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Revision 1

Trends in the discovery of new minerals over the last century

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Abstract

Patterns in the discovery and description of new minerals over the last century emerge from a new database of 4,046 mineral discovery reports (roughly ¾ of all known minerals). The number of new minerals discovered per year was steady over time from 1917 to the early 1950s, when it began a rapid increase punctuated by spikes in 1962-1969, 1978-1982, and 2008-2016, the last of which is probably still ongoing. A detailed breakdown of the technological, geographic, institutional, and other characteristics of mineral discovery in this dataset elucidates factors leading to increases in mineral discovery. (1) The availability of instrumentation for a particular analytical technique has

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a far larger impact on the rate of its uptake in mineral discovery than the technique's invention or computer-automation. (2) Samples from mines, quarries, and resource exploration have produced around 2/3 of all new mineral discoveries due to geochemical peculiarity and good exposure; lunar and meteoritic samples have contributed relatively few new minerals. (3) Peralkaline intrusions and volcanic fumaroles are the next most productive sites of new mineral discovery. (4) Which countries host mineralogists who discover large numbers of new minerals has varied over time, but is always a relatively small number (< 20) and mineral discovery is highly concentrated in specific laboratories or workgroups. (5) Involvement of governmental organizations in new mineral discovery peaked in the aftermath of World War II and has since declined to almost nil, with new mineral discoveries now coming primarily from universities and similar academic institutions (75%) and from museums (25%). (6) The average number of authors on mineral discovery papers has risen from < 1.5 in 1950 to > 6 now and follows an exponential trend. (7) The average number of methods used to characterize new minerals has not changed significantly since 1960, and about half of new mineral descriptions are made using roughly the minimum of analyses required for a new mineral to be recognized. (8) A partial study of discredited or redefined minerals identified changes to nomenclature and classification as the primary causes for discreditation; failure to replicate analytical results is a distant second. Only five cases of fraudulent mineral discovery are known. This article presents the data underlying these analyses and discusses some possible reasons for the observed trends in the rate of new mineral discovery, as well as the implications for the history (and future) of mineralogy.

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Introduction

The discovery of new minerals can help to extend the range of known compositions and structures, provide geologists and petrologists with valuable data on phase relations and parageneses in natural systems of the past, and extend our understanding of chemical and crystal structure (e.g. Dana, 1892; Hazen et al., 2008; Heaney, 2016). However, much remains to be discovered about the process of making such discoveries, especially what technological, historical, and other factors affect it. This article presents the results of compiling and analyzing data from 4,046 minerals discovered between 1917 and 2016. Principal foci include what historical events have influenced new mineral discovery; the influence of technological progress and new analytical techniques; the geographical, geological, and institutional demographics of past and current mineral discoveries; and various other factors that have affected the discovery of new minerals.

Methods

The approved International Mineralogical Association (IMA) Mineral List as of April 2017 was exported from the RRUFF database (rruff.info) into a spreadsheet and sorted by year. Minerals that were "discovered" through renaming, without the presentation of extensive new analytical work, were removed from the list. The remaining 4,046 minerals represent about ¾ of currently approved IMA minerals. From each of the published articles that first described the new mineral, I recorded the

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technique used for structure or symmetry determination, chemical analysis, and supplementary analyses; the institutional affiliation of the corresponding author and the country that the institution was located in; and whether or not the study had been directly supported by a government funding agency (exclusive of paying for capital equipment, chaired professorships, generic postdoctoral scholarships, and other sponsorship not directed toward the specific study in which the new mineral was discovered). To examine the relative contributions of meteoritic studies, space exploration, and mining activities to mineral discovery, I also recorded whether or not the type sample was derived from a lunar or meteoritic rock and whether or not it came from mining, quarrying, or exploration sampling.

Original discovery papers written in English, Spanish, and French were read and used. Discovery reports written in other languages were not accessible, and database entries for those minerals are based on the figures and tables, the English abstracts where available, and the summary of the paper provided in the year's "New mineral names" compilation by the *American Mineralogist* and/or the *Canadian Mineralogist*. Attempts to use Google Translate largely failed owing to a combination of poor optical character recognition and Google's lack of appropriate technical vocabulary. Thus a disproportionate number of the "unknown" entries in the database (Digital Appendix) pertain to minerals whose original descriptions were in Russian or Chinese. Another large group of "unknown" entries is from minerals discovered from 2016 to the present, as the details of discovery of many of these have not yet been published. "Unknowns" were not excluded from the statistics calculated and presented here (e.g. if 85 of 100 minerals were analyzed by electron microprobe and the remaining 15 by unknown methods that may or

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may not include the electron microprobe, the statistics will show a microprobe usage rate of 85% even though the actual number would likely be higher).

Results and reasons for them

Mineral discoveries over time

The graph of mineral discoveries per year (Fig. 1) shows several secular trends, most notably a general overall increase. Low points are obvious during and immediately after both world wars. The slight upward trend in mineral discoveries during the 1920s, followed by the sharp decrease in 1929, is probably due to the onset of the Great Depression. Not until the mid-1950s did the number of minerals discovered per year consistently exceed the 1920s average. Thereafter a strong upward trend began, and continues today.

The prominent spikes between 1962-1969, 1978-1982, and 2008-2016 (Fig. 1) reflect a variety of potential factors. The most likely contributors to the first spike are advances in X-ray diffractometry (XRD) and/or microprobe technology and availability (Fig. 2). The Bragg family solved the first mineral structure in 1913, but for several decades afterwards obtaining structural data from XRD remained laborious, intricate, and imprecise, and XRD equipment was scarce (e.g. Hawthorne, 1993; Angel and Nestola, 2016). The advent of computers, among other advances, made crystal structure determination faster and easier. Additional, ancillary factors include the creation of the U.S. National Science Foundation (NSF), which throughout the 1950s-60s helped American universities and government institutions to obtain advanced analytical equipment; the American uranium exploration boom, in which many new U and V minerals were discovered; and the organization of the U.S.S.R.'s Commission on New Minerals (1955) and the IMA's analogous Commission on New Minerals and Mineral Names (1959) (now the Commission on New Minerals, Nomenclature, and Classification or CNMNC). The second spike (1978-1982) is also probably technological, as the computer-automation of the X-ray diffractometer and the electron microprobe made chemical analyses far easier (e.g. Sheldrick, 2008) and the number and availability of the computer-readable diffraction data from the ICDD database expanded.

The 2008-2016 spike, which is likely still ongoing, is probably due to different reasons. The previous decade saw no major exploration booms, and technological changes (such as the adoption of CCD XRD detectors) were gradual and continuous rather than stepwise (Angel and Nestola, 2016). Three different explanations, not mutually exclusive, are possible. Firstly, the spike may relate to the launches of several online mineralogical databases in the preceding years (Fig. 1), which would have made it easier to obtain comparative spectral, chemical, and XRD data for known mineral species. Secondly, the number of mineral discovery articles that reported government funding closely tracks the late-1990s increase and the late-2000s spike in the number of new minerals discovered (Fig. 3). This correlation between funded studies and new mineral discoveries indicates that increased government funding has likely driven the recent spike in new mineral discovery. Thirdly, this third spike may reflect the recent "mineralogy renaissance" or renewal of interest and research on minerals, especially at the nano-scale (Putirka, 2015). A possible contributing factor is the high price of mineral specimens in collecting circles, which creates incentives to scrutinize specimens closely and which may lead to the discovery of previously unknown minerals in the sample.

Why were the increases in mineral discovery rate spikes, not sustained rises? The reasons are uncertain. The end of the first spike (1969 to early 1970s) coincides with the dramatic slowdown in the American uranium exploration program, which had supplied a large number of new minerals during the previous years, but new minerals continued to be found in shelved samples for decades afterward. The end of the second spike (mid-1980s) is a mystery. The improvements in XRD, microprobe, and computer technology had not gone away, but the number of minerals discovered per year still dropped by half, perhaps reflecting a loss of interest in finding more new minerals at key centers of mineral discovery. The apparent end of the third spike is probably fictive, since many of the 2016 entries in the database are "unknown" due to lack of publication. Preliminary CNMNC figures from 2017-18 suggest that the third spike is in fact continuing (A. Kampf, pers. comm., 2018).

Evolution of methods

Technological progress over the last century has led to numerous changes in the rate and methods of describing new minerals (e.g. Angel and Nestola, 2016; Grew et al., 2017). From 1917 to the early 1950s, wet-chemical determination was the only available means of quantitatively analyzing mineral composition and thus monopolized new mineral discoveries (Fig. 2). (Deviations from 100% represent studies in which the means of chemical analysis was marked "unknown" in the database due to a language barrier; however, it can be safely assumed that before the 1950s virtually all new minerals were chemically analyzed by wet methods or spectrography.) The first viable electron microprobe was invented in the late 1940s and commercialized by Cameca in 1956, but some five years later there were still fewer than 20 electron microprobes worldwide

(Rinaldi and Llovet, 2015). Moreover, for a long time microprobe analyses offered no advantages in quality, efficiency, or ease compared to wet-chemical methods (P. Barton, pers. comm., 2018). Making standards, analyzing them, and making measurements of a single sample on early microprobes often took days. (For scale, a University of Michigan professor was skeptical of the minerals "discovered" in the notorious 1970s mineral fraud in part because the discoverer had used far less than the several hundred hours of microprobe time that he would plausibly have needed to analyze the five new minerals; Crook v. Baker, 584 F. Supp. 1531.) Early microprobes could not precisely analyze light elements or oxygen, so many new minerals required further analysis by wet-chemical or other techniques to complement the microprobe work (some still do). Because of all these factors, until the late 1960s the microprobe was a technique of last resort for minerals that could not be separated with sufficient purity, or in enough quantity, for wet-chemical analysis. Starting around 1970, developments in computer technology enabled the development of automated, computer-based programs for focusing, standardization, and data collection; at the same time, both microprobes themselves and ancillary supplies like well-characterized standards became far more widely available. The electron microprobe overtook wet-chemical methods in 1970, and since then its dominance has been nearly complete (Fig. 2).

Infrared spectrometry (IR) was commercially available by 1944. While IR was never a primary technique in mineral discovery, it did start to become a significant feature of new mineral discoveries around the early 1970s. From that time IR use grew steadily until about 1999, perhaps since it was useful as a supplement to the increasingly popular electron microprobe, which (unlike some wet-chemical methods) did not yield quantitative measurements of water. A contemporaneous decline in the use of thermogravimetric and differential thermal analysis – never very widely used – supports this (Fig. 2).

As with all the other analytical techniques, Raman spectrometry was not widely used for some decades after its invention and commercialization in the early 1950s. In the 1990s Raman use began to increase, but was used in < 10% of all new mineral discoveries through 2006. Between 2006 and 2007 this share jumped to 25%, and has not dipped below 20% since. The likely explanations for the sudden sharp rise in Raman use are the increasing availability of Raman spectrometers in mineralogy labs and of comparative Raman data in online databases such as RRUFF.

X-ray diffractometry did not come into wide use until the early 1930s, nearly two decades after the first XRD crystal structure solution. Before the 1930s XRD instruments and expertise were rare, measurements were tedious to make and difficult to interpret, and comparatively large amounts of pure material were required. Although many of the materials first analyzed in early XRD work were minerals, most were specimens already identified, as the difficulty of making and interpreting measurements discouraged use on unknown samples. From 1930 to 1950 XRD use in describing new minerals rose dramatically. This was in large part due to a proliferation of X-ray research groups and equipment at laboratories in Britain and the United States in the 1930s (Wyckoff, 1962; Bernal, 1962). Subsidiary factors in the later years of this increase included the easy referencing facilitated by the ICDD (International Center for Diffraction Data, formerly Joint Committee on Powder Diffraction Standards or JCDPS) starting in 1941 and the availability of commercial XRD equipment starting in 1945.

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Computerization and automated analytical routines have been given much of the credit for increasing usage of XRD and other analytical during the 20th century (e.g. Angel and Nestola, 2016). However, Figure 2 shows that more than 85% of new minerals were already being examined by XRD by the time the first computer programs were made widely available. Similarly, the electron microprobe was already being used in nearly 60% of new mineral descriptions by the time the first automated microprobe routines were published (Fig. 2). From these it is safe to conclude that a newly invented analytical technique can achieve extensive use before computerization makes it easy or convenient to use. Rather, delays between invention of an instrument and its widespread usage in new mineral descriptions most likely reflect the rarity of instruments for some years after their invention.

Geographical distribution of new mineral discovery

The geographical loci of new mineral discoveries, as assessed from the geographical location of the first author's institution, have shifted over time (Fig. 4a) and correlate only loosely with the places where new minerals are discovered (Fig. 4b). Both, however, are highly localized in a relatively small number of specific places, compared with the range of possible locations over the globe. Together, mineralogists working in the former U.S.S.R., the U.S.A., Canada, Italy, Germany, Australia, Japan, the U.K., France, and China have contributed > 80% of all new minerals discovered from 2000 to 2016. Type localities are more geographically diverse, but 65% of new mineral discoveries from 2000 to 2016 have come from localities in 10 countries (the U.S.A., the former U.S.S.R., Germany, Canada, Italy, Australia, Japan, China, Namibia, Chile).

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This highly localized distribution of modern mineral discovery arises from several factors, beyond the minimum of geopolitical stability needed for research to flourish and the minimum of geological variety and exposure necessary to find undiscovered minerals. Firstly, most new minerals come from complex and geochemically unusual rocks, particularly ore deposits, peralkaline intrusions, and volcanic fumaroles. Thus countries without many known examples of these, and researchers working in them, face automatic disadvantages in the hunt for new minerals. Secondly, the rate of new mineral discovery depends in part on the availability of national government funding for mineralogical studies, as described above (Fig. 3), which varies from country to country. Thirdly, mining and exploration activity are additional factors (discussed below), which are heavily concentrated in a relatively small fraction of the earth's crustal volume. Fourthly, as Bulakh et al. (2003) observed, some laboratories and workgroups emphasize the discovery of new minerals, and a disproportionate number of minerals are reported by the same people and groups – and ipso facto, with the same national affiliations. Lastly, the existence and discovery of new minerals would be expected to correlate with countries with more land area and more scientists at work, giving large nations with large populations an advantage.

Roles of academia, government agencies, and museums

Until the end of World War II, academic mineralogists described most new minerals, mineralogists working at museums described most of the remainder, and relatively few were described by mineralogists working at geological surveys, bureaus of mines, or other governmental entities (Fig. 5). Geologists working in mining, petroleum, consulting, or other industry jobs have consistently been first authors on mineral discovery papers describing 1-2 minerals per year. This institutional breakdown is about the same today as in the pre-war era, but from 1946 to the early 1970s nearly half of all new minerals were described by mineralogists at governmental entities. The nearly 30-year high in governmental contributions primarily reflects the American exploration boom for uranium and other strategic mineral resources, which led to a rash of new discoveries of Colorado Plateau minerals by U.S. Geological Survey geologists. The decline of uranium exploration coincides with the decline in governmental mineral discoveries. The reason for the surge in museum involvement around the same time is not clear, but may be related to an increase in available analytical facilities in museums at the time related to research in the space program.

The rise of university researchers to modern mineral discovery dominance could be explained in several ways. The first is that university lab facilities and researchers simply outnumber their equivalents in government agencies and museums. Another interpretation is that mineral discovery has become a much more crowd-sourced activity than in the past, with networks of collectors and dealers working hand in glove with mineralogists and analysts. Universities are natural foci for these networks, and the development of these networks could have led to the increase in the role of academic institutions. A less charitable explanation is that the increase in new mineral discovery at universities is at least partly due to the increasing consequence attached to numbers of publications in the academic environment, which incentivizes research projects that can be completed more quickly than (for example) a new geological map. This incentive is absent from governmental and industry environments, and could contribute to the comparatively greater emphasis on mineral discovery in academic than in government or industry environments.

Authorship of mineral discovery articles

One might assume that describing a new mineral was more difficult with the technology of 1960 than it is at present, and would have required more personnel then than now. The exponential increase in the number of people credited with authorship in describing new minerals defies this assumption (Fig. 6). If the present trend continues, the average mineral discovery publication in 2118 A.D. will include more than 30 authors.

The disconnection between the number of minerals described each year and the number of authors describing them is new. Until the late 1950s, the number of authors on mineral discovery papers closely tracked, and only slightly exceeded, the number of new minerals discovered (Fig. 6), and until 1955 no new mineral description required more than four researchers (Fig. 7a). In 1960, it took about two researchers, on average, to describe a new mineral. The average today is slightly over six, and single-author mineral discovery papers are becoming rarer (Fig. 7a). The increase is driven partly by the larger numbers of new minerals described by researchers in Brazil, Poland, the Czech Republic, and the former U.S.S.R., which have high average ratios of authors per new mineral (Fig. 7b). In part, the increase also reflects the broader trend toward increasing authorship in modern scientific publications, as well as increasing specialization and collaborative tendencies among academic researchers. Additionally, mineral discovery these days involves a much broader network than in the past. New minerals throughout most of the 20th century were generally found either by the same mineralogist(s) who examined their symmetry, analyzed their compositions, and measured their optical properties, or by a curious prospector or citizen who sent a mystery sample for analysis. In contrast, modern mineralogists are part of a worldwide constellation of mineral collectors, dealers, and enthusiasts, many of whom make new mineral discoveries a particular specialty. The increased size of this network has its reflection in the swelling numbers of co-authors on mineral discovery publications.

Geological and geographical distribution of new mineral finds

The highly localized geographic distribution of mineral type localities has been highlighted above. A major contributor to this localization at a few, highly prolific sites is geochemistry. The most prospective places to seek new minerals are geochemically anomalous, particularly (1) ore deposits, (2) peralkaline intrusions, and (3) fumaroles. (Ore deposits located in peralkaline intrusions have been particularly bounteous.) Of these locales, mines are by far the most productive. Some 62% to 69% of new minerals discovered in the last century were found through mining, quarrying, or resource exploration activities, and the share has been remarkably consistent over time (Fig. 8). This is probably due to a combination of improved subsurface access and the fact that mines coincide with ore deposits, which ipso facto contain elevated concentrations of normally rare elements, important for the formation and discovery of previously unknown minerals (Khomyakov, 2011; Atencio, 2015). However, most exploration and mining activities do not appear to drive mineral discovery in a direct sense, as there is little correlation between (for instance) Cu prices or production and the discovery of related minerals (Fig. 9). There are exceptions, such as a generalized increase in U and V mineral discoveries with increasing U price (Fig. 9). However, in general the data

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indicate that the role of exploration and mining is mostly to dig up and expose less weathered, perhaps metastable species in diverse geological environments.

A disproportionate number of new minerals are discovered from the same well-known collecting sites, mainly the Khibiny alkaline massif (108 new minerals), the Tobalchik volcanic vent system (94) and the Lovozero massif (92) in Russia. Tsumeb (Namibia), Långban (Sweden), Franklin and Sterling Hill (New Jersey, USA), and Mont Saint-Hilaire (Quebec, Canada) are also hotbeds of mineral discovery. These numbers from the database are lower than some published values (e.g. Atencio, 2015) owing to the exclusion of definitions based on nomenclature, pre-1917 minerals, and the "unknown" category. The totals for Russian sites are particularly low, since many U.S.S.R. mineral discovery papers from the Cold War era are deliberately vague in discussing the whereabouts of the type locality. In total, some 746 minerals, or 18.4% of the minerals in the database, were found at the same 20 locales, and this is probably an underestimate. This extreme concentration of new minerals at a few sites partly reflects a self-reinforcing cycle in which a locality becomes famous for producing new minerals, attracts more study from mineralogists, and consequently becomes likelier to produce still more.

The space missions of the 1969-1970s era have had little apparent effect on new mineral discovery (Fig. 8) with < 10 new minerals discovered in extraterrestrial samples in any given year and < 3 in most years. Most new minerals from extraterrestrial samples have come from meteorites, not the Moon. As Skinner and Skinner (1980) have pointed out, the Moon differs in geochemistry only slightly from the Earth, and the different

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physical conditions of the lunar surface are evidently not enough to change the nature of stable mineral species by very much.

Discreditations of minerals

I attempted to assess the reasons why minerals are discredited or redefined by exporting the IMA list of discredited minerals from the RRUFF database and looking up the reasons given for the discreditation. Nomenclature decisions are clearly the leading cause of mineral discreditation or redefinition, particularly among the amphiboles (Hawthorne et al., 2012) and pyrochlores (Atencio et al., 2010). The second most common cause of discreditation is failure to replicate by follow-up analytical work, either because the mineral turned out to be identical to one already discovered or because the type specimen deposited turned out not to contain the new mineral at all. No reason was given for the discreditation of six minerals, and two were discredited upon finding that the original work had been misunderstood or lost in translation (Ciriotti, 2015). The list in RRUFF includes only minerals discredited since 2006, but an evaluation of Burke (2006) and other discreditation reports suggests that the RRUFF list is reasonably representative.

The principal exception to this is the notorious episode summarized in the discreditation report by Peacor et al. (1982) and in court documents related to an ensuing lawsuit (Crook v. Baker, 584 F. Supp. 1531). A University of Michigan graduate student claimed to have discovered five new mineral species, which were approved by his thesis committee and the IMA despite some skepticism about their geochemical plausibility. The “minerals” turned out to be synthetic, chemically-purified rare earth element phases abstracted from a laboratory shelf, and some of their structural features were fabricated or copied from preexisting illustrations of other minerals (Peacor et al., 1982). No other cases of such apparently deliberate falsification are documented among new mineral descriptions.

As Hawthorne (1993) has pointed out, cross-checking results with multiple complementary or redundant analytical methods is one of the surest ways of ensuring that a mineral is properly described and remains valid. However, the present dataset shows that this is not commonly done. The average number of techniques used to document the characteristics of a new mineral in a published paper has stayed constant at about 2.5 since 1960, not counting optical measurements (techniques included are XRD, electron diffraction, wet chemistry, EPMA/SEM, X-ray fluorescence, IR spectrometry, Raman spectrometry, thermogravimetric or differential thermal analysis, and synthesis experiments). This is despite the increasing availability and diversity of analytical instrumentation since 1960, which suggests that reliance on a single technique for chemical analysis is cultural rather than technological. Chemical analyses are the IMA's requirements for approving a new mineral; a structure determination and optical properties are considered desirable but not required. So roughly half of all new mineral descriptions apply close to the bare minimum of analyses necessary to gather enough data for IMA approval. The lack of cross-checking probably contributes to the number of minerals later discredited on the basis of follow-up analytical work.

Discussion

Comparison with previous work

Bulakh et al. (2003) made a study of trends in the history of new mineral descriptions. Their paper did not quantitatively explore some of the social and

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technological aspects discussed, such as the time of uptake of different methods of analysis. However, they found the same general characteristics that we have in the pattern of mineral discoveries over time. Their pattern diverges slightly from ours in having major spikes in 1978 and 1997 due to the publication of IMA Reports of the Subcommittee on Amphiboles. In these reports many “new” minerals were listed, which are excluded from the database here since they arise from modifications in nomenclature. Our database has also served to quantify the details of methodological changes that Bulakh et al. discussed: the uptake of XRD and microprobe, the centralization of mineral discoveries among a relatively small group of mineralogists, and the geographical distribution of new mineral discoveries. In all of these, our results are substantially the same as theirs.

An article by Grew et al. (2017) provides similar insights into the discovery history of boron minerals. Their research found a large increase in the number of annual B mineral discoveries from the 1910s to the present, punctuated by a decline in the aftermath of World War I and a large spike in the late 1950s to mid-1960s (coincident with the first of the three spikes reported here). Although their article focused mainly on the potential future of boron mineral discovery and not on the history, they did trace the observed patterns back to several of the same factors identified above. Minerals exploration played a crucial role, with the Soviet pursuit of evaporite and skarn deposits leading to the 1950s-60s spike in discoveries. So did the uptake of the electron microprobe and related instrumentation, which caused a less sudden rise in B mineral discoveries. Grew et al. did not consider some of the other social, technological, and

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cultural factors identified above, and their work considers only B-bearing minerals, but in general their results are similar to those presented here.

Mineral discovery, present and future

In 1980, Skinner and Skinner published an article reporting briefly on the previous six decades of new mineral discovery and looking toward the future. Its title asked the question, Is there a limit to the number of new minerals? Nearly forty years later, it is interesting to revisit this and some of the additional problems they posed, which form some of the principal questions discussed in the literature on the future of mineralogy (e.g. Fleischer, 1969; Hawthorne, 1993; Bulakh et al., 2003; Khomyakov, 2011; Hazen et al., 2015). Will the rate of new mineral discovery be sustained? How, and where from, will new minerals be discovered in the future?

The first, titular question has been debated extensively and mineralogists over the last century have given varying answers (e.g. Fleischer, 1969 and references therein). A.E. Fersman thought that geological processes maintain physicochemical conditions that are too steady to permit most of the myriad possible elemental combinations to form. However, his suggested upper limit was 3000 species (Fersman, 1938), which has been passed with no end in sight. The Skinners themselves inclined to the opposite view. They noted that the original strict definition of a mineral has been extended to embrace some organic compounds as well as inorganic compounds that have grown on manmade objects, and suggested that further expansions of the definition, along with space travel, could make the number of possible minerals functionally infinite (Skinner and Skinner, 1980). Bulakh et al. (2003) also agreed on the near-infinity of possible minerals, but based on the conventions of nomenclature, particularly the IMA’s 50% rule. Khomyakov

(2011) likewise proposed that the universe of possible minerals is infinite for all practical purposes, based on recent discoveries of "unstable" minerals and on the diversity of possible geochemical environments. In contrast, Hazen et al. (2015b) state that "6394… is the predicted total number of distinct mineral species on Earth today," based on the statistics of known mineral occurrences compiled from crowd-sourced databases. More rigorous treatments of this question have been based on topological and geometrical studies of the possible structures in particular mineral groups, which elucidate the physically possible range of structural configurations given particular chemical constraints (e.g. Moore, 1965). The historical and modern trends presented here offer shaky ground for prognostications, but there is little reason to believe that the number of currently known mineral species is even close to the number that exist.

The Skinners' second question has been clearly answered in the negative (Fig. 1). In the 1990s the rate of new mineral discoveries ceased to follow the exponential pattern that they had identified. The number of minerals discovered since 1917 is about half of what it would be if the increase were truly exponential. The rate of new mineral discoveries per year may approach a linear increase in the future. An absolute decrease in the rate seems unlikely in the near term, since the most productive new mineral localities show no signs of exhaustion and there is no hint that all the possible compositional variations in even the most-studied mineral groups have been found (e.g. Grew et al., 2017).

The third question, where new minerals will come from, has had at most a partial answer from various sources. Urusov (2010) considered that the roughly 3,000 known mineral species known at that time reasonably represented the mineralogical possibilities

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of the crust, and that further major discoveries would come from the mantle and core. So far this has not proven to be the case, as nearly all of the new minerals discovered since then have been crustal. Many are what the Skinners foresaw: minerals small enough to have escaped detection in the past. Electron diffraction and high-precision Raman and EPMA now enable the quantitative characterization of crystals less than a micron in size (e.g. Ma and Rossman, 2008). Grew et al. (2017) found that in general, more recent boron mineral discoveries were made on samples with smaller grain sizes than earlier ones. Such "nanomineralogical" discoveries are likely to increase in future (perhaps limited only by the size of the cell edge) as analytical equipment grows ever more refined. And Khomyakov (2011) opined that even among macroscopic minerals, the number currently known is < 10% of the total. Where they will come from is difficult to predict. The earth's crust contains an enormous diversity of geochemical environments, varying greatly over time, and in a temperature range that allows many minerals to persist after formation in a metastable state. There is no prospect of an end to its mineralogical diversity.

Approaches to mineral discovery

How researchers approach the search for new minerals is seldom discussed in the articles in the database, and therefore was not recorded systematically. However, it became evident on a qualitative basis that serendipity plays the principal role in most discoveries. In certain cases luck is entirely responsible: a mineralogist stumbles upon or receives a sample containing a previously unknown species. But especially in modern times, mineral discovery is usually a combination of luck and deliberation: a mineralogist interested in finding a new mineral seeks out a geochemically anomalous location, or examines samples from it, looking empirically for minerals that do not match any in the catalog. This is one reason why so many new minerals come from the same few, well-known collecting sites. Only in a very few cases has a mineralogist made a discovery by examining compositional space, calculating that an undiscovered phase should be stable therein, and searching for it in samples containing the appropriate assemblages (e.g. Barton et al., 1978). Other approaches, such as searching for matches to known synthetic analogs, have not been very successful (Grew et al., 2017).

How minerals will be discovered in the future is uncertain. In the long run, diminishing returns will clearly affect the part-luck and part-deliberate ("find a promising site and look") approach that is currently the standard, since the mineralogical variety of any site is finite. The predictive approach may become more common in future, particularly as further new mineral discoveries increase the scientific understanding of the permissible structural and chemical arrangements within individual mineral groups.

Implications

This study has highlighted several conspicuous trends in mineral discovery from 1917-2016. The number of new minerals described each year has fluctuated strongly over time, its rate influenced by the availability of analytical techniques, of government funding for mineralogical studies, and perhaps of centralized databases of mineralogical information. New minerals are most likely to be discovered by mining or mining-related activities, with peralkaline intrusions and fumaroles being the next most productive sites after mines. Geographically, the distribution of mineralogists discovering the most new minerals has shifted over time, and the number of personnel involved in discovering new minerals has increased exponentially.

The > 5,300 minerals known today probably represent a small fraction of the minerals that exist. The future of new mineral discovery will likely differ from the trends of the past, but the analysis presented here may shed light on the technological, geological, and social factors that facilitate the discovery of previously unknown minerals and mineral structures. However, the results of this study can only hint at the answers to two important questions about new mineral discovery: What motivates mineralogists to search for previously undiscovered minerals? and What does the discovery of new minerals represent – scientific progress or stamp-collecting?

The answer to the first question never makes it into the descriptions of new minerals, and the database presented here gives only hints of a possible answer. Relevant evidence includes (1) the observed extreme concentration of new mineral discovery at a small number of research units (labs) worldwide and (2) the observed brevity of most mineral discovery papers. Most contain information about the mineral’s occurrence; paragenesis and other geological context; analytical techniques; compositional and crystallographic data; interpretation of mineral structure; implications for the structure of the mineral group; and little else. The comparatively minor space devoted to explaining how the new mineral affects concepts in mineralogy or geochemistry as a whole suggests that many mineralogists view the main point of discovering a new mineral as – making a new discovery. The concentration of mineral discovery at a relatively small number of centers offers support for the conjecture that many mineralogists engage in serial mineral discovery largely for its own sake, as the form of scientific endeavor they prefer over others.

As for the second question, the description of a new mineral by itself does little to advance mineralogical science, but progress does come from the information that the mineral yields about larger theoretical aspects of mineralogy. This includes everything from a new development in crystal chemistry, for example that some combination of factors makes a previously unknown substitution or bonding structure possible, to the information that the mineral contains about the geochemical environment where it formed. New minerals are new data useful for addressing such questions. The majority of mineral discoveries today, however, do not address them; a few discuss the insights the new mineral provides into crystal chemistry or the structures of other natural or synthetic phases. But the average mineral discovery paper is only a few pages long and contains minimal information about the new mineral's implications for phase equilibria, the geochemistry of the environment of formation, the permissible structural topologies of a mineral group, the earth's mineralogical makeup, or other large-scale considerations. Thus current practice in mineralogy largely separates the acquisition of new data points (new minerals) from many of the insights the new data can provide.

Whether this is the most effective scientific practice is not certain, but it is plausibly related to the narrowing of the definition of "mineralogy" highlighted by Putirka (2015). Mineralogy, interpreted in the sense he suggests, includes much of geochemistry and geology, but has recently come to signify the study of minerals sensu stricto. Fostering a close connection between the acquisition of new mineral data and their significance – rather than separating the two – would help to broaden the definition of mineralogy and clearly distinguish new mineral discovery from the stamp-collecting to which it has sometimes been compared (for example Hawthorne, 1993).

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Figure Captions

1. Mineral discoveries in the database by year, with timeline of relevant events. JCPDS = Joint Committee on Powder Diffraction Standards (now ICDD); IMA = International Mineralogical Association; ICDD = International Center for Diffraction Data; PDF = Powder Diffraction File.
2. Historical changes in the percentage of new mineral discoveries using XRD, EPMA/SEM, IR and Raman spectrometry, thermogravimetric or differential thermal analysis, and wet-chemical methods. Deviations from 100% in certain intervals represent “unknown” database entries or techniques that were too seldom used to include.
3. Mineral discovery studies that reported governmental funding, compared to all mineral discovery studies. The U.S. and former U.S.S.R. account for about half of all funded studies, and the numbers from the former U.S.S.R. are almost certainly underestimates for the reasons discussed in the text.
4. Geography of new mineral discovery, by A: Nation of affiliation of the first author of the mineral discovery report; and B: Nation containing the locality where the new mineral was discovered, smoothed by averaging over 4-year bins.

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5. Institutional demographics of new mineral discovery by affiliation of first author, 1917-2016. Researchers employed in industry are not shown and typically contributed < 5% of new mineral discoveries in all years.
6. Comparative growth of new mineral discoveries and authorship, along with best-fit line (dashed) showing the exponential nature of the latter.
7. A: Changes over time in the number of authors on mineral discovery papers. B: Geographical breakdown of authorship numbers since 2000.
8. Proportion of new minerals originating from mines, quarries, resource exploration, and astronomical (meteorite and lunar) samples.
9. Effect of metal prices and production on the rate of discovery of related minerals, for U (top) and Cu (bottom). Vanadium is included since V minerals are common to ubiquitous in numerous U deposits. Discovery rates are averaged over 4-year bins to reduce noise.

Digital Appendix

A. Database of 4,046 new mineral discoveries from 1917-2016.

Reason for discreditation	**Number discredited since 2006**	
Follow-up analysis showed sample was heterogeneous mixture	5	16
Follow-up analysis showed mineral structure or composition matched known mineral	11	
Misunderstanding or mistranslation of original description	2	
Nomenclature decision	52	65
Nomenclature decision based on polytypism	8	
Nomenclature decision based on solid solution or compositional variance	5	
Not given or unknown	6	

Table 1. Causes of mineral discreditations since 2006.

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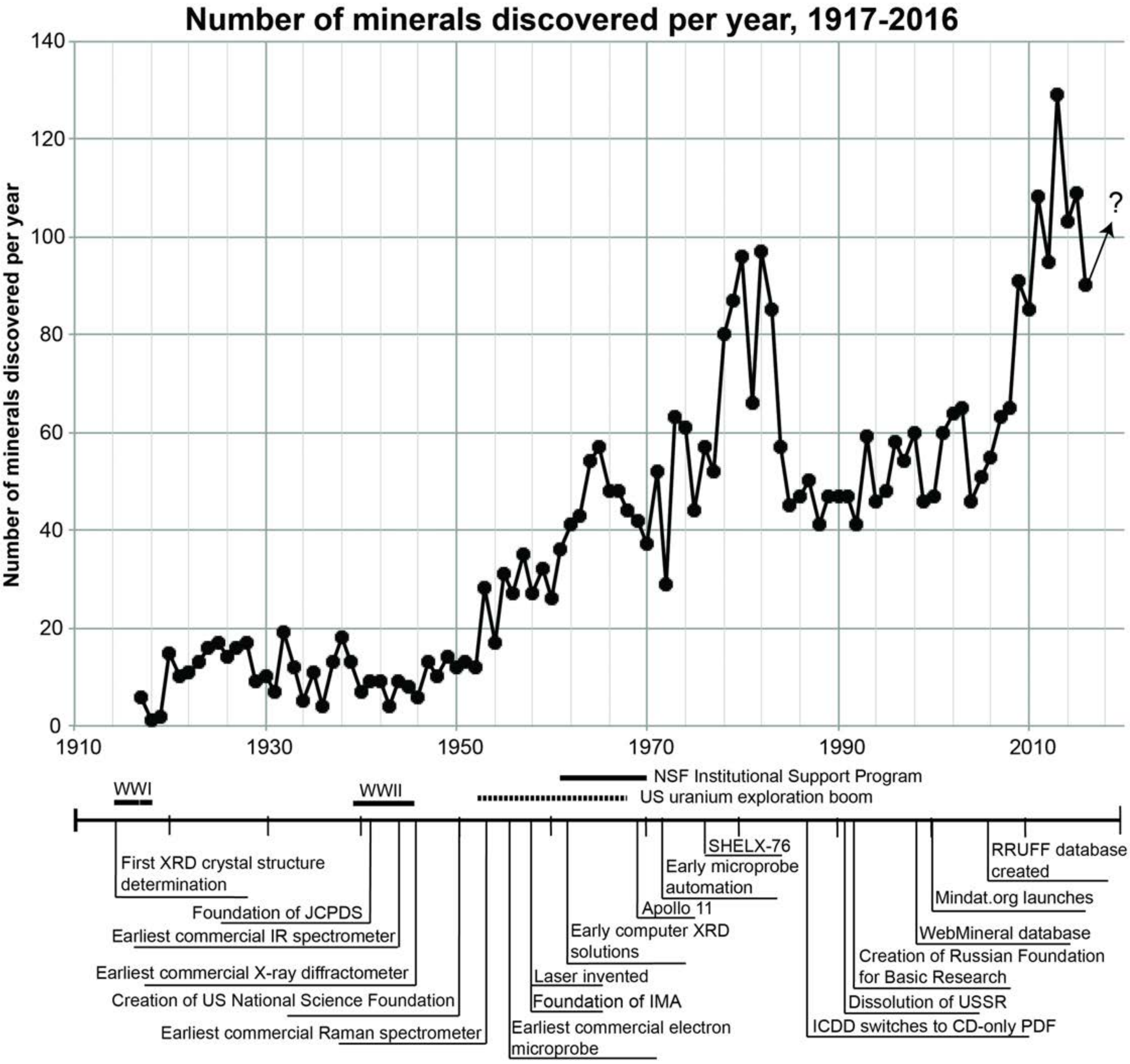

Fig. 1

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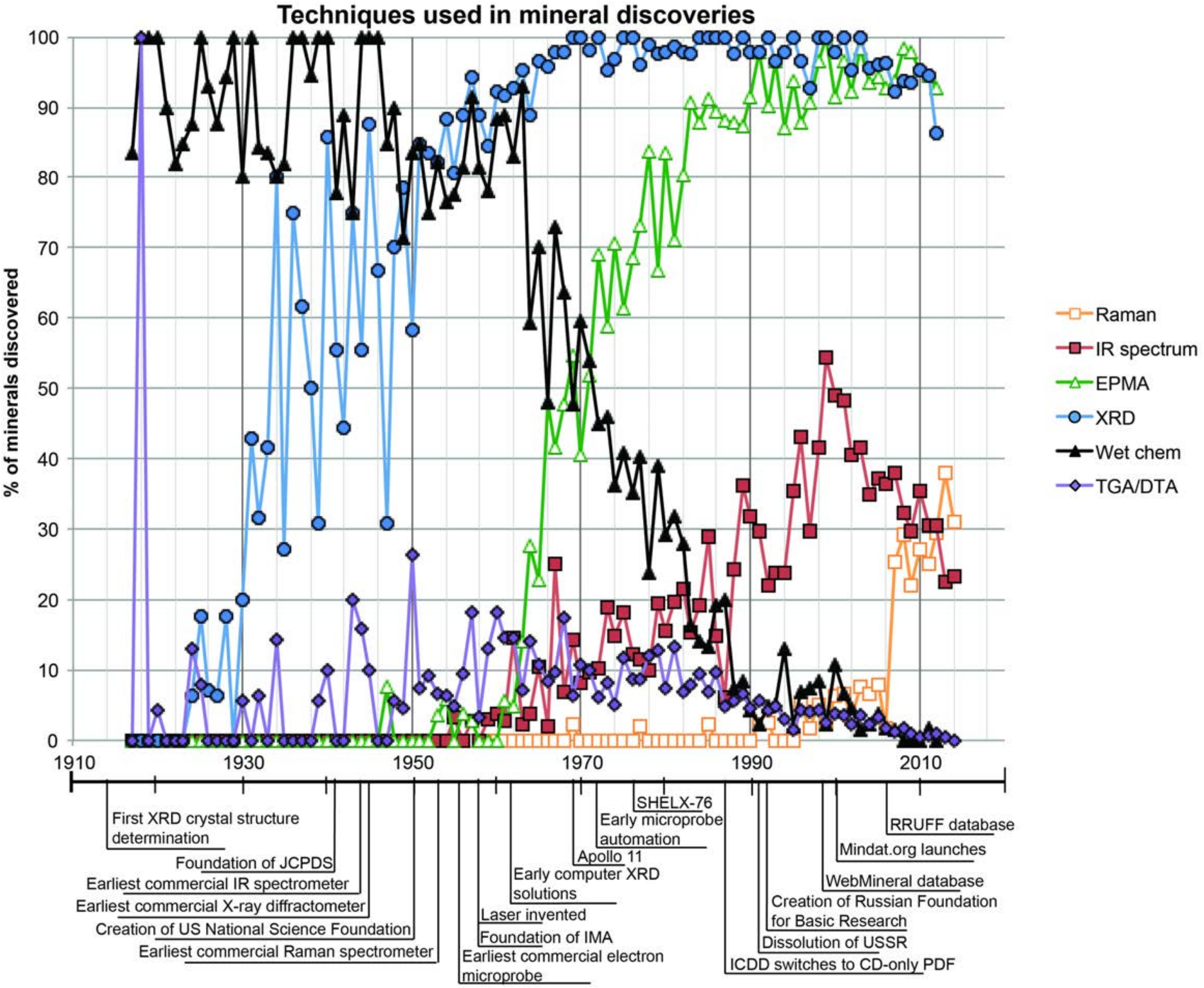
Techniques used in mineral discoveries
% of minerals discovered
100
90
80
70
60
50
40
30
20
10
0
1910
1930
1950
1970
1990
2010
Raman
IR spectrum
EPMA
XRD
Wet chem
TGA/DTA
First XRD crystal structure determination
Foundation of JCPDS
Earliest commercial IR spectrometer
Earliest commercial X-ray diffractometer
Creation of US National Science Foundation
Earliest commercial Raman spectrometer
Earliest commercial electron microprobe
Foundation of IMA
Laser invented
Early computer XRD solutions
Apollo 11
Early microprobe automation
SHELX-76
ICDD switches to CD-only PDF
Dissolution of USSR
Creation of Russian Foundation for Basic Research
WebMineral database
Mindat.org launches
RRUFF database

Fig. 2

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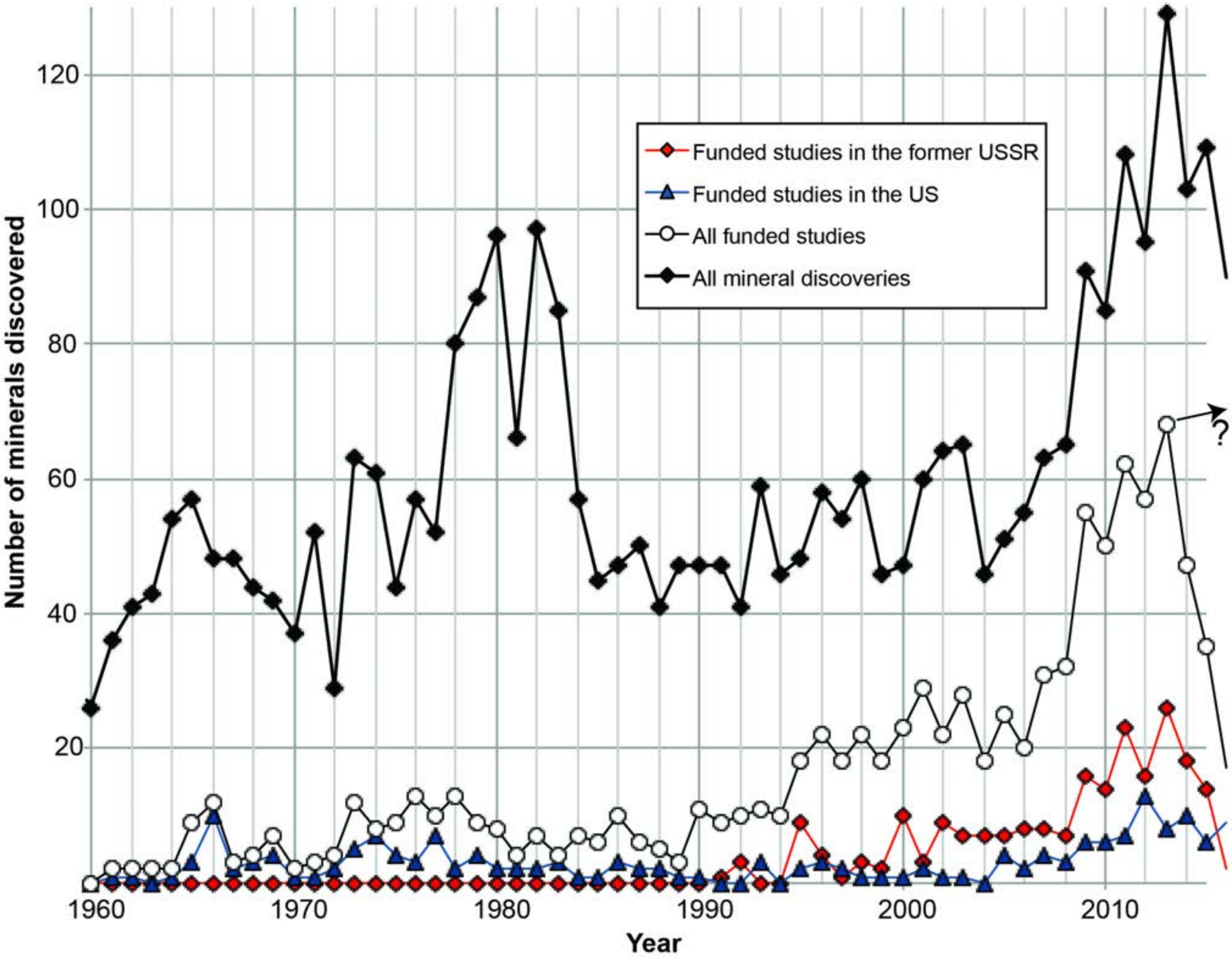

Fig. 3

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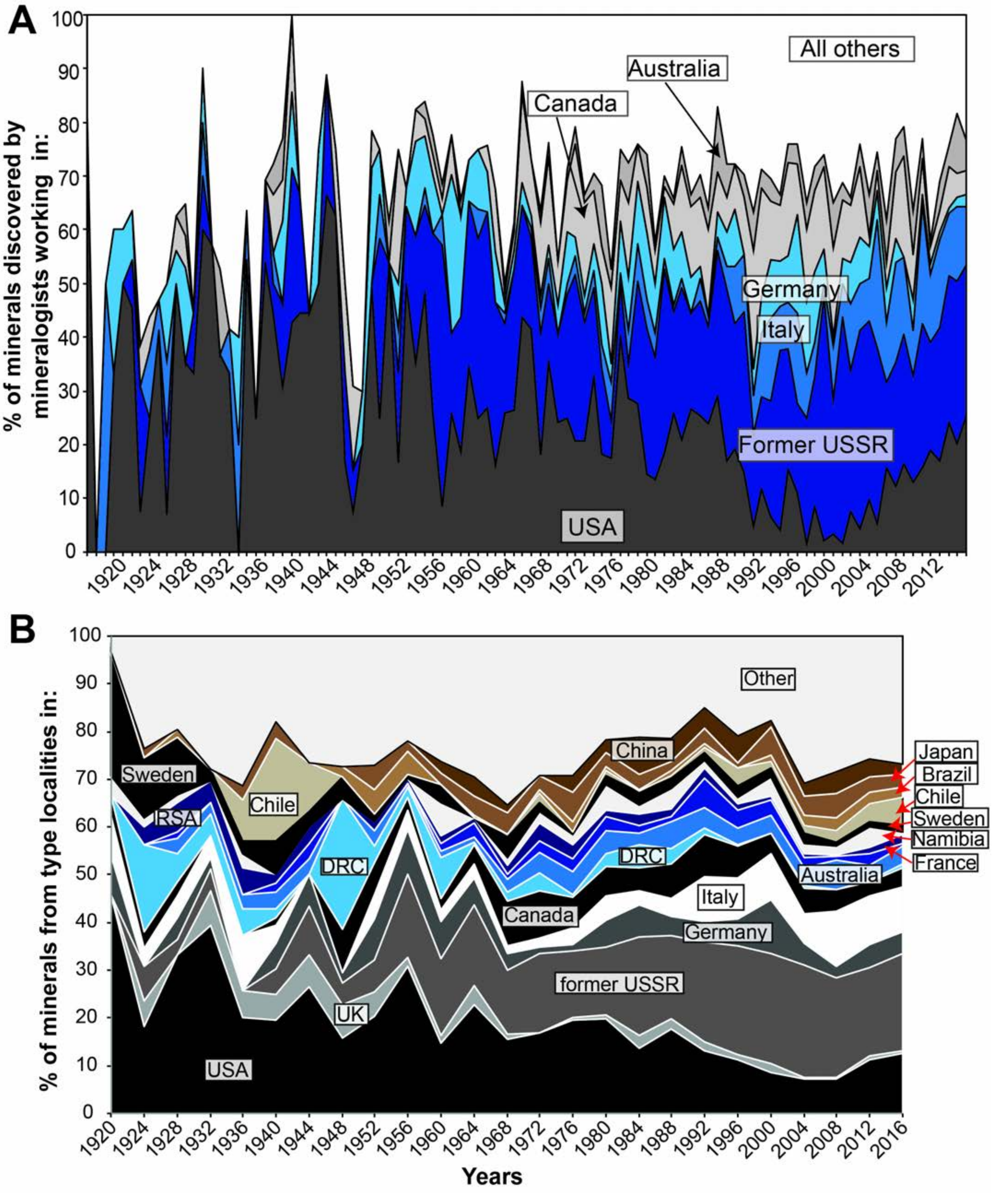

Fig. 4

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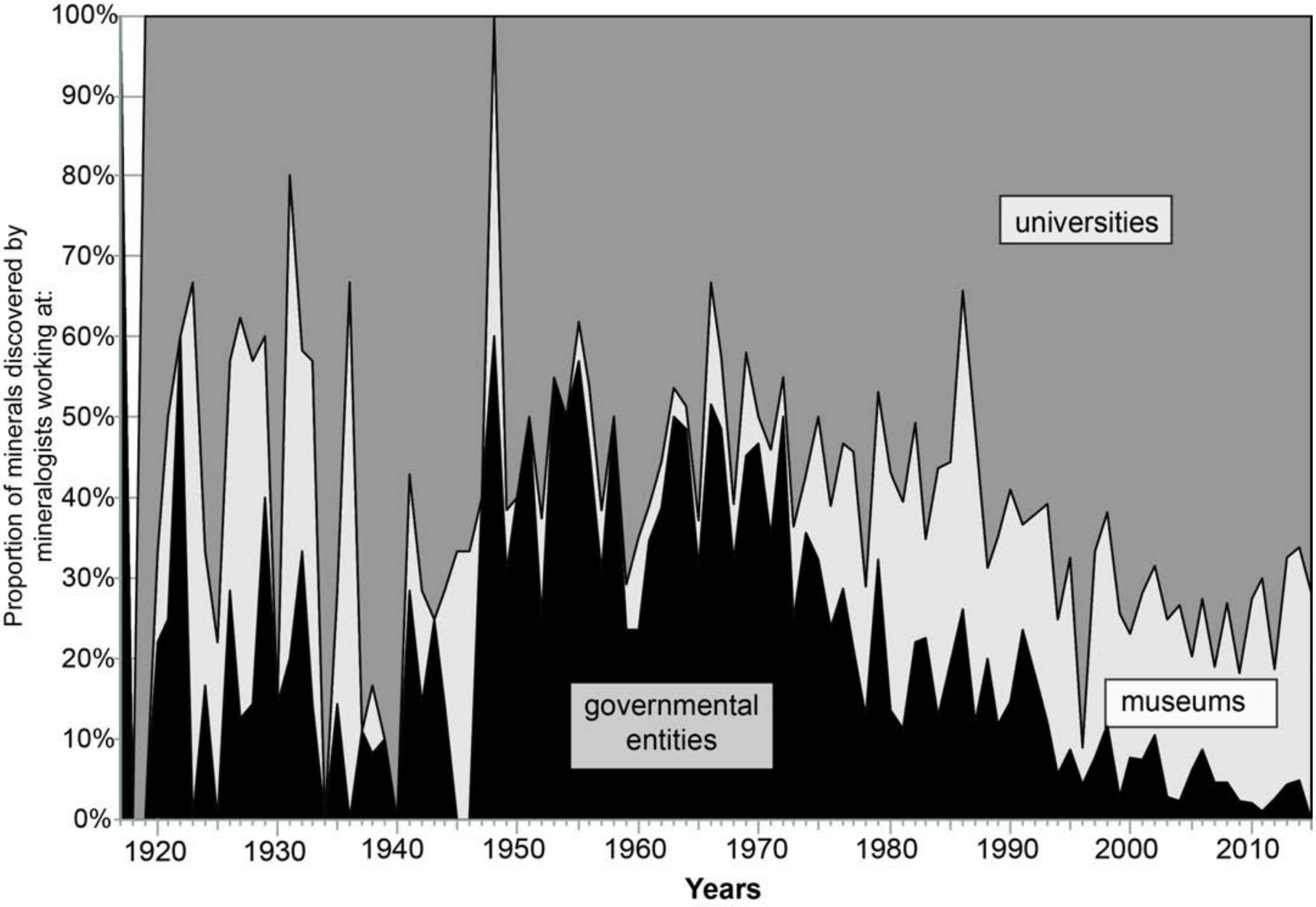

Fig. 5

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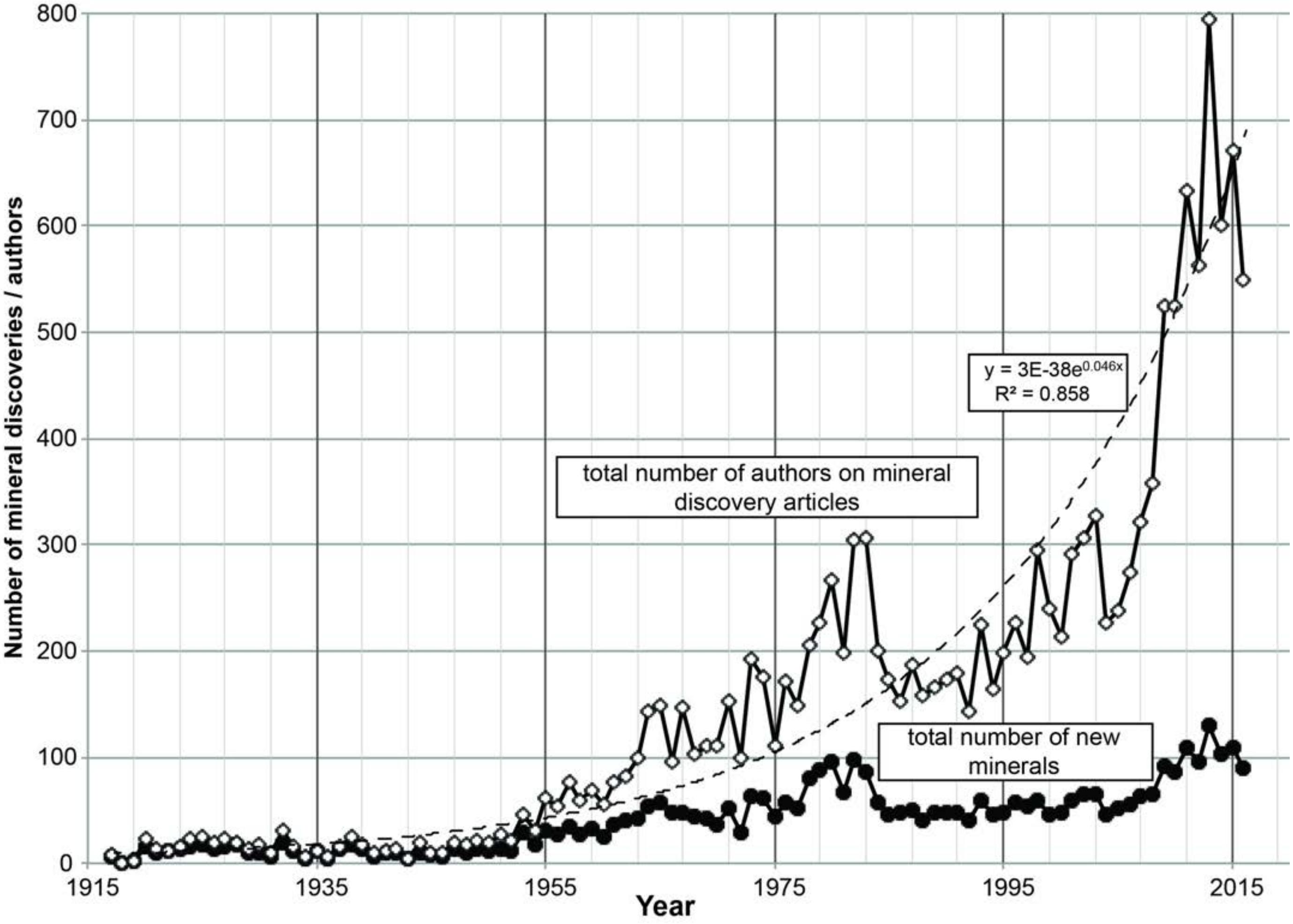

Fig. 6

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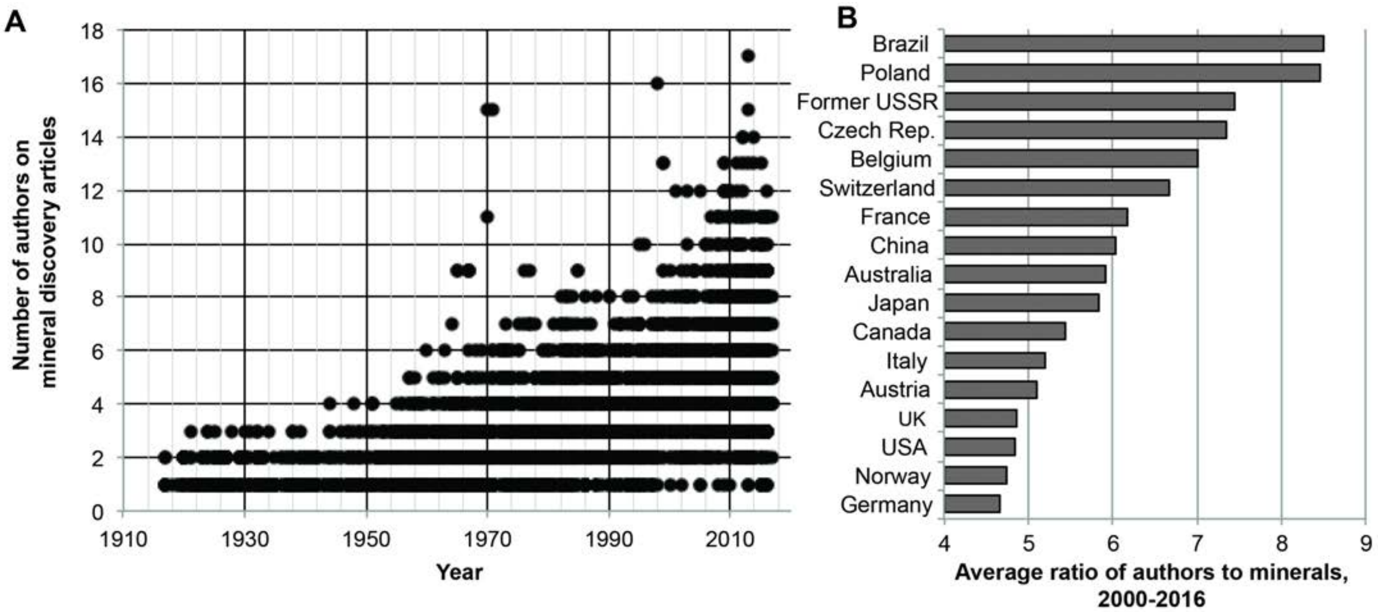

Fig. 7

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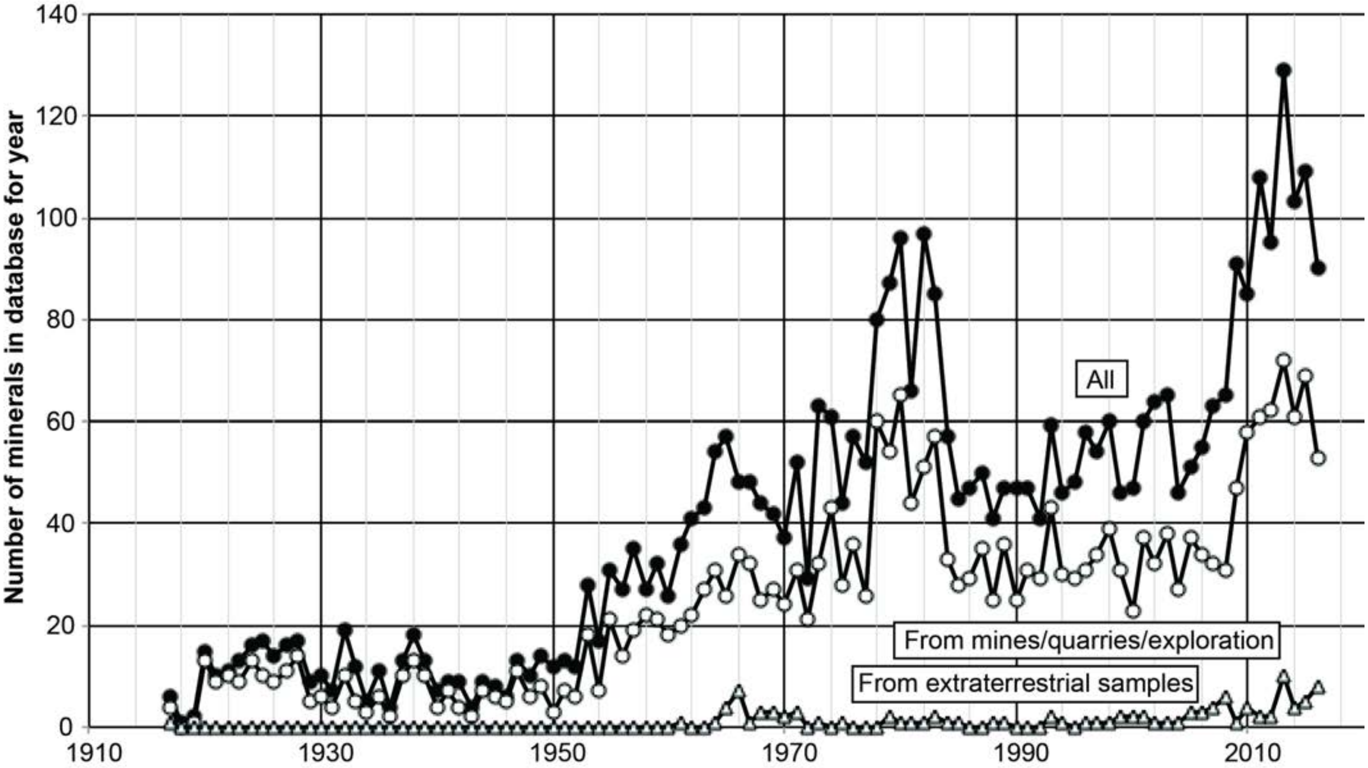

Fig. 8

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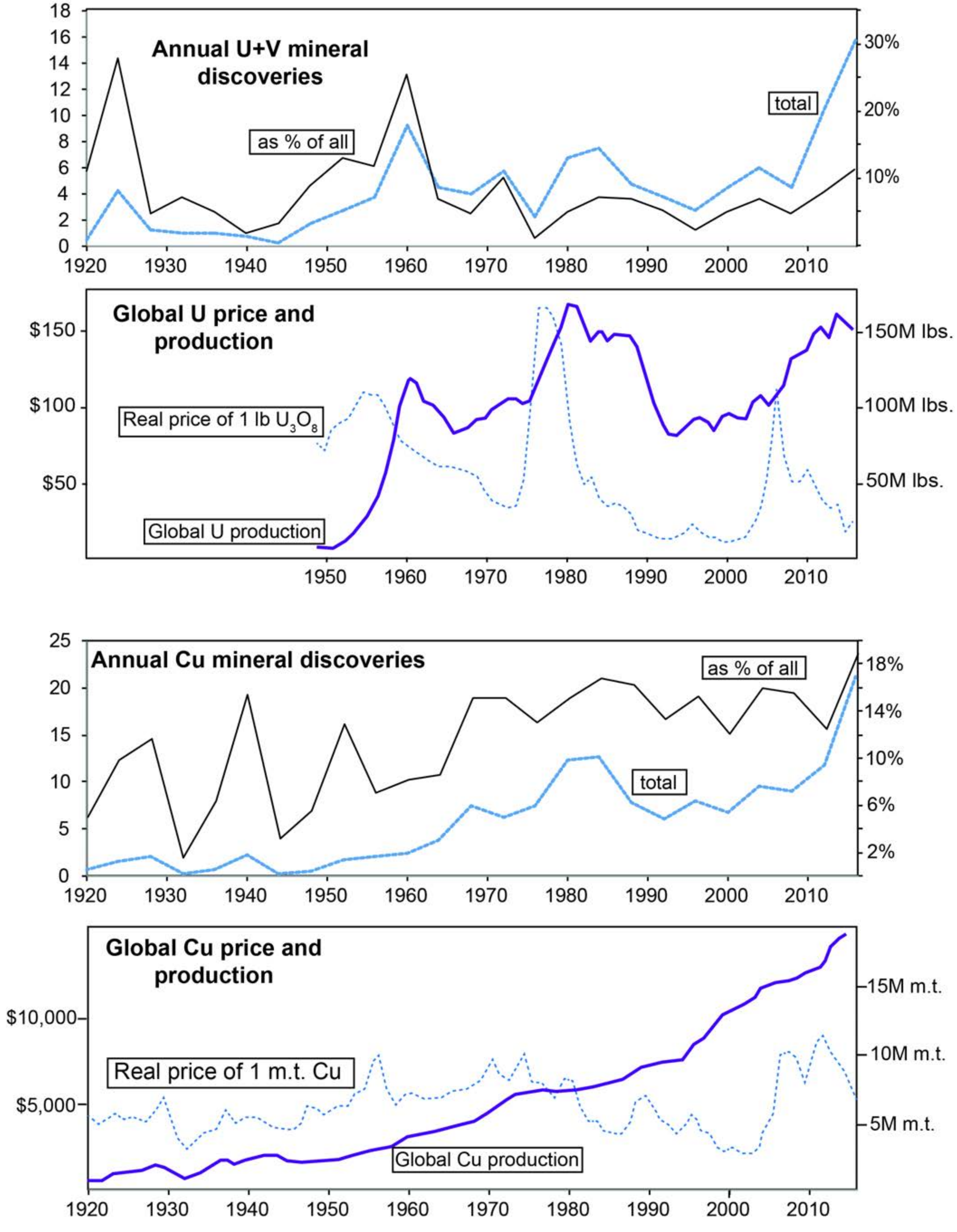

Fig. 9

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