från Stockholms Universitets Institution för Geologi och Geokemi 318.

Juve, G. and Bergstøl, S. (1988) Cesian bazzite in granite pegmatite in Tørdal, Telemark, Norway. Mineralogy and Petrology, 43, 131-136.

Kalsbeek, N. and Rønsbo, J.G. (1992) Refinement of the vinogradovite structure, positioning of Be and excess Na. Zeitschrift für Kristallographie 200, 237-245

Kampf, A.R., Dunn, P.J. and Foord, E.E. (1992) Parafransoletite, a new dimorph of fransoletite from the Tip Top Pegmatite, Custer, South Dakota. American Mineralogist, 77, 843-847.

King, V.T. and Foord, E.E. (1994) Mineralogy of Maine. Volume 1: Descriptive Mineralogy. Maine Geological Survey, Augusta, Maine

Konev, A.A, Vorob'yev, Ye.I., Sapozhnikov, A.N., Piskunova, L.F. and Ushchapovskaya, Z.F. (1995) Odintsovite – $K_2Na_4Ca_3Ti_2Be_4Si_{12}O_{38}$ – a new mineral (Murunskiy Massif) Zapiski Vserossiiskogo Mineralogicheskogo Obshchestva 124(5), 92-96 (in Russian)

Kopchenova, Ye.V. and Sidorenko, G.A. (1962) Bearsite—the arsenic analogue of moraesite. Zapiski Vsesoyuznogo Mineralogicheskogo Obshchestva, 91, 442-446 (in Russian).

Kristiansen, R. (1994) Two new minerals for Norway- manganokolumbite and hingganite-(Yb). Stein 21(2), 88-93 (in Norwegian)

Krivovichev, S.V. (2013) Structural complexity of minerals: information storage and processing in the mineral world. Mineralogical Magazine, 77, 275-326.

Krivovichev, S.V., Yakovenchuk, V.N., Armbruster, T., Mikhailova, Y. and Pakhomovsky, Ya. K. (2004) Clinobarylite, $BaBe_2Si_2O_7$: structure refinement, and revision of symmetry and physical properties.. Neues Jahrbuch für Mineralogie Monatshefte, 2004, 373-384..

Krogstad, E.J. and Walker, R.J. (1994) High closure temperatures of the U-Pb system in large apatites from the Tin Mountain pegmatite, Black Hills, South Dakota, USA. Geochimica et Cosmochimica Acta, 58, 3845-3853.

Krumrei, T.V., Villa, I.M., Marks, M.A.W. & Markl, G. (2006): A $^{40}Ar/^{39}Ar$ and U/Pb isotopic study of the Ilímaussaq complex, South Greenland: Implications for the ^{40}K decay constant and for the duration of magmatic activity in a peralkaline complex. Chemical Geology **227**, 258-273.

Lahti, S.I. (1989) The granitoids and pegmatites of the Eräjärvi area. In, Lahti, S.I., ed. Excursion C1, Late orogenic and synorogenic Svecofennian granitoids and associated pegmatites of southern Finland. Opas – Geologian Tutkimuskeskus, 26, 26-36.

Langhof, J., Holtstam, D. and Gustafsson, L. (2000) Chiavennite and zoned genthelvite-helvite as late-stage minerals of the Proterozoic LCT pegmatites at Utö, Stockholm, Sweden. GFF, 122(2), 207-212.

Larsen, A.O., editor (2010) The Langesundfjord. History · Geology · Pegmatites · Minerals. Bode Verlag, Salzhemmendorf, Germany.

Larsen, A.O., Kolitsch, U., Gault, R.A. and Geister, G. (2010) Eirikite, a new mineral species of the leifite group from the Langesundsfjord district, Norway. European Journal of Mineralogy, 22, 875-880.

Larsen, B.T., Olauseen, S., Sundvoll, B. and Heeremans, M. (2008) The Permo-Carboniferous Oslo Rift through six stages and 65 million years. Episodes, 31(1), 52-58.

Lauretta, D.S. (2011) A cosmochemical view of the solar system. Elements, 7, 11-16.

Lauretta, D.S. and Lodders, K. (1997) The cosmochemical behavior of beryllium and boron. Earth and Planetary Science Letters, 146, 315-327.

Laurs, B.M., Dilles, J.H., Wairrach, Y., Kausar, A.B. & Snee, L.W. (1998): Geological setting and petrogenesis of symmetrically zoned, miarolitic granitic pegmatites at Stak Nala, Nanga Parbat-Haramosh Massif, northern Pakistan.Canadian Mineralogist **36,** 1-47.

Lengauer, C.L., Hrauda, N., Kolitsch, U., Krickl, R. & Tillmanns, E. (2009): Friedrichbeckeite, $K(\square_{0.5}Na_{0.5})_2(Mg_{0.8}Mn_{0.1}Fe_{0.1})_2(Be_{0.6}Mg_{0.4})_3[Si_{12}O_{30}]$, a new milarite-type mineral from the Bellerberg volcano, Eifel area, Germany. Mineralogy and Petrology **96**, 221-232.

1225 Lin, J.-C. and Guggenheim, S. (1983) The crystal structure of a Li,Be-rich brittle mica: a
1226 dioctahedral-trioctahedral intermediate. American Mineralogist, 68, 130-142.

1227 Lindberg, M.L. and Murata, K.J. (1953) Faheyite, a new phosphate mineral from the Sapucaia
1228 pegmatite mine, Minas Gerais, Brazil. American Mineralogist, 38, 263-270.

1229 Lindroos, A., Romer, R.L. Ehlers, C. and Alviola, R. (1996) Late-orogenic Svecofennian
1230 deformation in SW Finland constrained by pegmatite emplacement ages. Terra Nova, 8,
1231 567-574.

1232 Lindsey, D.A. (1977) Epithermal beryllium deposits in water-laid tuff, western Utah. Economic
1233 Geology, 72, 219-232.

1234 Lodders, K. (2003) Solar system abundances and condensation temperatures of the elements.
1235 Astrophysical Journal, 591, 1220-1247.

1236 Lodders, K. (2010) Solar system abundances of the elements. In: A. Goswami and B.E. Reddy
1237 (eds.), Principles and Perspectives in Cosmochemistry. Astrophysics and Space Science
1238 Proceedings. Springer-Verlag, Berlin Heidelberg, p. 379-417.

1239 London, D. and Evensen, J.M. (2002): Beryllium in silicic magmas and the origin of beryl-
1240 bearing pegmatites. Reviews in Mineralogy and Geochemistry, 50, 445-486.

1241 Loomis, T.A. and Campbell, T.J. (2002) The Tip Top pegmatite: A historical review and
1242 mineralogical update. Matrix, 10(3), 138-146.

1243 Lussier, A.J. and Hawthorne, F.C. (2011) Short-range constraints on chemical and structural
1244 variations in bavenite. Mineralogical Magazine, 75, 213-239.

1245 Lyalina, L.M., Savchenko, Ye. E., Selivanova, E.A. and Zozulya, D.R. (2009) Behoite and
1246 mimetite from the Sakharyok alkalic massif (Kola Peninsula). Zapiski Rossiykogo
1247 Mineralogicheskogo Obshchestvo, 138, 118-126 [in Russian; English abstract].

1248 Magnusson, N.H. (1930) The iron and manganese ores of the Långban district. Sveriges Geol
1249 Undersökning Avhandlingar och Uppsatser, Series Ca, no. 23, 1-111 (in Swedish with
1250 extended English summary).

1251 Mahler, D.L., Ingram, T., Revell, L.J. and Losos, J.B. (2013) Exceptional convergence on the
1252 macroevolutionary landscape in island lizard radiations. Science, 341-292-295.

1253 Maphalala, R.M. and Kröner, A. Pb-Pb single zircon ages for the younger Archaean granitoids of
1254 Swaziland, southern Africa. 16th International Colloquium on African Geology, Extended
1255 Abstracts, 14-16 September, 1993, 2, 201-206.

1256 Markl, G. (2001) Stability of Na-Be minerals in late-magmatic fluids of the Ilímaussaq alkaline
1257 complex, South Greenland. Geology of Greenland Survey Bulletin, 190, 145-158.

McCreath, J.A., Finch, A.A., Simonsen, Donaldson, C.H. and Armour-Brown, A. (2012) Independent ages of magmatic and hydrothermal activity in alkaline igneous rocks: The Motzfeldt Centre, Gardar Province, South Greenland. Contributions to Mineralogy and Petrology, 163, 967–982.

McLemore, V.T., Lueth, V.W., Pease, T.C. and Guilinger, J.R. (1996) Petrology and mineral resources of the Wind Mountain laccolith, Cornudas Mountains, New Mexico and Texas. Canadian Mineralogist, 34, 335-347.

Mereiter, K., Niedermayr, G. and Walter, F. (1994) Uralolite, $Ca_2Be_4(P0_4)_3(OH)_3{\cdot}5H_2O$: new data and crystal structure. European Journal of Mineralogy, 6, 887-896.

Meyer, C. (1981) Ore-forming processes in the geologic history of the Earth. Economic Geology 75th Anniversary Volume, 6-41.

Meyer, C. (1985) Ore metals through geologic history. Science, 227, 1421-1428.

Mihajlović T, Lengauer CL, Ntaflos T, Kolitsch U, Tillmanns E (2004) Two new minerals, rondorfite, $Ca_8Mg[SiO_4]_4Cl_2$, and almarudite, $K(\square, Na)_2(Mn,Fe,Mg)_2(Be,Al)_3[Si_{12}O_{30}]$, and a study on iron-rich wadalite, $Ca_{12}[(Al_8Si_4Fe_2)O_{32}]Cl_6$, from the Bellerberg (Bellberg) volcano, Eifel, Germany. Neues Jahrbuch für Mineralogie Abhandlungen 179, 265–294

Miller, R.R., Heaman, L.M. and Birkett, T.C. (1997) U–Pb zircon age of the Strange Lake peralkaline complex: implications for Mesoproterozoic peralkaline magmatism in north-central Labrador. Precambrian Research, 81, 67-82.

Mills, S.J., Hatert, F., Nickel, E.H., & Ferraris, G. (2009) The standardization of mineral group hierarchies: application to recent nomenclature proposals. European Journal of Mineralogy **21**, 1073-1080.

Minakawa, T. and Yoshimoto, Y. (1998) Gugiaite from the Yuge Island, Ehime Prefecture. Abstracts of the Annual Meeting of the Mineralogical Society of Japan 1997, Mineralogical Journal, 20(1), 27-28.

Miyawaki, R., Matsubara, S., Yokoyama, K. and Okamoto, A. (2007) Hingganite-(Ce) and hingganite-(Y) from Tahara, Hirukawa mura, Gifu Prefecture, Japan: The description on a new mineral species of the Ce-analogue of hingganite-(Y) with a refinement of the crystal structure of hingganite-(Y). Journal of Mineralogical and Petrological Sciences, 102, 1-7.

Montoya, J.W., Baur, G.S. and Wilson, S.R. (1964) Mineralogical investigation of beryllium-bearing tuff, Honeycomb Hills, Juab County, Utah. U. S. Bureau of Mines Report of Investigations, 6408, 1-11

Moore, P.B., Araki, T. Steele, I.M., Swihart, G.H. and Kampf, A.R. (1983) Gainesite, sodium zirconium, beryllophosphate; a new mineral and its crystal structure. American Mineralogist, 68, 1022-1028.

Morra, G., Seton, M., Quevedo, L. and Müller, R.D. (2013) Organization of the tectonic plates in the last 200 Myr. Earth and Planetary Science Letters, 373, 93–101.

Morteani, G., Preinfalk, C. & Horn, A.H. (2000): Classification and mineralization potential of the pegmatites of the eastern Brazilian pegmatite province. Mineralium Deposita **35**, 638-655.

Mullis, J., Dubessy, J., Poty, B. and O'Neil, J. (1994) Fluid regimes during late stages of continental collision; physical, chemical, and stable isotope measurements of fluid inclusions in fissure quartz from a geotraverse through the Central Alps, Switzerland. Geochimica et Cosmochimica Acta, 58, 2239-2267.

Nash, J.T., Granger, H.C., and Adams, S.S. (1981) Geology and concepts of genesis of important types of uranium deposits. Economic Geology, 75th Anniversary Volume, 63-116.

Nazarova, A.S., Solntseva, L.S. and Yurkina, K.V. (1975) Babefphite. Trudy Mineral Muz Akad Nauk SSSR, 24, 191-195 (in Russian).

Nefedov, Ye.I. (1967) Berborite, a new mineral. Doklady Akademii Nauk SSSR Earth Science Sections, 174, 114-117.

Nizamoff, J.W., Falster, A.U., Francis, C.A., Lange, D.E., Menezes, L. and Simmons, W.B. (2006) New Data on Roscherite-Group Minerals from New England and South Dakota, USA and Brazil. The MP^2 Research Group Abstracts. http://pegmatology.uno.edu/abstract/abstniz.html

Normand, C. and Williams, A.E. (2007) Physicochemical conditions and timing of rodingite formation: evidence from rodingite-hosted fluid inclusions in the JM Asbestos mine, Asbestos, Québec. Geochemical Transactions, 8: 11. doi:10.1186/1467-4866-8-11

Norton, J.J. and Redden, J.A. (1990): Relations of zoned pegmatites to other pegmatites, granite, and metamorphic rocks in the southern Black Hills, South Dakota. American Mineralogist 75, 631-655.

Novák, M., Burns, P.C. and Morgan, G.B. VI (1998) Fluorine variation in hambergite from granitic pegmatites. Canadian Mineralogist, 36, 441-446.

Novák, M., Kadlec, T. and Gadas, P. (2013) Geological position, mineral assemblages and contamination of granitic pegmatites in the Moldanubian Zone, Czech Republic; examples from the Vlastějovice region. Journal of Geosciences, 58, 21–47.

Nysten, P. (1996) Paragenetic setting and crystal chemistry of milarites from Proterozoic granitic pegmatites in Sweden. Neues Jahrbuch für Mineralogie Monatshefte, 1996, 564-576.

Nysten, P. and Gustafsson, L. (1993) Beryllium phosphates from the Proterozoic granitic pegmatite at Norro, southern Stockholm Archipelago, Sweden. Source:Geologiska Föreningens i Stockholm Förhandlingar, 115, 159-164

Orlova, M.P. (1987) Recent findings on the geology of the Malyy Murun alkalic pluton. International Geology Review, 30, 945-953.

Palme, H and O'Neill, H. St. C. (2005): Cosmochemical estimates of mantle composition. In: Carlson, R.W., ed., The Mantle and Core, Vol. 2, Holland, H.D. & Turekian, K.K., eds., Treatise on Geochemistry, p. 1-38. Elsevier-Pergamon, Oxford.

Paque, J.M., Burnett, D.S. and Chaussidon, M. (2003) USNM 3515: An Allende CAI with Li isotopic variations. Abstracts of Papers Submitted to the Lunar and Planetary Science Conference, 2003, Vol. 34, no. 1401, 2 pages.

Pautov, L.A., Popov, M.P., Yerokhin, Yu.V., Khiller, V.V. and Karpenko,V.Yu. (2012) Mariinskite BeCr2O4 ─ a new mineral, the chromium analogue of chrysoberyl. Zapiski Rossiiskogo Mineralogicheskogo Obshchesva, 141(6), 43-62 (in Russian).

Peacor, D.R., Dunn, P.J., Roberts, W.L., Campbell, T.J. and Newbury, D. (1983) Fransoletite, a new calcium beryllium phosphate from the Tip Top Pegmatite, Custer, South Dakota. Bulletin de Minéralogie, 106, 499-503.

Pedrosa-Soares, A.C., de Campos, C.P., Noce, C., Silva, L.C., Novo, T., Roncato, J., Medeiros, S., Castañeda, C., Queiroga, G., Dantas, E., Dussin, I., and Alkmim, F. (2011) Late Neoproterozoic-Cambrian granitic magmatism in the Aracuai Orogen (Brazil), the Eastern Brazilian pegmatite province and related mineral resources. In Sial, A.N., Bettencourt, J.S., de Campos, C.P. and Ferreira, V.P. (editors) Granite-related ore deposits. Geological Society Special Publications, 350, 25-51.

Pekov, I.V. (1998) Minerals First Discovered on the Territory of the Former Soviet Union. Ocean Pictures, Moscow

Pekov, I.V. (2000) Lovozero Massif: History, Pegmatites, Minerals. Ocean Pictures Ltd., Moscow.

Pekov, I.V., Chukanov, N.V., Larsen, A.O., Merlino, S., Pasero, M., Pushcharovsky, D.Yu., Ivaldi, G., Zadov, A.E., Grishin, V.G., Åsheim, A.,, Taftø, J., and Chistyakova, N.I. (2003) Sphaerobertrandite, $Be_3SiO_4(OH)_2$: new data, crystal structure and genesis. European Journal of Mineralogy, 15, 157-166.

Pekov, I.V., Zubkova, N.V.,Chukanov, N.V., Agakhanov, A.A., Belakovskiy, D.I., Horváth, L., Filinchuk, Y.E., Gobechiya, E.R., Pushcharovsky, D.Yu., and Rabadanov, M.Kh. (2008) Niveolanite, the first natural beryllium carbonate, a mineral species from Mont Saint-Hilaire, Quebec. Canadian Mineralogist, 46, 1343-1354.

Pekov, I.V., Voloshin, A.V., Pushcharovskii, D.Yu., Rastsvetaeva, R.K, Chukanov, N.V. and Belakovskii, D.I. (2000) New data on calcybeborosilite-(Y) $(REE,Ca)_2(B,Be)_2[SiO_4]2(OH,O)_2$, Moscow University Geology Bulletin, 55(2), 62-70.

Pekov, I.V., Yakubovich, O.V, Massa, W., Chukanov, N.V., Kononkova, N.N., Agakhanov, A.A. and Karpenko, V.Yu. (2010) Londonite from the Urals, and new aspects of the crystal chemistry of the rhodizite–londonite series. Canadian Mineralogist, 48, 241-254.

Petersen, O.V. and Secher, K. (1993): The minerals of Greenland. Mineralogical Record **24**, 1-88.

Petersen, O.V., Gault, R.A. and Balić-Žunić, T. (2001) Odintsovite from the Ilímaussaq alkaline complex, South Greenland. Neues Jahrbuch für Mineralogie Monatshefte, 2001(5), 35-240

Petersen, O.V., Niedermayr, G., Johnsen, O., Gault, R.A. and Brandstätter, F. (2002a) Lovdarite from the Ilímaussaq alkaline complex, South Greenland. Neues Jahrbuch für Mineralogie Monatshefte, 2002(1), 23-30

Petersen, O.V., Giester, G., Brandstätter, F. and Niedermayr G (2002b) Nabesite, $Na_2BeSi_4O_{10}{\cdot}4H_2O$, a new mineral from the Ilímaussaq alkaline complex, South Greenland. Canadian Mineralogist, 40, 173-181.

Pezzotta, F., Diella, V. and Guastoni (1999) Chemical and paragenetic data on gadolinite-group minerals from Baveno and Cuasso al Monte, southern Alps, Italy. American Mineralogist, 84, 782-789.

Piper, J.D.A. (1982) The Precambrian palaeomagnetic record: the case for the Proterozoic Supercontinent. Earth and Planetary Science Letters, 59, 61 – 89.

Piper, J.D.A. (2010) Palaeopangaea in Meso-Neoproterozoic times: The palaeomagnetic evidence and implications to continental integrity, supercontinent form and Eocambrian break-up. Journal of Geodynamics, 50, 191–223.

Pokrovskiy, P.V., Grigor'yev, N.A. and Potashko, K.A. (1965) Secondary beryllium phosphates and their distribution in the weathering crust on mica-fluorite greisens. Trudy Instituta Geologii, Ural'skiy Filial, Akademiya Nauk SSSR, 70, 205-209 (in Russian).

Poujol, M. (2001) U-Pb isotopic evidence for episodic granitoid emplacement in the Murchison greenstone belt, South Africa. Journal of African Earth Sciences, 33, 155-163.

Pring, A., Din, V.K., Jefferson, D.A. and Thomas, J.M. (1986) The crystal chemistry of rhodizite: a re-examination. Mineralogical Magazine, 50, 163-172.

Pršek, J., Ondrejka, M., Bačík, P., Budzyń, B. & Uher, P. (2010): Metamorphic-hydrothermal REE minerals in the Bacúch magnetite deposit, Western Carpathians, Slovakia: (Sr, S)-rich monazite-(Ce) and Nd-dominant hingganite. Canadian Mineralogist **48**, 81-94.

Raade, G. and Balić-Žuni, T. (2006) The crystal structure of $(Be,\square)(V, Ti)_3O_6$, a mineral related to kyzylkumite. Canadian Mineralogist, 44, 1147-1158.

Raade, G., Balić-Žuni, T. and Stanley, C.J. (2013) IMA 2013-045. CNMNC Newsletter No. 17, October 2013, page 3000, Mineralogical Magazine, 77, 2997-3005.

Raade, G., Bernhard, F. and Ottolini, L. (2004) Replacement textures involving four scandium silicate minerals in the Heftetjern granitic pegmatite, Norway. European Journal of Mineralogy, 16, 945-950.

Ramaty, R., Kozlovsky, B. and Lingenfelter, R.E. (1996) Light isotopes, extinct radioisotopes, and gamma-ray lines from low-energy cosmic-ray interactions. Astrophysical Journal, 456, 525-540.

Ramaty, R., Kozlovsky, B., Lingenfelter, R.E. and Reeves, H. (1997) Light elements and cosmic rays in the early galaxy. Astrophysical Journal, 488, 730-748.

Rao, C., Wang, R.C., Hu, H. & Zhang, W.L. (2009): Complex internal textures in oxide minerals from the Nanping No. 31 dyke of granitic pegmatite, Fujian Province, southeastern China. Canadian Mineralogist 47, 1195-1212.

Rao, C., Hatert, F., Wang, R.C., Gu, X.P., Dal, B.F. and Dong, C.W. (2013a) Minjuanite, IMA 2013-021. CNMNC Newsletter No. 16, August 2013, page 2705; Mineralogical Magazine, 77, 2695-2709.

Rao, C., Wang, R., Hatert, F., Gu, X., Ottolini, L., Hu, H., Dong, C., Dal Bo, F., Baijot, M. (2013b) Strontiohurlbutite, $SrBe_2(PO_4)_2$, a new mineral from Nanping No. 31 pegmatite, Fujian Province, Southeastern China. American Mineralogist (in press)

Redden, J.A., Peterman, Z.E., Zartman, R.E. and DeWitt, E. (1990) U-Th-Pb geochronology and preliminary interpretation of Precambrian tectonic events in the Black Hills, South Dakota. Special Paper - Geological Association of Canada, 37, 229-251.

Reeves, H. (1994) On the origin of the light elements ($Z < 6$). Reviews of Modern Physics, 66, 193-216.

Reeves, H., Fowler, W.A. and Hoyle, F. (1970) Galactic cosmic ray origin of Li, Be and B in stars. Nature, 226, 727-729.

Rivers, T. (2008) Assembly and preservation of lower, mid, and upper orogenic crust in the Grenville Province—Implications for the evolution of large hot long-duration orogens. Precambrian Research, 167, 237–259.

Robinson, G.W., Grice, J.D. and Van Velthuizen, J. (1985) Ehrleite, a new calcium beryllium zinc phosphate hydrate from the Tip Top Pegmatite, Custer, South Dakota. Canadian Mineralogist, 23, 507-510.

Robinson, G.W., King, V.T., Asselborn, E., Cureton, F., Tschernich, R. and Sielecki, R. (1992) What's new in minerals? Annual world summary of mineral discoveries covering April 1991 through April 1992. Mineralogical Record, 23, 423-437.

Robb, L. J., and Robb, V. M. (1986) Archean pegmatite deposits in the northeastern Transvaal. In C. R. Anhaeusser & S. Maske, editors, Mineral Deposits of Southern Africa, Geological Society of South Africa, v. 1, p. 437-450.

Rogers, J.J.W. and Santosh, M. (2002) Configuration of Columbia, a Mesoproterozoic supercontinent. Gondwana Research, 5, 5-22.

Romer, R.L. and Smeds, S.-A. (1994) Implications of U-Pb ages of columbite-tantalites from granitic pegmatites for the Palaeoproterozoic accretion of 1.90-1.85 Ga magmatic arcs to the Baltic Shield. Precambrian Research, 67, 141-158.

Romer, R.L. and Smeds, S.-A. (1996) U-Pb columbite ages of pegmatites from Sveconorwegian terranes in southwestern Sweden. Precambrian Research, 76, 15-30.

Romer, R.L. and Smeds, S.-A. (1996) U-Pb columbite chronology of post-kinematic Palaeoproterozoic pegmatites in Sweden. Precambrian Research, 82, 85-99.

Ross, M. (1964) Crystal chemistry of beryllium. U.S. Geological Survey Professional Paper 468, 30 p.

Rossi, P., Bellatreccia, F., Caprilli, E., Parodi, G.C., Della Ventura, G. and Mottana, A. (1995) A new occurrence of rare minerals in an ejectum in the pyroclastics of Vico Volcano, Roman Comagmatic Region, Italy. Atti della Accademia Nazionale dei Lincei. Classe di Scienze Fisiche, Matematiche e Naturali. Rendiconti Lincei. Scienze Fisiche e Naturali, Series 9, 6, 147-156

Rouse, R.C., Peacor, D.R., Dunn, P.J., Campbell, T.J., Roberts, W.L., Wicks, F. J. and Newbury, D. (1987) Pahasapaite; a beryllophosphate zeolite related to synthetic zeolite rho, from the Tip Top Pegmatite of South Dakota. Neues Jahrbuch für Mineralogie. Monatshefte, 1987, 433-440.

Rouse, R.C., Peacor, D.R., Dunn, P.J., Su, S.-C., Chi, P.H. and Yeates, H. (1994) Samfowlerite, a new Ca Mn Zn beryllosilicate mineral from Franklin, New Jersey: Its characterization and crystal structure. Canadian Mineralogist, 32, 43-53.

Rudnik, R.L. and Gao, S. (2005) Composition of the continental crust. In Rudnick, R.L. (ed.) The Crust, volume 3 of Holland, H.D. and Turekian, K.K. (eds.) Treatise on Geochemistry, p. 1-64. Elsevier-Pergamon, Oxford.

Rundkvist, D.V. (1982) Application of laws in the development of mineral formations with time during investigations and prognosis of metallogenesis. Zapiski Vsesoyuznogo Mineralogicheskogo Obshchestva, 111, 407-421 (in Russian).

Ryback, G., Clark, A.M. and Stanley, C.J. (1998) Re-examination of the A.W.R. Kingsbury collection of British minerals at the Natural History Museum, London. Geological Curator, 6, 317-322.

Ryback, G., Hart, A.D. and Stanley, C.J. (2001) A.W.G. Kingsbury's specimens of British minerals. Part 1: Some examples of falsified localities. Journal of the Russell Society, 7(2), 51-69.

Sacerdoti, M., Parodi, G.C., Mottana, A., Maras, A. and Della Ventura, G.A. (1993) Asbecasite: crystal structure refinement and crystal chemistry. Mineralogical Magazine, 57, 315-322.

Sarazin, G. and Forestier, H. (1959) Étude de la substitution d'ions V^{3+} aux ions Al^{3+} dans chrysobéryl. Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences, Paris, 248(15), 2208-2210.

Schmetzer, K. (1983) Crystal chemistry of natural Be-Mg-Al oxides: taaffeite, taprobanite, musgravite. Neues Jahrbuch für Mineralogie Abhandlungen, 146:15-28.

Schmetzer, K., Kiefert, L. and Bernhardt, H.-J. (2000) Purple to purplish red chromium-bearing taaffeites. Gems & Gemology, 36(1), 50–59.

Schmincke, H.-U. (2007). The Quaternary volcanic fields of the east and west Eifel (Germany). In: Ritter, J. R. R. & Christensen, U.R. (eds) Mantle Plumes. A Multidisciplinary Approach. Berlin: Springer, pp. 241-322.

Semenov, E I., Bohnshtedt-Kupletskaya, E.M., Moleva, V.A. and Sludskaya, N.N. (1956) Vinogradovite - a new mineral, Doklady Akademii Nauk SSSR 109, 617-620 (in Russian)

Shearer, C.K. (2002) Behavior of beryllium during solar system and planetary evolution: Evidence from planetary materials. Reviews in Mineralogy and Geochemistry, 50, 77-120.

Shibata, K. and Ishihara, S. (1979) Rb-Sr whole-rock and K-Ar mineral ages of granitic rocks in Japan. Geochemical Journal, 13, 113-119.

Simmons, W.B., Pezzotta, F., Falster, A.U. and Webber, K.L. (2001) Londonite, a new mineral species; the Cs-dominant analogue of rhodizite from the Antandrokomby granitic pegmatite, Madagascar. Canadian Mineralogist, 39, 747-755.

Sirbescu, M.-L. and Nabelek, P.I. (2003) Crystallization conditions and evolution of magmatic fluids in the Harney Peak Granite and associated pegmatites, Black Hills, South Dakota—Evidence from fluid inclusions. Geochimica et Cosmochimica Acta, 67, 2443–2465.

Sirbescu, M.-L. C., Hartwick, E.E. and Student, J.J. (2008) Rapid crystallization of the Animikie Red Ace Pegmatite, Florence county, northeastern Wisconsin: inclusion microthermometry and conductive-cooling modeling. Contributions to Mineralogy and Petrology, 156, 289–305.

Skår, Ø. (2002) U–Pb geochronology and geochemistry of early Proterozoic rocks of the tectonic basement windows in central Nordland, Caledonides of north-central Norway. Precambrian Research, 116, 265-283.

Smith, D.G.W. & Nickel, E.H. (2007): A system of codification for unnamed minerals: Report of the SubCommittee for Unnamed Minerals of the IMA Commission on New Minerals, Nomenclature and Classification. Canadian Mineralogist **45**, 983-1055.

Stein, H., Scherstén, A., Hannah, J. and Markey, R. (2003) Subgrain-scale decoupling of Re and ^{187}Os and assessment of laser ablation ICP-MS spot dating in molybdenite. Geochimica et Cosmochimica Acta, 67, 3673–3686.

Stilling, A., Černý, P. and Vanstone, P.J. (2006) The Tanco pegmatite at Bernic Lake, Manitoba. XVI. Zonal and bulk compositions and their petrogenetic significance. Canadian Mineralogist, 44, 599-623.

Stowe, C.W. (1994) Compositions and settings of chromium deposits through time. Economic Geology, 89, 528-546.

Strunz, H. and Nickel, E.H. (2001) Strunz Mineralogical Tables. Chemical-Structural Mineral Classification System, Ninth edition, 870 p. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Sundvoll, B., Neumann, E.-R., Larsen, B.T. and Tuen, E. (1990) Age relations among Oslo Rift magmatic rocks: implications for tectonic and magmatic modelling. Tectonophysics, 178, 67-87.

Sviridenko, L.P. and Ivashchenko, V.I. (2000) Ore-bearing granites of Karelia, Russia. In Kremenetsky, A.A., Lehmann, __ and Seltmann, __ (eds) Ore-bearing Granites of Russia and Adjacent Countries, p. 281-294. INTAS-93-1783 Project, IGCP-373 Project, Moscow.

Swanson, S.E. (2012) Mineralogy of spodumene pegmatites and related rocks in the tin-spodumene belt of North Carolina and South Carolina, USA. The Canadian Mineralogist, 50, 1589-1608.

Sweetapple, M.T. and Collins, P.L.F. (2002): Genetic framework for the classification and distribution of Archean rare metal pegmatites in the North Pilbara Craton, Western Australia. Economic Geology, 97, 873-895.

Takahashi, T., Tanaka, K. and Kawabe, I. (2007) Lanthanide tetrad effect of Naegi granite-pegmatite suite, central Japan:Convex tetrad effect by fractional loss of fluid from hydrous felsic melt. Journal of Earth and Planetary Sciences, Nagoya University, 54, 13-35.

Themelis, T. (2008) Gems & Mines of Mogôk. T. Themelis, ISBN 0940965-30-5.

Thöni, M. and Miller, C. (2000) Permo-Triassic pegmatites in the eo-Alpine eclogite-facies Koralpe Complex, Austria; age and magma source constraints from mineral chemical, Rb-Sr and Sm-Nd isotope data. Schweizerische Mineralogische und Petrographische Mitteilungen, 80, 169-186.

Tkachev, A.V. (2011) Evolution of metallogeny of granitic pegmatites associated with orogens throughout geological time. In Bettencourt, A.N., De Campos, C.P. and Ferreira, V.P. (eds.) Granite-Related Ore Deposits. Geological Society, London, Special Publications, 350, 7-23.

Tomascak, P.B., Krogstad, Eirik J., Walker and Richard J. (1996) U-Pb monazite geochronology of granitic rocks from Maine; implications for late Paleozoic tectonics in the Northern Appalachians. Journal of Geology, 104, 185-195.

Tropper, P., Harlov, D., Krenn, E., Finge r, F., Rhede , D. and Bernhard, F. (2007): Zr-bearing minerals as indicators for the polymetamorphic evolution of the eastern, lower Austroalpine nappes (Stubenberg Granite contact aureole, Styria, Eastern Alps, Austria). Lithos 95, 72-86.

Trumbull, R.B. (1993) A petrological and Rb–Sr isotopic study of an early Archean fertile granite–pegmatite system: the Sinceni Pluton in Swaziland. Precambrian Research 61, 89-116.

Upton, B.G.J., Emeleus, C.H., Hearman, L.M., Goodenough, K.M. and Finch, A.A. (2003) Magmatism of the mid-Proterozoic Gardar Province, South Greenland: chronology, petrogenesis and geological setting. Lithos, 68, 43-65.

Vidal, P., Lasnier, B. and Poirot, J.-P. (1992) Dtermination of the age and origin of emeralds using rubidium-strontium analyses. Journal of Gemmology, 23(4), 198-200.

Voice, P.J., Kowalewski, M., and Eriksson, K.A. (2011) Quantifying the timing and rate of crustal evolution: Global compilation of radiometrically dated detrital zircon grains: The Journal of Geology, 119, 109–126.

Volkert, R.A., Zartman, R.E. and Moore, P.B. (2005) U–Pb zircon geochronology of Mesoproterozoic postorogenic rocks and implications for post-Ottawan magmatism and metallogenesis, New Jersey Highlands and contiguous areas, USA. Precambrian Research, 139, 1-19.

Voloshin, A.V., Pakhomovskiy, Ya.A., Rogachev, D.L., Tyusheva, F.N. and Shishkin, N.M. (1986) Ginzburgite—a new calcium-beryllium silicate from desilicated pegmatites. Mineralogicheskiy Zhurnal 8(4), 85-90 (in Russian).

Voloshin, A.V., Pakhomovskiy, Ya.A., Rogachev, D.L., Nadezhnina, T.N., Pushcharovskiy, D.Yu. and Bakhchisaraytsev, A.Yu. (1989) Clinobehoite—a new natural modification of $Be(OH)_2$ from desilicated pegmatites. Mineralogicheskiy Zhurnal, 11(5), 88-95 (in Russian)

Von Blanckenburg, F. (1992) Combined high-precision chronometry and geochemical tracing using accessory minerals; applied to the Central-Alpine Bergell Intrusion (Central Europe). Chemical Geology, 100, 19-40.

Walter, F. (1992) Weinebeneite, $CaBe_3(PO_4)_2(OH)_2 \cdot 4H_2O$, a new mineral species: mineral data and crystal structure. European Journal of Mineralogy, 4, 1275-1283.

Wang, S., Ye, N., Li, Wei and Zhao, D. (2010) Alkaline beryllium borate $NaBeB_3O_6$ and $ABe_2B_3O_7$ (A = K, Rb) as UV nonlinear optical crystals. Journal of the American Chemical Society, 132, 8779–8786

Weibel, M., Graeser, S., Oberholzer, W.F., Stalder, H.-A. and Gabriel, W. (1990) Die Mineralien der Schweiz. Ein mineralogischer Führer. Fifth edition. Birkhäuser Verlag, Berlin.

Wise, M.A. and Brown, C.D. (2010) Mineral chemistry, petrology and geochemistry of the Sebago granite-pegmatite system, southern Maine, USA. Journal of Geosciences, 55, 3-26

Yakovenchuk, V.N., Ivanyuk, G.Yu., Pakhomobskiy and Men'shikov, Yu.P. (1999) Minerals of the Khibiny Massif. Zemlya, Moscow.

Yang, Z., Ding K., de Fourestier, J., Mao Q. and Li, H. (2012) Ferrotaaffeite-2*N*'2*S*, a new mineral species, and the crystal structure of Fe (super $^{2+}$) -rich magnesiotaaffeite-2*N*'2*S* from the Xianghualing tin-polymetallic ore field, Hunan Province, China. Canadian Mineralogist, 50, 21-29.

Yuan, S., Peng, J., Hu, R., Li, H., Shen, N. and Zhang, D. (2008) A precise U–Pb age on cassiterite from the Xianghualing tin-polymetallic deposit (Hunan, South China). Mineralium Deposita, 43, 375-382.

Yushkin, N.P. (1982) Evolutionary ideas in modern mineralogy. Zapiski Vsesoyuznogo Mineralogicheskogo Obshchestva, 116, 432-442 (in Russian).

Zhabin, A.G. (1979): Is there evolution of mineral speciation on Earth? Doklady Akademii Nauk **247**, 199-202 (in Russian)

Zhabin, A.G. (1981): Is there evolution of mineral speciation on Earth? Doklady Earth Science Sections **247**, 142-144 [translation of Zhabin 1979]

Zozulya, D.R., Bayanova, T.B. and Eby, G.N. (2005): Geology and Age of the Late Archean Keivy Alkaline Province, Northeastern Baltic Shield. Journal of Geology, 113, 601-608.

Figure Captions

Figure 1. Photographs of minerals containing essential beryllium. A. Emerald in mica schist matrix from Murchison greenstone belt, South Africa; 90 x 75 mm. © Peter Lyckberg, and published with permission courtesy of Peter Lyckberg. This specimen is in the collection of Peter Lyckberg. Sinkankas's painting of this specimen was published as Figure 5 of the colored section in Sinkankas (1981) B. Beryllonite, $NaBe(PO_4)$, in columnar aggregate from Kunar Province, Afghanistan and in glassy fragments from the type locality of Stoneham, Maine, U.S.A. Coin diameter is ~1 cm. E.S. Grew samples and photo. C. Sørensenite, $Na_4Be_2Sn(Si_3O_9)_2 \cdot 2H_2O$, pink, columnar masses from Kvanefjeld, Ilímaussaq complex, West Greenland. Coin diameter is ~1 cm. E.S. Grew sample (gift of Ted Johnson) and photo. D. Pezzottaite, $CsLiBe_2Al_2Si_6O_{18}$. Ambatovita, Mandrosonoro area, Fianarantsoa Province, Madagascar. R060583 reproduced with permission from the RRUFF Project (Downs 2006). E. Welshite, $Ca_4[Mg_9(Sb^{5+})_3]O_4[Si_6Be_3Al(Fe^{3+})_2O_{36}]$, crystal 3.5x2 mm, from Långban, Sweden. Photograph by Erik Jonnson. Reproduced with permission courtesy of the Swedish Museum of Natural History. F. Rhodizite, $KBe_4Al_4(B_{11}Be)O_{28}$, pale yellow crystal with pink tourmaline (rubellite) from Manjaka, Sahatany Pegmatite Field, Antananarivo Province, Madagascar. Coin diameter is ~1 cm. E.S. Grew sample (gift of François Fontan) and photo. G. Niveolanite, $NaBeCO_3(OH) \cdot 2H_2O$, as a fibrous aggregate 1.5 cm across, part of type specimen, from Mont Saint-Hilaire, Rouville, Montérégie, Québec, Canada. Horváth Collection HC11128. Photo © László Horváth. Reproduced with permission courtesy of László Horváth. H. Chrysoberyl, Be_2AlO_4, Twinned crystals from the Ratnapura district, Sri Lanka. Photograph of sample R100130 reproduced with

1616 permission from the RRUFF Project (Downs 2006). I. Bertrandite, $Be_4Si_2O_7(OH)_2$, in
1617 pseudohexagonal prisms from the Golconda mine, Governador Valadares, Minas Gerais,
1618 Brazil. Photograph of sample R060800 reproduced with permission from the RRUFF
1619 Project (Downs 2006).

1620

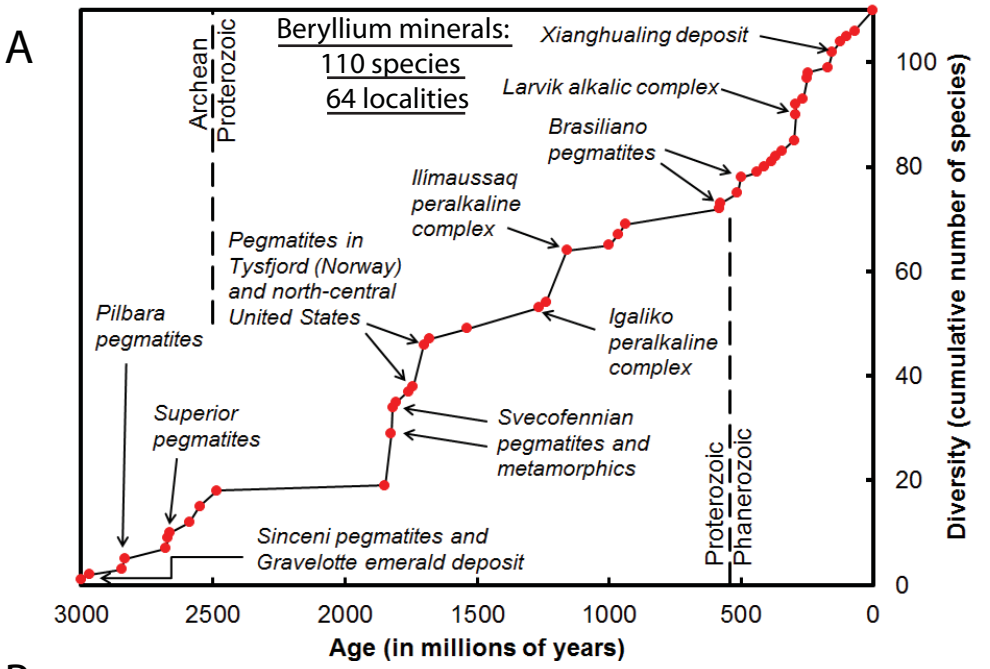
1621 Figure 2. A Diagram showing cumulative diversity based on the reported earliest
1622 occurrences of 110 Be minerals in the geologic record (Table 2). The diagram is
1623 cumulative in that each reported new occurrence is added to the number of minerals that
1624 had been reported from older rocks, i.e., the y-axis indicates the number of new minerals
1625 that are reported to have appeared by a certain time, but not the number of minerals
1626 forming at that time (updated from Hazen et al. 2012 and Grew and Hazen 2013). B.
1627 Histogram showing our estimates of the number of minerals that formed in a given 50 Ma
1628 interval based on the reported earliest (Table 2), latest (Table 3) and intermediate
1629 occurrences (generally if 4-5 or fewer occurrences; if more than 4-5 occurrences, we have
1630 assumed the mineral formed in all the 50-Ma intervals between the earliest and latest
1631 occurrences). The number of localities does not include all the localities for minerals
1632 reported at 10 or more localities (“many” in Table 3). C. Histogram of U-Pb
1633 crystallization ages for 100,445 detrital zircon analyses at 20 Ma bin intervals (modified
1634 from Voice et al. 2011, Fig. 1c and A3). Yellow boxes are based on the time periods for
1635 supercontinent assembly, where the period for Kenorland is taken from that for
1636 Superia/Sclavia (Cawood et al. (2013).

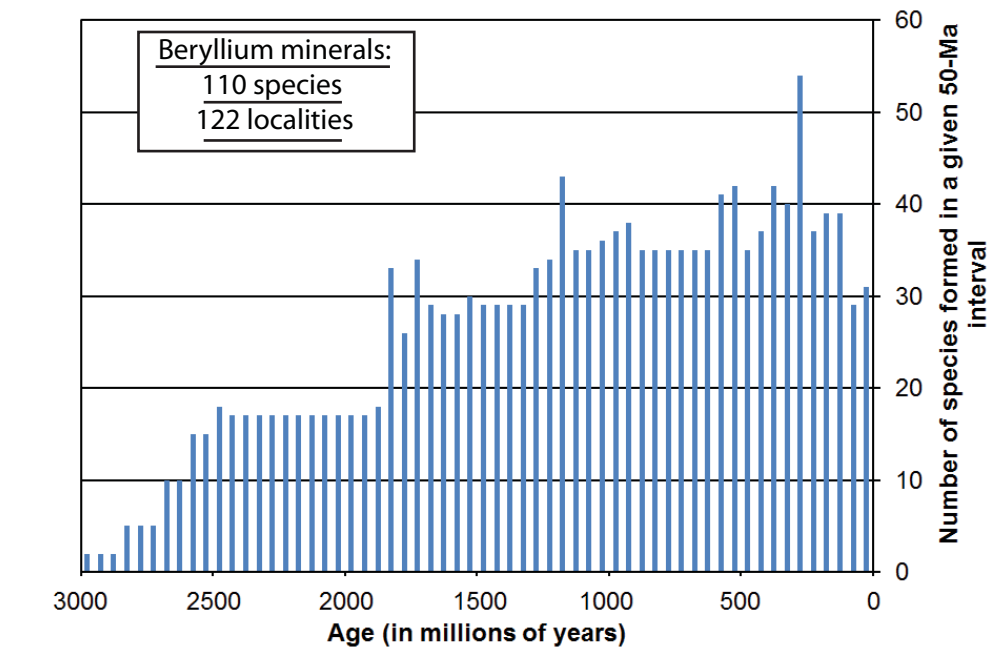
1637

Figure 3. Diagram showing structural complexity (total information content as bits per unit cell) based on Table 1 from the data compiled by Krivovichev (2013) as a function of the first reported occurrence of beryllium minerals in the geologic record (Table 2). The degree of complexity (total information content) is based on Krivovichev (2013).

Figure 4. Photographs of minerals from the Himalaya orogenic belt, Gilgit District, northern Pakistan. A. Väyrynenite from the Shengus pegmatite, Nanga Parbat-Haramosh massif. Age is estimated to be 5 Ma (Laurs et al. 1998). Photograph of sample R050590 reproduced with permission from the RRUFF Project (Downs 2006). B. Aquamarine with muscovite from Fikar (Fiqhar), Hunza River area. Age is estimated to not exceed 9 Ma (Fraser et al. 2001). The prism faces are 1 cm wide. E.S. Grew sample and photographs.

Figure 1


A
Beryllium minerals:
110 species
64 localities
Archean
Proterozoic
Xianghualing deposit
Larvik alkalic complex
Brasiliano pegmatites
Ilímaussaq peralkaline complex
Pegmatites in Tysfjord (Norway) and north-central United States
Igaliko peralkaline complex
Pilbara pegmatites
Superior pegmatites
Svecofennian pegmatites and metamorphics
Sinceni pegmatites and Gravelotte emerald deposit
Proterozoic
Phanerozoic
Diversity (cumulative number of species)
0
20
40
60
80
100
3000
2500
2000
1500
1000
500
0
Age (in millions of years)


B
Beryllium minerals:
110 species
122 localities
Number of species formed in a given 50-Ma interval
0
10
20
30
40
50
60
3000
2500
2000
1500
1000
500
0
Age (in millions of years)

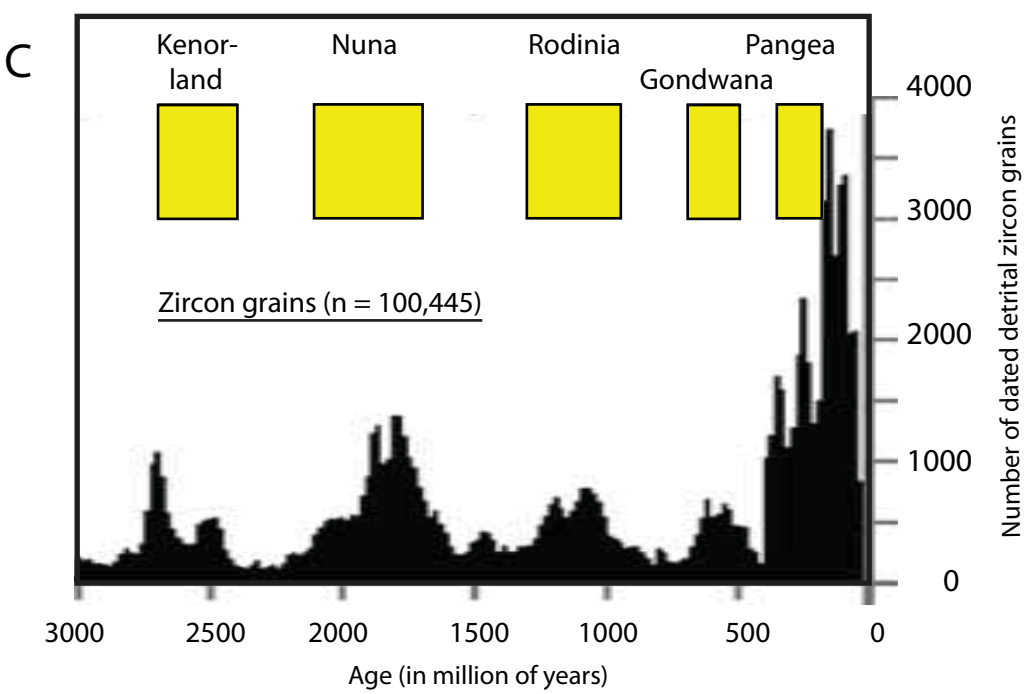

C
Kenor-land
Nuna
Rodinia
Gondwana
Pangea
Zircon grains (n = 100,445)
Number of dated detrital zircon grains
0
1000
2000
3000
4000
3000
2500
2000
1500
1000
500
0
Age (in million of years)

Figure 2

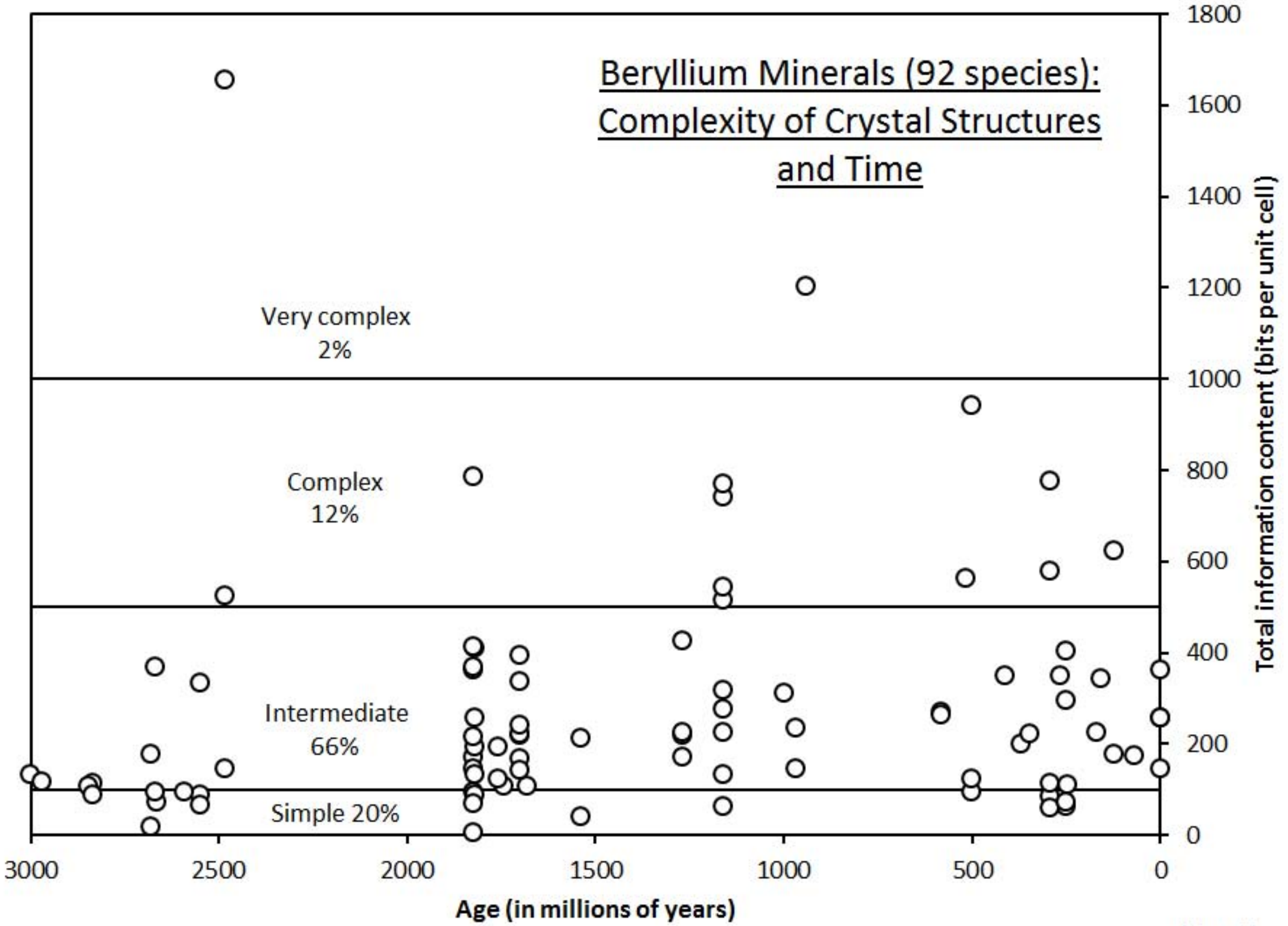
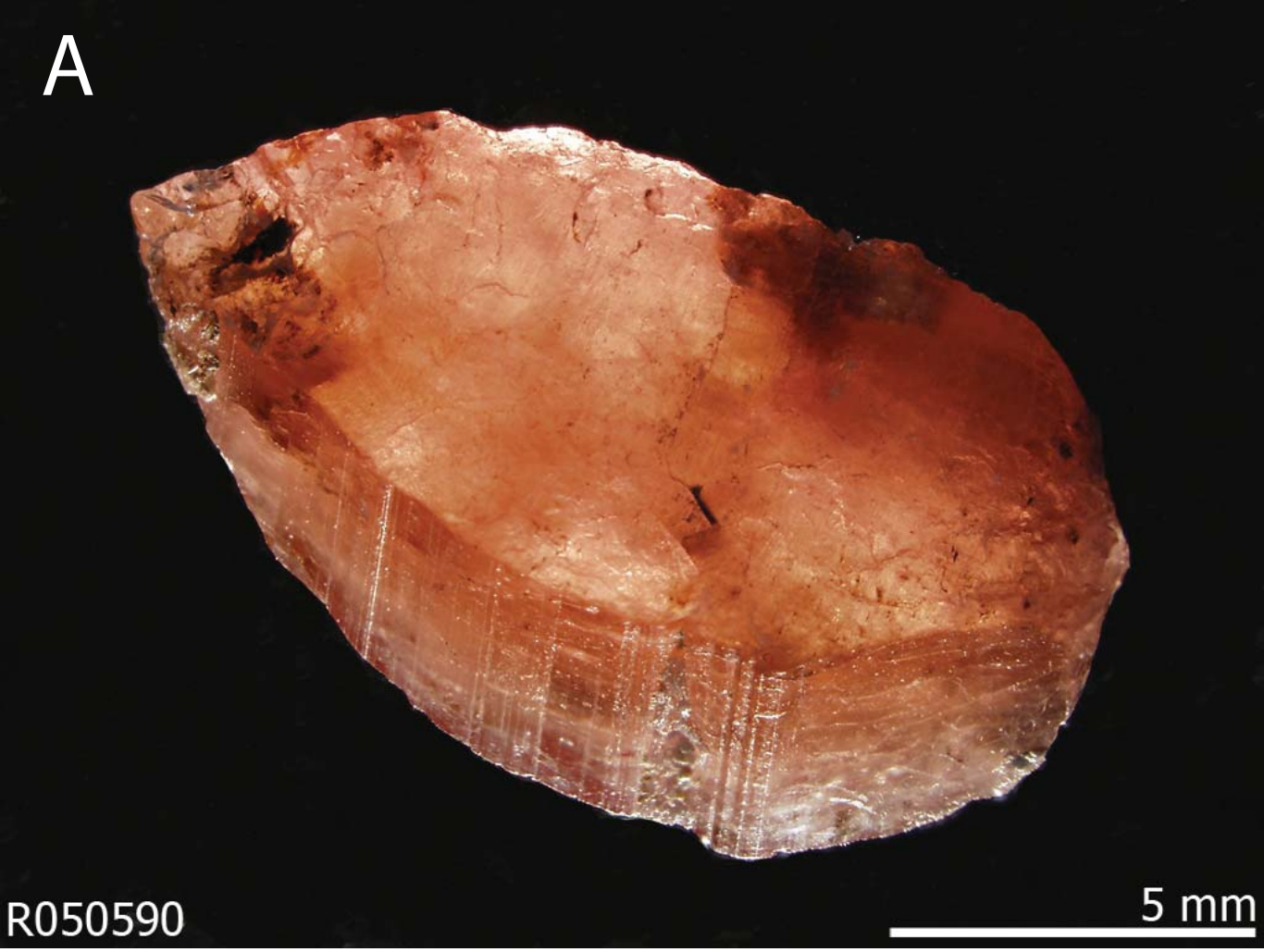

Beryllium Minerals (92 species):
Complexity of Crystal Structures
and Time
Very complex
2%
Complex
12%
Intermediate
66%
Simple 20%
1800
1600
1400
1200
1000
800
600
400
200
0
Total information content (bits per unit cell)
3000
2500
2000
1500
1000
500
0
Age (in millions of years)

Figure 3


A
R050590
5 mm


B

Table 1. List of beryllium minerals (as of October, 2013)

Number	Mineral name	Formula	Class (Strunz and Nickel (2001)	Supergroup or Group	Complexity, $I_{G,\ total}$
Be1	Alflarsenite	$NaCa_2Be_3Si_4O_{13}(OH)\cdot 2H_2O$	Silicate		579
Be2	Almarudite	$K(\square,Na)_2(Mn,Fe,Mg)_2[(Be,Al)_3Si_{12}]O_{30}$	Silicate	Milarite	258
Be3	Aminoffite	$Ca_3(BeOH)_2Si_3O_{10}$	Silicate		312
Be4	Asbecasite	$Ca_3TiAs_6Be_2Si_2O_{20}$	Arsenite		200
Be5	Atencioite	$Ca_2(Fe^{2+})_3Mg_2Be_4(PO_4)_6(OH)_4\cdot 6H_2O$	Phosphate	Roscherite	271[a]
Be6	Babefphite	$BaBePO_4F$	Phosphate		64
Be7	Barylite	$BaBe_2Si_2O_7$	Silicate		172
Be8	Bavenite	$Ca_4Be_2Al_2Si_9O_{26}(OH)_2$	Silicate		335
Be9	Bazzite	$Be_3(Sc,Fe^{3+},Mg)_2Si_6O_{18}\cdot Na_x\cdot nH_2O$	Silicate	Beryl	146
Be10	Bearsite	$Be_2(AsO_4)(OH)\cdot 4H_2O$	Arsenate	Cf. moreasite	369
Be11	Behoite	$Be(OH)_2$	Hydroxide		19
Be12	Berborite	$Be_2(BO_3)(OH)\cdot H_2O$	Borate		39[b]
Be13	Bergslagite	$CaBeAsO_4(OH)$	Arsenate	Herderite	96
Be14	Bertrandite	$Be_4Si_2O_7(OH)_2$	Silicate		115
Be15	Beryl	$Be_3Al_2Si_6O_{18}$	Silicate	Beryl	133
Be16	Beryllite	$Be_3(SiO_4)(OH)_2\cdot H_2O$	Silicate		
Be17	Beryllonite	$NaBe(PO_4)$	Phosphate	Cf. trimerite	369
Be18	Bityite	$CaLiAl_2(Si_2BeAl)O_{10}(OH)_2$	Silicate	Mica	[c]
	Bohseite	$Ca_4Be_3AlSi_9O_{25}(OH)_3$		Cf. bavenite	
Be19	Bromellite	BeO	Oxide		4
Be20	Bussyite-(Ce)	$(Ce,REE)_3(Na,H_2O)_6MnSi_9Be_5(O,OH)_{30}F_4$	Silicate		622
	Calcybeborosilite-(Y)	$(Y,REE,Ca)(B,Be)_2(SiO_4)_2(OH,O)_2$		Gadolinite-Datolite	
Be21	Chiavennite	$CaMn^{2+}(BeOH)_2Si_5O_{13}\cdot 2H_2O$	Silicate	Zeolite	409
Be22	Chkalovite	$Na_2BeSi_2O_6$	Silicate	Cf. liberite	277
Be23	Chrysoberyl	$BeAl_2O_4$	Oxide	Cf. forsterite	71
	Clinobarylite	$BaBe_2Si_2O_7$		Cf. barylite	
Be24	Clinobehoite	$Be(OH)_2$	Hydroxide		294

Be25	Danalite	$Be_3(Fe^{2+})_4(SiO_4)_3S$	Silicate	Cancrinite-Sodalite	87
Be26	Ehrleite	$Ca_2ZnBe(PO_4)_2(PO_3OH)\cdot 4H_2O$	Phosphate		220
Be27	Eirikite	$KNa_6Be_2(Si_{15}Al_3)O_{39}F_2$	Silicate	Leifite	226
Be28	Epididymite	$Na_2Be_3Si_6O_{15}\cdot H_2O$	Silicate		426
Be29	Euclase	$BeAlSiO_4(OH)$	Silicate		96
Be30	Eudidymite	$Na_2Be_3Si_6O_{15}\cdot H_2O$	Silicate		217
Be31	Faheyite	$Be_2Mn^{2+}(Fe^{3+})_2(PO_4)_4\cdot 6H_2O$	Phosphate		
Be32	Ferrochiavennite[e]	$Ca_{1-2}Fe[(Si,Al,Be)_5Be_2O_{13}(OH)_2]\cdot 2H_2O$	Silicate	Zeolite	775[a]
Be33	Ferrotaaffeite-2*N*'2*S*	$Be(Fe^{2+})_3Al_8O_{16}$	Oxide	Högbomite	
Be34	Ferrotaaffeite-6*N*'3*S*	$Be(Fe^{2+})_2Al_6O_{12}$	Oxide	Högbomite	
Be35	Footemineite	$Ca_2(Mn^{2+})_5Be_4(PO_4)_6(OH)_4\cdot 6H_2O$	Phosphate	Roscherite	222
Be36	Fransoletite	$Ca_3Be_2(PO_4)_2(PO_3OH)_2\cdot 4H_2O$	Phosphate		336
Be37	Friedrichbeckeite	$K(\square Na)Mg_2(Be_2Al)Si_{12}O_{30}$	Silicate	Milarite	258
Be38	Gadolinite-(Ce)	$Ce_2Fe^{2+}Be_2O_2(SiO_4)_2$	Silicate	Gadolinite-Datolite	
Be39	Gadolinite-(Y)	$Y_2Fe^{2+}Be_2O_2(SiO_4)_2$	Silicate	Gadolinite-Datolite	107
Be40	Gainesite	$Na_2(Be,Li)(Zr,Zn)_2(PO_4)_4\cdot 1.5H_2O$	Phosphate	Gainesite	84
Be41	Genthelvite	$Be_3Zn_4(SiO_4)_3S$	Silicate	Cancrinite-Sodalite	87
Be42	Glucine	$CaBe_4(PO_4)_2(OH)_4\cdot 0.5H_2O$	Phosphate		
Be43	Greifensteinite	$Ca_2(Fe^{2+})_5Be_4(PO_4)_6(OH)_4\cdot 6H_2O$	Phosphate	Roscherite	221
Be44	Gugiaite	$Ca_2BeSi_2O_7$	Silicate	Melilite	58
Be45	Guimarãesite	$Ca_2Zn_5Be_4(PO_4)_6(OH)_4\cdot 6H_2O$	Phosphate	Roscherite	
Be46	Hambergite	$Be_2BO_3(OH)$	Borate		192
Be47	Harstigite	$Ca_6Be_4Mn^{2+}(SiO_4)_2(Si_2O_7)_2(OH)_2$	Silicate		786
Be48	Helvite	$Be_3(Mn^{2+})_4(SiO_4)_3S$	Silicate	Cancrinite-Sodalite	87
Be49	Herderite	$CaBePO_4(F,OH)$	Phosphate	Herderite	96
Be50	Hingganite-(Ce)	$BeCe(SiO_4)OH$	Silicate	Gadolinite-Datolite	114

Be51	“Hingganite-(Nd)”	$BeNd(SiO_4)OH$	Silicate	Gadolinite-Datolite	
Be52	Hingganite-(Y)	$BeY(SiO_4)OH$	Silicate	Gadolinite-Datolite	107
Be53	Hingganite-(Yb)	$BeYb(SiO_4)OH$	Silicate	Gadolinite-Datolite	107
Be54	Høgtuvaite	$Ca_4[(Fe^{2+})_6(Fe^{3+})_6]O_4[Si_8Be_2Al_2O_{36}]$	Silicate	Sapphirine	348
Be55	Hsianghualite	$Li_2Ca_3Be_3(SiO_4)_3F_2$	Silicate	Zeolite	343
Be56	Hurlbutite	$CaBe_2(PO_4)_2$	Phosphate		192
Be57	Hyalotekite	$(Pb,Ba,K)_4(Ca,Y)_2(B,Be)_2(Si,B)_2Si_8O_{28}F$	Silicate		215
Be58	Hydroxylherderite	$CaBePO_4(OH)$	Phosphate	Herderite	96
Be59	Jeffreyite	$(Ca,Na)_2(Be,Al)Si_2(O,OH)_7$	Silicate		
Be60	Joesmithite	$Pb^{2+}Ca_2(Mg_3Fe^{3+}{}_2)(Si_6Be_2)O_{22}(OH)_2$	Silicate	Amphibole	362
Be61	Khmaralite	$Mg_4(Mg_3Al_9)O_4[Si_5Be_2Al_5O_{36}]$	Silicate	Sapphirine	1656
Be62	Leifite	$Na_7Be_2(Si_{15}Al_3)O_{39}(F,OH)_2$	Silicate	Leifite	226
Be63	Leucophanite	$NaCaBeSi_2O_6F$	Silicate		172
Be64	Liberite	Li_2BeSiO_4	Silicate	Cf. chkalovite	48[f]
Be65	Londonite	$CsBe_4Al_4(B_{11}Be)O_{28}$	Borate		122
Be66	Lovdarite	$K_2Na_6Be_4Si_{14}O_{36}\cdot 9H_2O$	Silicate		741
Be67	Mg-taaffeite-2*N*’2*S*	$BeMg_3Al_8O_{16}$	Oxide	Högbomite	212
Be68	Mg-taaffeite-6*N*’3*S*	$BeMg_2Al_6O_{12}$	Oxide	Högbomite	146
Be69	Makarochkinite	$Ca_4[(Fe^{2+})_8(Fe^{3+})_2Ti_2]O_4[Si_8Be_2Al_2O_{36}]$	Silicate	Sapphirine	348
Be70	Mariinskite	$BeCr_2O_4$	Oxide		71[a,d]
Be71	Mccrillisite	$NaCs(Be,Li)Zr_2(PO_4)_4\cdot 1\text{-}2H_2O$	Phosphate	Gainesite	
Be72	Meliphanite	$Ca_4(Na,Ca)_4Be_4AlSi_7O_{24}(F,O)_4$	Silicate		178
Be73	Milarite	$KCa_2(Be_2AlSi_{12})O_{30}\cdot H_2O$	Silicate	Milarite	258
Be74	Minasgeraisite-(Y)	$CaBe_2Y_2Si_2O_{10}$	Silicate	Gadolinite-datolite	
Be75	Minjiangite	$Ba[Be_2P_2O_8]$	Phosphate		
Be76	Moraesite	$Be_2(PO_4)(OH)\cdot 4H_2O$	Phosphate	Cf. bearsite	66
Be77	Mottanaite-(Ce)	$Ca_4(CeCa)AlBe_2(Si_4B_4O_{22})O_2$	Silicate	Hellandite	363
Be78	Nabesite	$Na_2BeSi_4O_{10}\cdot 4H_2O$	Silicate	Zeolite	514

Be79	Niveolanite	$NaBeCO_3(OH)\cdot 2H_2O$	Carbonate		176
Be80	Odintsovite	$K_2Na_4Ca_3Ti_2Be_4Si_{12}O_{38}$	Silicate		543
Be81	Oftedalite[g]	$K(CaSc)Be_3Si_{12}O_{30}$	Silicate	Milarite	234[a]
Be82	Pahasapaite	$Li_8(Ca,Li,K)_{10}Be_{24}(PO_4)_{24}\cdot 38H_2O$	Phosphate	Zeolite	3920
Be83	Parafransoletite	$Ca_3Be_2(PO_4)_2(PO_3OH)_2\cdot 4H_2O$	Phosphate		168
Be84	Pezzottaite	$CsLiBe_2Al_2Si_6O_{18}$	Silicate	Beryl	941
Be85	Phenakite	Be_2SiO_4	Silicate	Willemite	118
Be86	Rhodizite	$KBe_4Al_4(B_{11}Be)O_{28}$	Borate		122
Be87	Roggianite	$Ca_2BeAl_2Si_4O_{13}(OH)_2\cdot nH_2O$ (n < 2.5)	Silicate	Zeolite	402
Be88	Roscherite	$Ca_2(Mn^{2+})_5Be_4(PO_4)_6(OH)_4\cdot 6H_2O$	Phosphate	Roscherite	242
Be89	Ruifrancoite	Ca_2 ($\square$,Mn^{2+})$_2$(Fe^{3+},Mn^{2+},Mg)$_4$-$Be_4(PO_4)_6(OH)_4\cdot 6H_2O$	Phosphate	Roscherite	
Be90	Samfowlerite	$Ca_{14}(Mn^{3+})_3Zn_3Be_2Be_6Si_{14}O_{52}(OH)_6$	Silicate		1202
Be91	Selwynite	$NaKBeZr_2(PO_4)_4\cdot 2H_2O$	Phosphate	Gainesite	
Be92	Semenovite-(Ce)	$(Na,Ca)_9Fe^{2+}Ce_2(Si,Be)_{20}(O,OH,F)_{48}$	Silicate		771
Be93	Sørensenite	$Na_4Be_2Sn(Si_3O_9)_2\cdot 2H_2O$	Silicate		318
Be94	Sphaerobertrandite	$Be_3SiO_4(OH)_2$	Silicate		133
Be95	Stoppaniite	$Fe^{3+}{}_2Be_3Si_6O_{18}\cdot H_2O$	Silicate	Beryl	146
Be96	Strontiohurlbutite	$SrBe_2(PO_4)_2$	Phosphate		
Be97	Surinamite	$Mg_3Al_3O(Si_3BeAlO_{15})$	Silicate	Sapphirine	526
Be98	Sverigeite	$NaBe_2(Mn^{2+})_2SnSi_3O_{12}(OH)$	Silicate		144
Be99	Swedenborgite	$NaBe_4Sb^{5+}O_7$	Oxide		68
Be100	Telyushenkoite	$CsNa_6Be_2(Si_{15}Al_3)O_{39}F_2$	Silicate	Leifite	226
Be101	Tiptopite	$K_2(Li,Na,Ca)_6(Be_6P_6)O_{24}(OH)_2\cdot 1.3H_2O$	Phosphate	Cancrinite-Sodalite	142
Be102	Trimerite	$CaBe_3(Mn^{2+})_2(SiO_4)_3$	Silicate	Cf. beryllonite	369
Be103	Tugtupite	$Na_4BeAlSi_4O_{12}Cl$	Silicate	Cancrinite-Sodalite	64
Be104	Tvedalite	$Ca_4Be_3Si_6O_{17}(OH)_4\cdot 3H_2O$	Silicate		
Be105	Unnamed-1	$K(CaY)Be_3Si_{12}O_{30}$	Silicate	Milarite	
Be106	Unnamed-2 (IMA No.	$(Be,\square)(V^{3+}, Ti)_3O_6$	Oxide	Cf.	109[a]

	2013-045)			kyzylkumite, tivanite[h]	
Be107	Uralolite	$Ca_2Be_4(PO_4)_3(OH)_3 \cdot 5H_2O$			564
Be108	Väyrynenite	$BeMn^{2+}PO_4(OH)$			133
	Vinogradovite	Not a Be mineral – see text			
Be109	Wawayandaite	$Ca_6Be_9(Mn^{2+})_2BSi_6O_{23}(OH,Cl)_{15}$			
Be110	Weinebeneite	$CaBe_3(PO_4)_2(OH)_2 \cdot 4H_2O$		Zeolite	173
Be111	Welshite	$Ca_4[Mg_9(Sb^{5+})_3]O_4[Si_6Be_3Al(Fe^{3+})_2O_{36}]$		Sapphirine	414[a]
Be112	Zanazziite	$Ca_2Mg_5Be_4(PO_4)_6(OH)_4 \cdot 6H_2O$		Roscherite	

Notes: Complexity is given in terms of total structural information content as bits per unit cell (Krivovichev 2013, Supplementary Information). [a]Krivovichev (personal communication) [b]Value for berborite-1T, space group *P*3, which is the polytype reported from both Lupikko and Larvik (Giuseppetti et al. 1990). [c]Two values are given for a bityite-margarite intermediate (Lin and Guggenheim 1983), one each for a different space group. [d]From the synthetic analogue (Frazer et al. 1969).). [e]We give the general formula reported by Grice et al (2013) instead of the ideal end-member formula $Ca_{1\ \ 2}FeSi_5Be_2O_{13}(OH)_2 \cdot 2H_2O$, which is not balanced in charge. [f]The complexity for liberite has not been plotted because of an error in reported structure (Hawthorne and Huminicki 2002). [g]Formula from end-member composition given in Cooper and Hawthorne (2006). [h]Raade et al. (2013)

Table 2. Reported earliest occurrences of beryllium minerals in the geologic record

Mineral name	Age (Ma)	Locality
Alflarsenite	294	[a]Tuften quarry, Tvedalen, Larvik, Vestfold, Norway
Almarudite	0.4	[a]Bellerberg volcano, Ettringen, Eifel, Rhineland-Palatinate, Germany
Aminoffite	1000	[a]Långban deposit, Filipstad, Värmland, Sweden
Asbecasite	370	Tennvatn pegmatite, Sørfold, Nordland, Norway
Atencioite	582	[a]Linópolis, Divino das Laranjeiras, Minas Gerais State, Brazil
Babefphite	250	[a,b]Aunik fluorite deposit. Buryatiya, Transbaikal, Russia
Barylite	1825	Långban deposit, Filipstad, Värmland, Sweden
Bavenite	2550	Londonderry pegmatite, Coolgardie, Western Australia, Australia
Bazzite	967	Heftetjern pegmatite, Tørdal, Telemark, Norway
Bearsite	S[c]	[a,b]Bota-Burum deposit, Chu-Ili Mountains, Balkash Region, Kazakhstan
Behoite	2680	Sakharijok massif, Kola Peninsula, Russia
Berborite	1538	[b]Lupikko deposit, Pitkäranta, Lake Ladoga region, Karelia, Russia
Bergslagite	1825	Långban deposit, Filipstad, Värmland, Sweden
Bertrandite	2835	Mount Francisco pegmatites, East Pilbara, Western Australia, Australia
Beryl	3000	Sinceni pluton area, central Swaziland
Beryllite	1160	Ilímaussaq complex, Narsaq, West Greenland
Beryllonite	2670	BEP pegmatite, Bird River Greenstone Belt, Manitoba, Canada
Bityite	2590	Rothsay pegmatite, Rothsay, Western Australia, Australia
Bromellite	1825	Långban deposit, Filipstad, Värmland, Sweden
Bussyite-(Ce)	124	[a]Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada
Chiavennite	1820	Utö, Södermanland, Sweden
Chkalovite	1160	Ilímaussaq complex, Narsaq, West Greenland
Chrysoberyl	2665	Mavis Lake pegmatite group, Dryden Field, Superior Province, Manitoba, Canada
Clinobehoite	250	[a]Izumrudnye Kopi, Tokovaya River, Middle Urals, Russia
Danalite	2550	Barbara gold mine pegmatites, Coolgardie, Western Australia, Australia
Ehrleite	1702	[a]Tip Top mine, Fourmile quadrangle, Custer County, South Dakota, U.S.A.
Eirikite	1160	Ilímaussaq complex, Narsaq, West Greenland
Epididymite	1267	Igaliko complex, Narsaq, West Greenland
Euclase	2590	Dalgaranga pegmatite, near Mount Magnet, Western Australia, Australia
Eudidymite	1267	Igaliko complex, Narsaq, West Greenland
Faheyite	1702	Roosevelt mine, Custer County, South Dakota, U.S.A.

Ferrochiavennite	294	[a]Blåfjell, Langangen, Telemark and Tvedalen, Vestfold, Norway
Ferrotaaffeite-2*N'*2*S*	156	[a]Xianghualing ore field, Linwu County, Hunan Province, China
Ferrotaaffeite-6*N'*3*S*	1805	[a]Rosendal pegmatite, Kemiö Island, Southwestern Finland Region, Finland
Footemineite	345	[a]Foote mine, Kings Mountain, Cleveland County, North Carolina, U.S.A.
Fransoletite	1702	[a]Tip Top mine, Fourmile quadrangle, Custer County, South Dakota, U.S.A.
Friedrichbeckeite	0.4	[a]Bellerberg volcano, Ettringen, Eifel, Rhineland-Palatinate, Germany
Gadolinite-(Ce)	1850	Bastnäs mine, Skinnskatteberg District, Västmanland, Sweden
Gadolinite-(Y)	2847	Cooglegong pegmatites, East Pilbara, Western Australia, Australia
Gainesite	293	[a]Nevel quarry, Newry, Oxford County, Maine, U.S.A.
Genthelvite	1820	Utö, Södermanland, Sweden
Glucine	S[c]	[a,b]Boevskoye deposit, Kamensk-Ural'skii, Chelyabinsk Oblast', Russia
Greifensteinite	1702	Tip Top mine, Fourmile quadrangle, Custer County, South Dakota, U.S.A.
Gugiaite	294	Larvik plutonic complex, Norway
Guimarãesite	515	[a]Piauí valley, Taquaral, Itinga, Minas Gerais State, Brazil
Hambergite	1760	Animikie Red Ace pegmatite, Florence County, Wisconsin, USA
Harstigite	1825	[a]Harstigen Mine, Pajsberg, Persberg district, Värmland, Sweden
Helvite	2835	Mount Francisco pegmatites, East Pilbara, Western Australia, Australia
Herderite	500	Brazil: specific locality unknown
Hingganite-(Ce)	294	Arent quarry, Tvedalen, Larvik, Vestfold, Norway
"Hingganite-(Nd)"	100	[a]Bacúch deposit, western Carpathian Mountains, Slovakia
Hingganite-(Y)	1742	Hundholmen, Tysfjord, Nordland, Norway
Hingganite-(Yb)	1682	[b]Mount Ploskaya, western Keivy Massif, Kola Peninsula, Russia
Høgtuvaite	414	[a]Høgtuva, near Mo i Rana, Nordland, Norway
Hsianghualite	156	[a]Xianghualing ore field, Linwu County, Hunan Province, China
Hurlbutite	1820	Norrö, Södermanland, Sweden
Hyalotekite	1825	Långban deposit, Filipstad, Värmland, Sweden
Hydroxylherderite	2670	BEP pegmatite, Bird River Greenstone Belt, Manitoba, Canada
Jeffreyite	440	[a]Jeffrey mine, Asbestos, Quebec, Canada
Joesmithite	1825	[a]Långban deposit, Filipstad, Värmland, Sweden
Khmaralite	2485	[a]Khmara Bay, Enderby Land, East Antarctica
Leifite	1267	Igaliko complex, Narsaq, West Greenland
Leucophanite	1267	Igaliko complex, Narsaq, West Greenland

Liberite	156	[a]Xianghualing ore field, Linwu County, Hunan Province, China
Londonite	1760	[d]Animikie Red Ace pegmatite, Florence County, Wisconsin, USA
Lovdarite	1160	Ilímaussaq complex, Narsaq, West Greenland
Mg-taaffeite-2N'2S	1538	Lupikko deposit, Pitkäranta, Lake Ladoga region, Karelia, Russia
Mg-taaffeite-6N'3S	2485	Khmara Bay, Enderby Land, East Antarctica
Makarochkinite	265	[a]Pit 400 near Lake Ishkul', Il'men Mountains (southern Urals), Russia
Mariinskite	250	[a]Mariinskoye emerald deposit, Malysheva, Sverdlovskaya Oblast', Russia
Mccrillisite	293	[a]Mount Mica quarry, South Paris, Oxford County, Maine, U.S.A.
Meliphanite	2680	Sakharijok massif, Kola Peninsula, Russia
Milarite	1820	Utö, Södermanland, Sweden
Minasgeraisite-(Y)	580	[a]Lavra de Sr. José Pinto, Jaguaraçu, Minas Gerais, Brazil
Minjiangite	300	[a]Nanping No. 31 pegmatite, Fujian Province, China
Moraesite	2550	Londonderry pegmatite, Coolgardie, Western Australia, Australia
Mottanaite-(Ce)	0.4	[a]Monte Cavalluccio, Roman Comagmatic Province, Latium, Italy
Nabesite	1160	[a]Ilímaussaq complex, Narsaq, West Greenland
Niveolanite	124	[a]Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada
Odintsovite	1160	Ilímaussaq complex, Narsaq, West Greenland
Oftedalite	967	[a]Heftetjern pegmatite, Tørdal, Telemark, Norway
Pahasapaite	1702	[a]Tip Top mine, Fourmile quadrangle, Custer County, South Dakota, U.S.A.
Parafransoletite	1702	[a]Tip Top mine, Fourmile quadrangle, Custer County, South Dakota, U.S.A.
Pezzottaite	500	Sakavalana pegmatite, Ambatovita, Amoron'I Mania Region, Madagascar
Phenakite	2969	Gravelotte, Murchison greenstone belt, South Africa
Rhodizite	500	[a]Ambatofinandrahana, Ankarata Mountains, Madagascar
Roggianite	250	Izumrudnye Kopi, Tokovaya River, Middle Urals, Russia
Roscherite	1702	Tip Top mine, Fourmile quadrangle, Custer County, South Dakota, U.S.A.
Ruifrancoite	582	[a]Sapucaia mine, Galiléia County, Minas Gerais, Brazil
Samfowlerite	940	[a]Franklin mine, Franklin, Sussex County, New Jersey, U.S.A.
Selwynite	385	[a]Wycheproof quarry, Wycheproof, Victoria, Australia
Semenovite-(Ce)	1160	[a]Ilímaussaq complex, Narsaq, West Greenland
Sørensenite	1160	[a]Ilímaussaq complex, Narsaq, West Greenland
Sphaerobertrandite	1160	Ilímaussaq complex, Narsaq, West Greenland

Stoppaniite	0.4	[a]Vico Lake, Roman Comagmatic Province, Latium, Italy
Strontiohurlbutite	300	[a]Nanping No. 31 pegmatite, Fujian Province, China
Surinamite	2485	Khmara Bay, Enderby Land, East Antarctica
Sverigeite	1825	[a]Långban deposit, Filipstad, Värmland, Sweden
Swedenborgite	1825	[a]Långban deposit, Filipstad, Värmland, Sweden
Telyushenkoite	170	[a]Darai-Pioz Glacier, Alai Range, Tien Shan Mountains Tajikistan
Tiptopite	1702	[a]Tip Top mine, Fourmile quadrangle, Custer County, South Dakota, U.S.A.
Trimerite	1825	[a]Långban deposit, Filipstad, Värmland, Sweden
Tugtupite	1160	Ilímaussaq complex, Narsaq, West Greenland
Tvedalite	294	[a]Vevja quarry, Tvedalen, Larvik, Vestfold, Norway
Unnamed (IMA 2013-045)	248	[a]Byrud Emerald Mine, Minnesund, Eidsvoll, Akershus, Norway
Unnamed	1240	Strange Lake peralkaline complex, Quebec-Labrador, Canada
Uralolite	515	Piauí valley, Taquaral, Itinga, Minas Gerais State, Brazil
Väyrynenite	1820	Norrö, Södermanland, Sweden
Wawayandaite	940	[a]Franklin mine, Franklin, Sussex County, New Jersey, U.S.A.
Weinebeneite	70	[a]Weinebene Pass, Koralpe, Carinthia, Austria
Welshite	1825	[a]Långban deposit, Filipstad, Värmland, Sweden
Zanazziite	582	Linópolis, Divino das Laranjeiras, Minas Gerais State, Brazil

Notes: [a]Mineral is reported from only one locality.

[b]Locality given in Pekov (1998), together with brief description of the mineral

[c]Supergene, and the age cannot be determined

[d]Reported as rhodizite

n.d. - not determined

Reference for mineral	Reference for age	Single locality	
Raade et al. (2009)	Larsen (2010)		1
Mihajlović et al. (2004)	Schminke (2007)		1
Holtstam and Langhof (2007) Husdal (2011)	Jonsson (2004) Husdal (2008)		1
Chuganov et al. (2006)	Pedrosa-Soares et al. (2011)		1
Nazarova et al. (1975 Holtstam and Langhof (2007) Jacobson et al. (2007) Bergstøl and Juve (1988)	Bulnaev (2006) Jonsson (2004) Jacobson et al. (2007) Andersen et al. (2007)		1
Kopchenova and Sidorenko (1962) Lyalina et al. (2009)	Kopchenova and Sidorenko (1962) Zozulya et al. (2007)		1
Nefedov (1967) Holtstam and Langhof (2007) Jacobson et al. (2007) Trumbull (1993) Markl (2001) Černa et al (2002) Jacobson et al. (2007) Holtstam and Langhof (2007)	Stein et al. (2003) Jonsson (2004) Jacobson et al. (2007) Trumbull (1993) Krumrei et al. (2006) Černý (2005) Jacobson et al. (2007) Jonsson (2004)		
Grice et al. (2009) Langhof et al. (2000) Markl (2001) Breaks et al. (2005)	Gilbert and Foland (1986) Romer and Smeds (1994) Krumrei et al. (2006) Breaks et al. (2005)		1
Voloshin et al. (1989) Jacobson et al. (2007)	Fershtater et al. (2007) Jacobson et al. (2007)		1
Robinson et al. (1985) Larsen et al. (2010) Petersen and Secher (1993) Jacobson et al. (2007) Petersen and Secher (1993) Robinson et al. (1992)	Dahl and Foland (2008) Krumrei et al. (2006) McCreath et al. (2012) Jacobson et al. (2007) McCreath et al. (2012) Dahl and Foland (2008)		1

Grice et al. (2013)	Larsen (2010)	1
Yang et al. (2012)	Yuan et al. (2008)	1
Burke and Lustenhouwer (1981)	Lindroos et al. (1996)	1
Atencio et al. (2008)	Swanson (2012)	1
Peacor et al. (1983)	Dahl and Foland (2008)	1
Lengauer et al. (2009)	Schminke (2007)	1
Holtstam and Andersson (2007)	Allen et al. (1996)	
Jacobson et al. (2007)	Jacobson et al. (2007)	
Moore et al. (1983)	Wise and Brown (2010)	1
Langhof et al. (2000)	Romer and Smeds (1994)	
Grigor'yev (1963)	Ginzberg et al. (1966)	1
Nizamoff et al. (2006)	Dahl and Foland (2008)	
Grice and Kristiansen (2013)	Larsen (2010)	
Chuganov et al. (2007)	Pedrosa-Soares et al. (2011)	1
Falster et al. (1996)	Sirbescu et al. (2008)	
Flink (1917)	Jonsson (2004)	1
Jacobson et al. (2007)	Jacobson et al. (2007)	
Dunn and Wight (1976)	Pedrosa-Soares et al. (2011)	
Larsen (2010)	Larsen (2010)	
Pršek et al. (2010)	Pršek et al. (2010)	1
Husdal (2008)	Andresen and Tull (1986)	
Belolipetskii and Voloshin (1996)	Bayanova and Voloshin (1999)	
Grauch et al. (1994)	Skår (2002)	1
Huang et al. (1988)	Yuan et al. (2008)	1
Nysten and Gustafsson (1993)	Romer and Smeds (1994)	
Grew et al. (1994)	Jonsson (2004)	
Černá et al (2002)	Černý (2005)	
Grice and Robinson (1984)	Normand and Williams (2007)	1
Holtstam and Langhof (2007)	Jonsson (2004)	1
Barbier et al. (1999)	Hokada and Harley (2004)	1
Petersen and Secher (1993)	McCreath et al. (2012)	
Petersen and Secher (1993)	McCreath et al. (2012)	

Chao (1964)	Yuan et al. (2008)	1
Falster et al. (2001a)	Sirbescu et al. (2008)	
Petersen et al. (2002a)	Krumrei et al. (2006)	
Schmetzer (1983)	Stein et al. (2003)	
Grew et al. (2000)	Hokada and Harley (2004)	
Grew et al. (2005)	Grew et al. (2005)	1
Pautov et al. (2012)	Fershtater et al. (2007)	1
Foord et al. (1994)	Wise and Brown (2010)	1
Bel'kov and Denisov (1968)	Zozulya et al. (2007)	
Langhof et al. (2000)	Romer and Smeds (1994)	
Foord et al. (1986)	Pedrosa-Soares et al. (2011)	1
Rao et al. (2013a)	Rao et al. (2009)	1
Jacobson et al. (2007)	Jacobson et al. (2007)	
Della Ventura et al. (2002)	De Rita et al. (1983)	1
Petersen et al. (2002b)	Krumrei et al. (2006)	1
Pekov et al. (2008)	Gilbert and Foland (1986)	1
Petersen et al. (2001)	Krumrei et al. (2006)	
Cooper et al. (2006)	Andersen et al. (2007)	1
Rouse et al. (1987)	Dahl and Foland (2008)	1
Kampf et al. (1992)	Dahl and Foland (2008)	1
Hawthorne et al. (2004)	Fernandez et al. (2003)	
Grundmann and Morteani (1989)	Poujol (2001)	
Pring et al. (1986)	Fernandez et al. (2003)	1
Voloshin et al. (1986)	Fershtater et al. (2007)	
Campbell and Roberts (1986)	Dahl and Foland (2008)	
Atencio et al. (2007)	Pedrosa-Soares et al. (2011)	1
Rouse et al. (1994)	Volkert et al. (2005)	1
Birch et al. (1995)	Birch et al. (1995)	1
Petersen and Secher (1993)	Krumrei et al. (2006)	1
Petersen and Secher (1993)	Krumrei et al. (2006)	1
Pekov et al. (2003)	Krumrei et al. (2006)	

Della Ventura et al. (2000)	Fornasera (1985)	1
Rao et al. (2013b)	Rao et al. (2009)	1
Grew et al. (2000)	Hokada and Harley (2004)	
Holtstam and Langhof (2007)	Jonsson (2004)	1
Holtstam and Langhof (2007)	Jonsson (2004)	1
Agakhanov et al. (2003)	Grew et al. (1993)	1
Grice et al. (1985)	Dahl and Foland (2008)	1
Holtstam and Langhof (2007)	Jonsson (2004)	1
Petersen and Secher (1993)	Krumrei et al. (2006)	
Larsen (2010)	Larsen (2010)	1
Raade and Balić-Žunić (2006)	Sundvoll et al. (1990)	1
Černý et al. (1991)	Miller et al. (1997)	
http://www.mindat.org/min-4099.html	Pedrosa-Soares et al. (2011)	
Nysten and Gustafsson (1993)	Romer and Smeds (1994)	
Dunn et al. (1990)	Volkert et al. (2005)	1
Walter (1992)	Thöni and Miller (2000)	1
Grew et al. (2007)	Jonsson (2004)	1
Atencio et al. (2005)	Pedrosa-Soares et al. (2011)	

Table 3. Reported latest occurrences and number of localities of be

Mineral name	No. of localities	Age (Ma)
Asbecasite	4	0.2
Barylite	many	113
Bavenite	many	17.5
Bazzite	many	17.5
Behoite	7	5
Berborite	2	294
Bergslagite	7	17.5
Bertrandite	many	5
Beryl	many	5
Beryllite	3	362
Beryllonite	many	5
Bityite	many	33
Bromellite	8	156
Chiavennite	4	30
Chkalovite	4	124
Chrysoberyl	many	20
Danalite	many	30
Eirikite	5	124
Epididymite	many	35
Euclase	many	17.5
Eudidymite	9	113
Faheyite	2	582
Gadolinite-(Ce)	3	294
Gadolinite-(Y)	many	0.4
Genthelvite	many	124
Greifensteinite	9	70
Gugiaite	5	90.5
Hambergite	many	5
Helvite	many	0.4
Herderite	4	20
Hingganite-(Ce)	5	67
Hingganite-(Y)	many	67

Hingganite-(Yb)	2	920
Hurlbutite	many	293
Hyalotekite	2	170
Hydroxylherderite	many	5
Leifite	5	124
Leucophanite	many	124
Londonite	3	250
Lovdarite	3	2
Mg-taaffeite-2N’2S	7	20
Mg-taaffeite-6N’3S	8	263
Meliphanite	5	33
Milarite	many	17.5
Moraesite	many	293
Odintsovite	2	118
Pezzottaite	3	20
Phenakite	many	6.8
Roggianite	2	33
Roscherite	5	70
Sphaerobertrandite	5	156
Surinamite	5	1050
Tugtupite	4	124
Uralite	6	70
Väyrynenite	many	5
Zanazziite	5	293

eryllium minerals in the geologic record

Locality	Reference for mineral
Tre Croci, Vico volcanic complex, Roman Comagmatic Province, Latium, Italy	Sacerdoti et al (1993)
Zomba–Malosa pluton, Chilwa Alkaline Province, southern Malawi	Demartin et al. (2003)
Alpine fissures Aar and Gotthard Massifs, Switzerland	Weibel et al. (1990)
Alpine fissures Aar and Gotthard Massifs, Switzerland	Weibel et al. (1990)
Honeycomb Hills, Juab County, Utah	Montoya et al. (1964)
Larvik plutonic complex, Langesundfjord-Porsgrunn area, Norway	Larsen (2010)
Alpine fissures, probably Gotthard Massif, Switzerland	Weibel et al. (1990)
Stak Nala, Nanga Parbat - Haramosh massif, northern Pakistan	Laurs et al. (1998)
Stak Nala, Nanga Parbat - Haramosh massif, northern Pakistan	Laurs et al. (1998)
Lovozero massif, Kola Peninsula, Russia	Pekov (2000)
Drot, Nanga Parbat - Haramosh massif, northern Pakistan	Laurs et al. (1998)
Vigezzo valley, Western Alps, Italy	Guastoni and Pezzotta (2008)
Xianghualing ore field, Linwu County, Hunan Province, China	Huang et al. (1988)
Chiavenna, Tanno, Sondrio, Lombardy, Italy	Bondi et al. (1983)
Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada	Horváth and Horváth-Pfenninger (2000)
Mogok gem mining area, Myanmar	Themelis (2008)
Pizzi dei Rossi, Forno, Bergell, Graubünden, Switerland	Weibel et al. (1990)
Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada	Larsen et al. (2010)
Wind Mountain, Cornudas Mountains, New Mexico	mindat; Horvath (pers. comm. 2013)
Alpine fissure, Pizzo Giubine (St Gotthard Pass), Switzerland	Demartin (1992)
Zomba–Malosa pluton, Chilwa Alkaline Province, southern Malawi	Gatta et al (2008)
Sapucaia mine, Galiléia County, Minas Gerais, Brazil	Lindberg and Murata (1953)
Larvik Intrusive Complex, Oslo	Larsen (2010)
Vico Lake, Roman Comagmatic Province, Latium, Italy	Camara et al (2008)
Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada	Horváth and Horváth-Pfenninger (2000)
Weinebene Pass, Koralpe, Carinthia, Austria	Chukanov et al. (2003)
Yuge Island, Ochigun, Ehime Prefecture, Japan	Minakawa and Yoshimoto (1998)
Stak Nala, Nanga Parbat - Haramosh massif, northern Pakistan	Laurs et al. (1998)
Vico Lake, Roman Comagmatic Province, Latium, Italy	Rossi et al. (1995)
Mogok gem mining area, Myanmar	Harlow and Hawthorne (2008)
Tahara, Hirukawa mura, Gifu Prefecture, Japan	Miyawaki et al. (2007)
Tahara, Hirukawa mura, Gifu Prefecture, Japan	Miyawaki et al. (2007)

Tangen-bruddet, Kragerø, Telemark, Norway	Kristiansen (1994)
Black Mtn quarries, Rumford, Maine	King and Foord (1994)
Darai-Pioz Glacier, Alai Range, Tien Shan Mountains Tajikistan	Grew et al. (1994)
Drot, Nanga Parbat - Haramosh massif, northern Pakistan	Laurs et al. (1998)
Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada	Larsen et al. (2010)
Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada	Horváth and Horváth-Pfenninger (2000)
Murzinka and Rezh districts, central Urals, Russia	Pekov et al. (2010)
Point of Rocks (formerly Peck's) Mesa, near Springer, Coalfax County, N.M.	DeMark (1984, 1989)
Mogok gem mining area, Myanmar	Schmetzer et al (2000)
Stubenberg am See, Styria, Austria	Bernhard et al. (2008)
Vigezzo valley, Western Alps, Italy	Guastoni and Pezzotta (2008)
Alpine fissures, mostly Aar massif	Weibel et al. (1990)
Greenwood, Newry and Paris, Maine	King and Foord (1994)
Malyy Murun alkalic pluton, Irkutsk Oblast, Russia	Konev et al. (1995)
Momeik, Mogok gem mining area, Myanmar	Devouard et al. (2007)
Facciatoia pegmatite, Island of Elba, Italy	Ceciliato (2007)
Vigezzo valley, Western Alps, Italy	Guastoni and Pezzotta (2008)
Weinebene Pass, Koralpe, Carinthia, Austria	Chukanov et al. (2003)
Xianghualing ore field, Linwu County, Hunan Province, China	Huang et al. (1988)
Chimwala area near Chipata, Eastern Province, Zambia	De Roever and Vrána (1985)
Mont Saint-Hilaire complex, Rouville RCM, Montérégie, Québec, Canada	Horváth and Horváth-Pfenninger (2000)
Weinebene Pass, Koralpe, Carinthia, Austria	Mereiter et al. (1994)
Sassi, Nanga Parbat - Haramosh massif, northern Pakistan	Huminicki and Hawthorne (2000)
Market Prospect, Newry, Maine	Nizamoff et al. (2006)

Reference for age
Sacerdoti et al (1993)
Eby et al. (1995)
Mullis et al. (1994)
Mullis et al. (1994)
Lindsey (1977)
Larsen (2010)
Mullis et al. (1994)
Laurs et al. (1998)
Laurs et al. (1998)
Pekov (2000)
Laurs et al. (1998)
Guastoni and Pezzotta (2008)
Yuan et al. (2008)
von Blanckenburg (1992)
Gilbert and Foland (1986)
Themelis (2008)
von Blanckenburg (1992)
Gilbert and Foland (1986)
McLemore et al. (1996)
Mullis et al. (1994)
Eby et al. (1995)
Pedrosa-Soares et al. (2011)
Larsen (2010)
Fornasera (1985)
Gilbert and Foland (1986)
Thöni and Miller (2000)
Shibata and Ishihara (1979)
Laurs et al. (1998)
Fornasera (1985)
Themelis (2008)
Takahashi et al (2007)
Takahashi et al (2007)

Andersen et al. (2002)
Wise and Brown (2010)
Grew et al. (1993)
Laurs et al. (1998)
Gilbert and Foland (1986)
Gilbert and Foland (1986)
Fershtater et al. (2007)
Collins (1949)
Themelis (2008)
Tropper et al. (2007)
Guastoni and Pezzotta (2008)
Mullis et al. (1994)
Wise and Brown (2010)
Orlova (1987)
Themelis (2008)
Aurisicchio et al (2002)
Guastoni and Pezzotta (2008)
Thöni and Miller (2000)
Yuan et al. (2008)
Johnson et al. (2006)
Gilbert and Foland (1986)
Thöni and Miller (2000)
Laurs et al. (1998)
Wise and Brown (2010)

Table 4. Beryllium minerals in alkalic complexes

Complex	Age (Ma)	Total species	New species[a]	Species found only in one complex	Species not found elsewhere	Other essential constituents in Be minerals[b]
Sakharijok	2680	2	2	0	0	–
Igaliko	1267	4	4	0	0	–
Ilímaussaq	1160	18	10	0	3	S, Cl, Ti, Mn, Zn, Sn, Ba, Ce
Khibiny	362	12	0	0	0	Cl, Ba, Ce
Lovozero	362	10	0	1	0	P, S, Zn
Larvik	294	26	3	4	3	B, S, Mn, Zn, Y, Ba, Ce
Saint-Hilaire	124	19	2	1	2	C, S, Cl, Mn, Zn, Y, Ba, Ce
Zomba-Malosa	113	7	0	1	0	S, Zn Y, Ba

Note: [a]First occurrence in the geologic record (Table 2). [b]Excluding Na, K, Ca, Al, Si, O, H and F. Y and Ce include heavy and light rare earth elements, respectively

Table 5. Coexisting elements in Be minerals.

Element	# minerals	# with Be	Element	#minerals	#with Be
Li	115	8	Se	115	0
B	263	7	Br	12	0
C	397	1	Rb	3	0
N	92	0	Sr	126	1
O	3957	112	Y	118	5
F	367	11	Zr	120	3
Na	919	28	Nb	142	0
Mg	626	12	Mo	60	0
Al	1009	28	Ag	167	0
Si	1434	66	Cd	28	0
P	567	28	In	12	0
S	1006	3	Sn	89	2
Cl	357	2	Sb	245	2
K	434	13	Te	159	0
Ca	1195	48	Cs	17	4
Sc	16	2	Ba	220	4
Ti	334	4	La	45	0
V	207	1	Ce	146	5
Cr	93	1	Nd	26	1
Mn	519	14	Yb	5	1
Fe	1060	18	Ta	58	0
Co	63	0	W	41	0
Ni	149	0	Hg	92	0
Cu	633	0	Pb	502	2
Zn	242	5	Bi	214	0
Ga	5	0	Th	33	0
Ge	29	0	U	245	0
As	562	3			

Note: For each element, the first column gives the number of approved mineral species for that element (based on the IMA master list at the RRUFF website, http://rruff.info/ima/ as of October 18, 2013), whereas the second column gives the number of Be minerals that also incorporate that element (Table 1), e.g., there are 115 known lithium minerals, of which 8 incorporate Be.