MINERAL ECOLOGY AND NETWORK ANALYSIS OF CHROMIUM, PLATINUM, GOLD AND PALLADIUM

A THESIS IN

ENVIRONMENTAL AND URBAN GEOSCIENCES

Presented to the Faculty of the University
Of Missouri-Kansas City in partial fulfillment of
The requirements for the degree

MASTER OF SCIENCE

By

CHARLES ANDENGENIE MWAIPOPO

B.S., University of Missouri-Kansas City, 2018

Kansas City, Missouri

2020

MINERAL ECOLOGY AND NETWORK ANALYSIS OF CHROMIUM, PLATINUM, GOLD AND PALLADIUM

Charles Andengenie Mwaipopo, Candidate for the Master of Science Degree

University of Missouri-Kansas City, 2020

ABSTRACT

Data collected on the location of mineral species and related minerals from the field have many great uses from mineral exploration to mineral analysis. Such data is useful for further exploration and discovery of other minerals as well as exploring relationships that were not as obvious even to a trained mineralogist.

Two fields of mineral analysis are examined in the paper, namely mineral ecology and mineral network analysis through mineral co-existence. Mineral ecology explores spatial distribution and diversity of the earth's minerals. Mineral network analysis uses mathematical functions to visualize and graph mineral relationships. Several functions such as the finite Zipf-Mandelbrot (fZM), chord diagrams and mineral network diagrams, processed data and provided information on the estimation of minerals at different localities and interrelationships between chromium, platinum, gold and palladium-bearing minerals. The results obtained are important in highlighting several connections that could prove useful in mineral exploration.

The main objective of the study is to provide any insight into the relationship among chromium, platinum, palladium and gold that could prove useful in mapping out potential locations of either mineral in the future. With more open data repositories available, more research could be done to further highlight the importance of mineral ecology and network

analysis in mineral exploration. Such a research is important in paving the way for data driven discovery on the field of geology by making use of the vast amount of data currently available. Mineral ecology and network analysis currently face a hindrance, because of more crucial data being held for proprietary reasons that tend to profit from its exclusivity.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the College of Arts and Sciences, have examined a thesis titled "Mineral Ecology and Network Analysis of Chromium, Platinum, Gold and Palladium" , presented by Charles Andengenie Mwaipopo, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

Supervisory Committee

Alison Graettinger, Ph.D., Committee Chair

Department of Geosciences

James Murowchick, Ph.D.

Department of Geosciences

Fengpeng Sun, Ph.D.

Department of Geosciences

CONTENTS

TABLES

Table | Page

ILLUSTRATIONS

ACKNOWLEDGEMENTS

I would like to thank Dr Alison Graettinger for having the patience to work with me during the period of my master's program. This project has been a challenge for all of us including the other members of my approval committee, namely, Dr James Murowchick and Fengpeng Sun. Dr James Murowchick has been an incredible promoter and supporter of my research by being informative, supportive, and very instrumental in helping me succeed. Without the guidance of Drs. Graettinger, Murowchick and Sun, I feel I might not have made it.

People behind the scenes are usually forgotten when it comes to providing the necessary acknowledgement. Much of what the geosciences department accomplishes is due to Megan Medley always working at peak efficiency. Joseph Nolan, a colleague of mine was also very supportive during my research, who often times took time off of his schedule to review my work. To both Megan and Joseph, I thank you very much for all your help.

Last but not the least, my wife deserves the credit for this degree as much, if not more than I do. She has been very supportive and understanding during this chaotic time period and I would not have been able to do it without her.

CHAPTER 1

INTRODUCTION

Data collection is a practice quite widespread in science and other art forms of study that serve the purpose of advancing the knowledge of the subject in question. The advancement usually comes in the form of observing the data collected over time and noticing patterns that do not happen by accident but are rather a result of a certain factor or factors. The subject in question is the geology of certain minerals. Analysis of minerals and mineralogical systems data could lead to more discoveries in their respective fields. Prior knowledge in mineralogy is essential for even more groundbreaking discoveries in the field. In this case, physical and chemical principles of minerals as well as their locality information all play a significant role in a better understanding of network like relationships among minerals. This paper will explore relationships between chromium and the selected precious minerals and by observing the data attempt to see if chromium can be a key identifier of precious metals close by. If successful it will support arguments of more resources being diverted into analyzing big bulks of data to aid in the exploration of precious metals thereby saving costs.

Network analysis compiles a powerful collection of mathematical and graphical methods that have proved quite useful in the presentation and clarification of data collected over the years (Morrison et al., 2017). Such methods have been employed in various fields such as in technological networks that comprise of physical infrastructures of power grids, roads and water supply systems (Morrison et al., 2017). But such methods have familiarly been used to visualize data in subjects such as the spread of diseases (Danon et al., 2011).

This data-driven discovery usually headlines as three different and wide fields known as mineral evolution, mineral ecology and mineral network analysis (Hazen et al., 2019).

Mineral evolution is referred to as the close evaluation of the Earth's ever-changing near surface mineralogy observed over the time of 4.5 billion years that has revealed the evolution of geosphere and biosphere coupled with increasing diversity as well as the complexity of minerals brought about by the chemical differentiation of the Earth (Hazen et al., 2019). However, mineral ecology dives into the diversity and spatial distributions of earth's minerals as well as the non-conforming distribution of earth's rare minerals (Hazen et al., 2019). Lastly, mineral network analysis involves the use of powerful mathematical tools to analyze and visualize the spatial distribution of minerals at a location (Hazen et al., 2019).

This paper will investigate statistics analysis tools and how they are used in the field of mineralogy. The main minerals of focus will be chromium and platinum but also accompanied with gold and palladium. Chromium and platinum were selected because of their cooccurrence in ultramafic ores of Stillwater and Bushveld in the USA and South Africa respectively. Their cooccurrence led me to believe that for them to cooccur they must have had the same magmatic source derived from the mantle. This brought forth a question of chromium's role in identifying large deposits of platinum close by. Gold and palladium were selected off of mindat's database because of their data attributes correlating more with chromium and platinum. It also helps that they are precious metals that are a subject of the proposed thesis. Several statistical programs will be used in analyzing the data and bring forth visualization techniques useful in determining patterns. The mineral ecology of the mentioned minerals will also be subjected to a series of statistical tools that will be used to analyze the mineral's spatial distribution. Such analysis could be useful in identifying or predicting the availability or lack thereof of certain mineral species at different locations. The goal is to pose a question and see if the tools that will be explored will at least provide some insight into answering the question at hand. The question in hand would be if there is a direct correlation among several chromium, platinum, gold and palladium minerals. Secondly, if that correlation can be used to determine or predict the location of minerals at locations that fit into conditions prescribed in the analysis. Before going forth into the next section, it is important to identify general information of the minerals being analyzed which are described as follows.

Chromium is a first-row transition element that is redox-sensitive and is of special interest because of its many uses (Liu et al. (2017)). Chromium serves several purposes such as making stainless steel and creating superalloys (Kropschot, 2010), color pigments and it is usually associated with minerals that are of great economic value such as platinum (Schulte et al., 2010). Chromium appears as trace elements in the earth's crust with an average of 100 μg/g of the earth's crust (Ball et al., 1998). The more mafic the rock is the more enriched in chromium it shall be as basaltic and ultramafic go as high as 200 and 2400 μg/g (Ball et al., 1998).

Platinum is a transition element that is extremely resistant to tarnishing and corrosion (Ross, 2016). It is usually silver-white (once known as "white gold") and is usually found to have a concentration of 5 parts per billion in the Earth's crust. According to mindat large deposits of platinum are mostly found in Russia and South Africa. Platinum along with other elements such as iridium, osmium, palladium, ruthenium, and rhodium belong to a group called platinum group metals or platinum group elements also known as PGEs (mindat). PGEs are highly sought after because of their physical and chemical properties (Reith et al., 2014). Most of platinum's use is in the making of catalytic converters, catalyst, jewelry, making magnets and pacemakers among some other uses (Ross, 2016; Yedemsky and

Varennikov, 2013). As of the 3rd of July 2020, Platinum is currently valued at 821$ per ounce (MONEX, 2020).

Palladium is one of the platinum group metals which is the least dense and has the lowest melting point in the group (British Geological Survey, 2009). It is greyish white and very resistant to tarnishing from the atmosphere or regular temperatures (British Geological Survey, 2009). Its uses include in jewelry where it serves as a substitute for platinum and its alloy with gold makes good white gold (Britannica). It can also be used in catalytic converters, electronic capacitors in laptops, mobile phones and as a catalyst in industrial processes (Britannica, 2019). It is also one of the most abundant PGEs with an abundance of 15 parts per billion in the earth's crust (Britannica, 2019). As of the 3rd of July 2020, Palladium is currently valued at 1916$ per ounce (MONEX, 2020).

One of the most popular elements in human history, gold is one of the densest metals and one that does not tarnish or corrode (Britannica, 2020). It is bright yellow, malleable and very durable. It is also a great conductor of electricity. Its uses include jewelry making, trade, currency, electronics and medicine (King). Its concentration in the earth's crust is numbered at 5 parts per billion and is quite widespread. The inclusion of gold in the research was because it had comparatively better numbers in terms of cooccurrence with platinum, palladium and chromium. As of the 3rd of July 2020, Gold is valued at 1783 per ounce (MONEX. 2020).

More information on the minerals with regards to how and where they formed will be displayed in chapter 4.

CHAPTER 2

PREVIOUS WORKS

There has been a great increase in data driven discovery in mineralogy because of a growing number of data repositories. A great influence in this line of study is a senior staff scientist at the Carnegie institutions professor of Earth sciences at George Mason University named Robert M. Hazen (https://hazen.carnegiescience.edu/cv/biography). Hazen and his colleagues have thoroughly examined the mineral ecology and mineral evolution of certain minerals by making use of growing mineral data repositories to visualize the interaction between the geosphere and biosphere (https://hazen.carnegiescience.edu/cv/biography).

Several papers have been dedicated to this line of work. Such papers include Morrison et al. (2017) which describes the temporal and spatial patterns that could be used to define relationships between ore bodies, sediments, meteorites among many other materials. The paper also briefly describes different kinds of network analysis methods such as force-directed graphs and the widely used method in mineralogy named cluster analysis which is key in producing phase diagrams.

Hazen et al. (2019) dives into the importance of utilizing large digital data resources and calls for more open and free ways to access such data to improve the analysis of minerals to better understand them. Hazen's paper describes three different ways such data can be manipulated to teach more about mineral evolution, mineral ecology as well as mineral network analysis. It heavily depends on data from mindat that compiles data of 5566 minerals found in at least 306,000 localities as of 21st May 2020. Such data was investigated with different mineral ecology and network analysis techniques leading to discoveries of minerals and relationships that could not be determined by roughly observing raw data. This has led to more advanced knowledge in the co-evolving geosphere and biosphere. It has also facilitated the prediction and discovery of minerals that were yet to be discovered. Such a method could prove invaluable to mineral exploration and discoveries which is detailed in the mineral challenge website for carbon discoveries.

Other papers such as Hystad et al. (2015, 2019 a and b) describe the computational and mathematical methods in use for analysis of data. The methods were useful in determining the expected values at certain mineral locations. Hystad et al. (2015) also describes the spatial distribution of minerals conforming to an LNRE distribution and what statistical model was used to identify that. Other network analysis methods are described in Kolaczyk (2010).

Liu et al. (2017) describes the mineral ecology of chromium as well as its properties. Hazen et al. (2016) shows the mineral ecology of carbon which inspired the carbon mineral challenge that led to the discovery of various carbon species. Hazen et al. (2016) was also instrumental in providing information for the parameters used in fZM. It was also useful in the discussion section regarding how useful the results of a research as this could accomplish for the betterment of mineral exploration.

Schulte et al., (2010) was a geological survey done to establish a model for the stratiform chromium deposits in the world. This extensive model goes in great detail to describe chromium’s physical and chemical attributes. The paper was a great inspiration in establishing the thesis because it states that sub-economic levels of platinum and other platinum group elements usually occur as byproducts in chromite ores.

Evans (1987) and Arndt, Kesler, and Ganino, (2010) provided information on ore formation and geologic settings of gold, chromium, platinum and palladium. Phillips and

Powell (2009) provided more data on gold ores, geologic setting and a model for gold ore formation. Knopf (1917) describes the relationship between gold, platinum and palladium in ores.

Hobart M King's article titled "The Many Uses of Gold" has details on gold's uses in everyday life and other important pieces of information.

Yedemsky and Varennikov (2013), British Geological Survey (2009) as well as Reith et al. (2014) and Ross (2016) were essential in providing more information on platinum and platinum group metals as minerals and formation of its ores. Peterson (1994) and Bindi et al., (2013) was used to establish a connection between platinum and palladium's relationship.

Baayen (2001) Evert and Baroni (2007) and (2008) were instrumental in providing the statistical methods and R codes to generate frequency spectrum graphs. Ognyanova (2015) illustrates various kinds of network graphs and their usages. It also dives into 3D graphing as well as complex ways to display data to match one's point of interest in the data analyzed. Gu et al., (2014) was the source for the code used to make chord diagrams and necessary adjustments for a good fit.

Other relevant and additional information on minerals and their localities were obtained from mindat and the RRUFF.info.

CHAPTER 3

DATA COLLECTION AND METHODOLOGY

Data collection

The data collected was from open access data resource websites such as RRUFF and Mindat. RRUFF's database has a list of minerals that are approved by the International Mineralogical Association (IMA). The database has at least 5400 mineral species with information on compositions, physical properties as well as the crystal structures of minerals (Hazen et al.,2019). For this research RRUFF's database provided information on the mineral species and properties for chromium, gold, palladium and platinum (Hazen et al., 2019).

Mindat also has a database full of the global distribution of minerals (Hazen et al., 2019). It houses data of at least 1.1 million mineral locality data that was an essential part of the research done for the paper (Hazen et al., 2019). Mindat's database was an essential source for data on chord diagrams and network diagrams through individual mineral cooccurrence pages.

More data was obtained from Liu et al. (2017), Morrison et al. (2017) and Hazen et al. (2019).

Methodology

fZM

Methods used include the finite Zipf-Mandelbrot also known as fZM is a statistical model that is used to estimate or predict the availability of certain events at different parameters (Liu et al., 2017). The tool is found in the zipfR package on R. The shape of the frequency distribution graph conforms to a Large Number of Rare Events (LNRE) frequency distribution with fewer minerals occurring in many locations as opposed to the majority of the minerals occurring at fewer locations (Baayen, 2001; Evert and Baroni, 2008). The statistical model is more accurately demonstrated in Evert and Baroni (2008) where they look at word distribution in a book. A few words and phrases occur many times, but most of the words and phrases occur a few numbers of times.

This method was also executed for all mineral species on RRUFF. The distribution ended up conforming to LNRE with 22% of all mineral species found at one locality (Hystad et al., 2015). It should be noted that the fZM model is made to follow an LNRE mathematically accurate graph which is an L shaped distribution of the frequency spectrum list. However, in real case scenarios individual mineral frequency distribution graphs do not closely conform to LNRE distribution graphs and will tend to have deviations in its distribution (Hystad et al., 2015). The selected minerals chromium, platinum, gold and palladium are also expected to behave like LNRE distribution as data on all mineral species did. Gold, chromium, platinum and palladium's data were collected individually and put into sample sizes (N) for the minerals. The sample sizes represented mineral locality pairs of each element mineral species. Each mineral was then modeled separately to see if they follow the LNRE distribution.

Several parameters were derived from the fZM package that aided in the making of frequency distribution graphs. These parameters are Alpha, A, B, and the p-value. Alpha is a shape parameter ranging from 0 to 1 (Evert and Baroni, 2007). A and B represent the lower and upper cutoff probability parameters of the graph (Liu et al., 2017). However, according to Evert and Baroni (2007) B values are permitted to be greater than 1 at the cost of not being inconsistent with the interpretation of B which is a probability value (maximum value should be 1 to be consistent with interpretation). The p-value is an indicator of the probability that the LNRE model will fit into the data (Hazen et al., 2016). The parameters are a result of mathematical calculations employed by the fZM model. It should be noted that one platinum mineral specie and two gold mineral species were omitted from the fZM analysis because of lacking locality data from the site's database.

Errors in the fZM model analysis

The uncertainty of the fZM calculation method was estimated through the brute force Monte-Carlo method whereby the standard deviation was the error estimate (Liu et al., 2017). The Monte-Carlo method measured the probability of the occurrence of minerals in their depositional environments which was calculated from random samples picked from the sample size (N). Then the analysis of the results determined that the standard deviation calculated to be the error estimated (Liu et al., 2017).

Chord Diagrams

Another method used to visualize of the data was the chord diagram. Diversity and spatial distribution analysis of minerals is considered a challenge and an even greater challenge when one must observe and analyze an assemblage of minerals simultaneously (Hazen et al., 2019). Therefore, to help in this predicament, powerful visualization tools such as the chord diagram could be of use. One notable use of chord diagrams was observing the migration of immigrants among continents. Data was collected from Gui J. Abel and used to construct a chord diagram by Yan Holtz and Conor Healy from to visually display the variation in immigration a "data to viz" process.

For this study, chord diagrams represent coexisting mineral species as arcs of a circle connected by curved lines (Hazen et al., 2019). The arcs represent pairwise mineral cooccurrence, with the thickness of the arc depicting the number of times the minerals occur together (Hazen et al., 2019).

Network Diagrams

Network diagrams are mathematical graphs used in exploring the interrelationships among different species in a sample size (Hazen et al., 2019). A network diagram is made up of nodes that are connected to other nodes by edges. Network diagrams serve their best use when they expose useful relationships and patterns from coexisting minerals such as clustering by chemistry or the sequence in which minerals are formed (Hazen et al., 2019). They can also be used to denote cooccurrence relationships between minerals to signify the strength of their relationship.

CHAPTER 4

MINERAL ECOLOGY ANALYSIS OF SELECTED MINERALS

Chromium

Chromium deposits are usually found in magmatic bodies that are mafic to ultramafic in composition (Arndt, Kesler and Ganino, 2010). Chromium bearing minerals such as chromite will have grains that nucleate as the magma slowly cools, the chromite grains then sink to the bottom of the magma body because of their density. As the crystals accumulate at the bottom of a magma chamber, a cumulate layer of chromite forms that in some cases lead to banding in an outcrop (Arndt, Kesler, and Ganino, 2010). Other forms of chromium deposits result from weathering of exposed outcrops containing chromium bearing minerals, releasing grains that accumulate to form chromium bearing minerals placer deposits (Evans, 1987: Haldar, 2013). The durability and high density of the grains containing chromium bearing minerals, permits the accumulation of economic placer deposits.

Current data on RRUFF shows that there are currently (as of 21st May 2020) 97 Cr known. This is 15 more minerals compared to the 82 Cr-bearing minerals reported in Liu et al. (2017). Of those 97 minerals, 81 are terrestrial and 16 species have been found in meteorites (RRUFF). Cr-rich minerals are quite common in igneous rocks, chromite ($FeCr_2O_4$) and magnesiochromite ($MgCr_2O_4$) being the most common (Liu et al., 2017). Metamorphism also provides favorable environments for the formation of Cr minerals, producing minerals such as uvarovite garnet ($Ca_3Cr_2Si_3O_{12}$) and eskolaite (Cr_2O_3) (Liu et al., 2017). The variety of geological environments in which Cr minerals are formed or accumulated are shown in Figure 4.1 (Liu et al., 2017). The figure is a network model with nodes having sizes corresponding to the number of occurrences, the lines (edges) marking minerals that occur together, often in more than one environment, and the color represents the geologic environment of formation ranging from igneous, metamorphic and weathering among others.

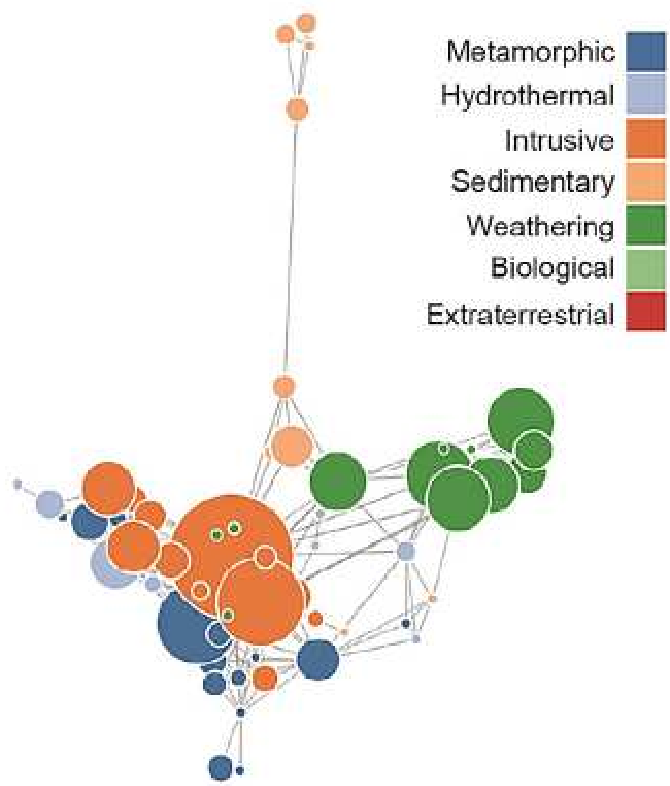

Figure 4.1: Network model depicting the frequency of occurrences and the different geologic environments of formation of Cr-bearing minerals. The size and color of the nodes correspond to the number of occurrences and environment of formation respectively (Liu et al., 2017).

Mineral Ecology of Chromium

The fZM model was used to establish that chromium does conform to a Large Number of Rare Events frequency distribution. The mineral list for chromium was extracted from RRUFF and then processed using R to be used by the fZM model. Table 4.1 shows the list of minerals containing chromium accompanied by their locality count and chemical formula obtained from RRUFF.

Table 4.1: Minerals of Chromium with chemical formula and their locality count.

No.	Mineral Name (No. of localities)	Chemical formula
1	Batisivite (2)	$BaTi^{4+}_6(V,Cr)_8Si_2O_{29}$
2	Bentorite (3)	$Ca_6Cr^{3+}_2(S^{6+}O_4)_3(OH)_{12}\cdot 26H_2O$
3	Bracewellite (2)	$Cr^{3+}O(OH)$
4	Carmichaelite (2)	$(Ti^{4+},Cr^{3+},Fe^{3+})(O,OH)_2$
5	Cassedanneite (3)	$Pb^{2+}_5(V^{5+}O_4)_2(Cr^{6+}O_4)_2\cdot H_2O$
6	Chenmingite (1)	$Fe^{2+}Cr^{3+}_2O_4$
7	Chromatite (6)	$CaCr^{6+}O_4$
8	Chrombismite (2)	$Bi^{3+}_{16}Cr^{6+}O_{27}$
9	Chromceladonite (1)	$KMgCr^{3+}Si_4O_{10}(OH)_2$
10	Chromferide (3)	$Fe_{1.5}Cr_{0.2}$
11	Chromio-pargasite (2)	$NaCa_2(Mg_4Cr^{3+})(Si_6Al_2)O_{22}(OH)_2$
12	Chromium (26)	Cr

No.	Mineral Name (No. of localities)	Chemical formula
13	Chromium-dravite (6)	$NaMg_3Cr^{3+}{}_6(Si_6O_{18})(BO_3)_3(OH)_3OH$
14	Chromite (3902)	$FeCr_2O_4$
15	Chromo-alumino-povondraite (2)	$NaCr^{3+}{}_3(Al_4Mg_2)(Si_6O_{18})(BO_3)_3(OH)_3O$
16	Chromphyllite (6)	$KCr^{3+}{}_2(Si_3Al)O_{10}(OH)_2$
17	Chromschieffelinite (1)	$Pb^{2+}{}_{10}Te^{6+}{}_6O_{20}(OH)_{14}(Cr^{6+}O_4)\cdot 5H_2O$
18	Cochromite (4)	$Co^{2+}Cr^{3+}{}_2O_4$
19	Crichtonite (27)	$Sr(Mn^{2+},Y^{3+},U^{6+})Fe^{2+}{}_2(Ti^{4+},Fe^{3+},Cr^{3+},V^{5+})_{18}(O,OH)_{38}$
20	Crocoite (81)	$Pb^{2+}Cr^{6+}O_4$
21	Cuprokalininite (1)	$Cu^{2+}Cr^{3+}{}_2S_2{}^{-4}$
22	Davidite-(Ce) (5)	$Ce^{3+}(Y^{3+},U^{4+})Fe^{3+}{}_2(Ti^{4+},Fe^{3+},Cr^{3+},V^{5+})_{18}(O,OH,F)_{38}$
23	Davidite-(La) (31)	$La^{3+}(Y^{3+},U^{4+})Fe^{3+}{}_2(Ti^{4+},Fe^{3+},Cr^{3+},V^{5+})_{18}(O,OH,F)_{38}$
24	Deanesmithite (1)	$Hg^{1+}{}_2Hg^{2+}{}_3S^{2-}{}_2OCr^{6+}O_4$
25	Dessauite-(Y) (9)	$Sr^{2+}(Y^{3+},U^{4+},Mn^{2+})Fe^{3+}{}_2(Ti^{4+},Fe^{3+},Cr^{3+},V^{5+})_{18}(O,OH)_{38}$
26	Dietzeite (4)	$Ca_2(I^{5+}O_3)_2Cr^{6+}O_4\cdot H_2O$
27	Dukeite (3)	$Bi^{3+}{}_{24}Cr^{6+}{}_8O_{57}(OH)_6\cdot 3H_2O$
28	Edoylerite (1)	$Hg^{2+}{}_3(Cr^{6+}O_4)S^{2-}{}_2$
29	Embreyite (5)	$Pb^{2+}{}_5(Cr^{6+}O_4)_2(P^{5+}O_4)_2\cdot H_2O$
30	Ferchromide (2)	Cr_3Fe_{1-x} (x = 0.6)
31	Florensovite (1)	$Cu^{1+}(Cr^{3+}{}_{1.5}Sb^{5+}{}_{0.5})S^{2-}{}_4$
32	Fornacite (85)	$Cu^{2+}Pb^{2+}{}_2(Cr^{6+}O_4)(As^{5+}O_4)(OH)$
33	George-ericksenite (1)	$Na_6CaMg(I^{5+}O_3)_6(Cr^{6+}O_4)_2\cdot 12H_2O$

No.	Mineral Name (No. of localities)	Chemical formula
34	Georgerobinsonite (1)	$Pb^{2+}{}_4(Cr^{6+}O_4)_2(OH)_2FCl$
35	Grimaldiite (5)	$Cr^{3+}O(OH)$
36	Guyanaite (6)	$Cr^{3+}O(OH)$
37	Hashemite (6)	$BaCr^{6+}O_4$
38	Hawthorneite (2)	$BaMgTi^{4+}{}_3Cr^{3+}{}_4Fe^{2+}2Fe^{3+}{}_2O_{19}$
39	Hemihedrite (14)	$Pb^{2+}{}_{10}Zn^{2+}(Cr^{6+}O_4)_6(SiO_4)_2(OH)_2$
40	Iquiqueite (2)	$K_3Na_4Mg(Cr^{6+}O_4)B_{24}O_{39}(OH)\cdot 12H_2O$
41	Iranite (11)	$Pb^{2+}{}_{10}Cu^{2+}(Cr^{6+}O_4)_6(SiO_4)_2(OH)_2$
42	Isovite (2)	$(Cr,Fe)_{23}C_6$
43	Kalininite (4)	$Zn^{2+}Cr^{3+}{}_2S_2{}^{-4}$
44	Lindsleyite (12)	$(Ba,Sr)(Zr^{4+},Ca)(Fe^{3+},Mg)_2(Ti^{4+},Cr^{3+},Fe^{3+})_{18}O_{38}$
45	Liudongshengite	$Zn^{2+}{}_4Cr^{3+}{}_2(OH)_{12}(CO_3)\cdot 3H_2O$
46	Lopezite (5)	$K_2Cr^{6+}{}_2O_7$
47	Loveringite (9)	$(Ca,Ce,La)(Zr^{4+},Fe^{3+})(Mg,Fe^{3+})_2(Ti^{4+},Fe^{3+},Cr^{3+},Al)_{18}$ O_{38}
48	Macquartite (1)	$Cu^{2+}{}_2Pb^{2+}{}_7(Cr^{6+}O_4)_4(SiO_4)_2(OH)_2$
49	Manganochromite (6)	$Mn^{2+}Cr^{3+}{}_2O_4$
50	Mariinskite (2)	$Cr^{3+}{}_2BeO_4$
51	Mathiasite (7)	$(K,Ba,Sr)(Zr^{4+},Fe^{3+})(Mg,Fe^{3+})_2(Ti^{4+},Cr^{3+},Fe^{3+})_{18}O_{38}$
52	Mcconnellite (2)	$Cu^{1+}Cr^{3+}O_2$
53	Olkhonskite (1)	$Cr^{3+}{}_2Ti_4{}^{+3}O_9$
54	Oxy-chromium-dravite (2)	$NaCr^{3+}{}_3(Cr^{3+}{}_4Mg_2)(Si_6O_{18})(BO_3)_3(OH)_3O$

No.	Mineral Name (No. of localities)	Chemical formula
55	Petterdite (2)	$Pb^{2+}Cr^{3+}_2(CO_3)_2(OH)_4 \cdot H_2O$
56	Phoenicochroite (35)	$Pb^{2+}_2O(Cr^{6+}O_4)$
57	Polyakovite-(Ce) (2)	$(Ce^{3+},Ca)_4MgCr^{3+}_2(Ti^{4+},Nb^{5+})_2Si_4O_{22}$
58	Putnisite (2)	$SrCa_4Cr^{3+}_8(CO_3)_8S^{6+}O_4(OH)_{16} \cdot 25H_2O$
59	Redingtonite (2)	$Fe^{2+}Cr^{3+}_2(S^{6+}O_4)_4 \cdot 22H_2O$
60	Redledgeite (4)	$Ba(Ti^{4+}_6Cr^{3+}_2)O_{16}$
61	Reynoldsite (3)	$Pb^{2+}_2Mn^{4+}_2O_5(Cr^{6+}O_4)$
62	Rilandite (1)	$Cr^{3+}_6SiO_{11} \cdot 5H_2O$
63	Santanaite (1)	$Pb^{2+}_9Pb^{4+}_2Cr^{6+}O_{16}$
64	Senaite (28)	$Pb^{2+}(Mn^{2+},Y^{3+},U)(Fe^{2+},Zn^{2+})_2(Ti^{4+},Fe^{3+},Cr^{3+},V^{5+})_{18}(O,OH)_{38}$
65	Shuiskite (2)	$Ca_2MgCr^{3+}_2(SiO_4)(Si_2O_7)(OH)_2 \cdot H_2O$
66	Siwaqaite (1)	$Ca_6Al_2(Cr^{6+}O_4)_3(OH)_{12} \cdot 26H_2O$
67	Stichtite (43)	$Mg_6Cr^{3+}_2CO_3(OH)_{16} \cdot 4H_2O$
68	Tarapacáite (4)	$K_2Cr^{6+}O_4$
69	Tongbaite (3)	Cr_3C_2
70	Uvarovite (212)	$Ca_3Cr^{3+}_2(SiO_4)_3$
71	Vanadio-oxy-chromium-dravite (1)	$NaV^{3+}_3(Cr^{3+}_4Mg_2)(Si_6O_{18})(BO_3)_3(OH)_3O$
72	Vauquelinite (63)	$Cu^{2+}Pb^{2+}_2(Cr^{6+}O_4)(P^{5+}O_4)(OH)$
73	Verbierite (1)	$BeCr^{3+}_2Ti^{4+}O_6$
74	Volkonskoite (22)	$Ca_{0.3}(Cr^{3+},Mg)_2(Si,Al)_4O_{10}(OH)_2 \cdot 4H_2O$
75	Warwickite (15)	$(Mg,Ti^{4+},Fe^{3+},Cr^{3+},Al)_2O(BO_3)$

No.	Mineral Name (No. of localities)	Chemical formula
76	Wattersite (3)	$Hg^{1+}{}_4Hg^{2+}O_2(Cr^{6+}O_4)$
77	Woodallite (2)	$Mg_6Cr^{3+}{}_2(OH)_{16}Cl^{1-}{}_2\cdot 4H_2O$
78	Yarlongite (1)	$Cr_4Fe_4NiC_4$
79	Yedlinite (1)	$Pb^{2+}{}_6Cr^{3+}Cl^{1-}{}_6O(OH)_7$
80	Yimengite (5)	$K(Cr^{3+},Ti^{4+},Fe^{3+},Mg)$
81	Zincochromite (11)	$Zn^{2+}Cr^{3+}{}_2O_4$

The information in table 4.1 was quite useful in creating a frequency spectrum plot of the 81 minerals listed on the table. The analysis used the number of localities of all the 81 minerals, accounting for at least 4000 terrestrial Cr mineral species/locality pairs. Table 4.2 included the parameters used in the fZM model that were essential in creating the frequency spectrum plot in Figure 4.2. As can be seen from Table 4.2, the model used the parameters it generated to produce the number of expected mineral species of chromium. That number of expected chromium species came is 95. leaving the estimated number of “missing” (yet to be discovered) chromium minerals to be 14.

Table 4.2: Parameters used in the statistical model finite Zipf- Mandelbrot (fZM).

Alpha	0.867003
A	0.0002236035
B	2021.654
p-value	0.276983
Terrestrial Cr	81
Sample size	4806
Expected Cr minerals	95

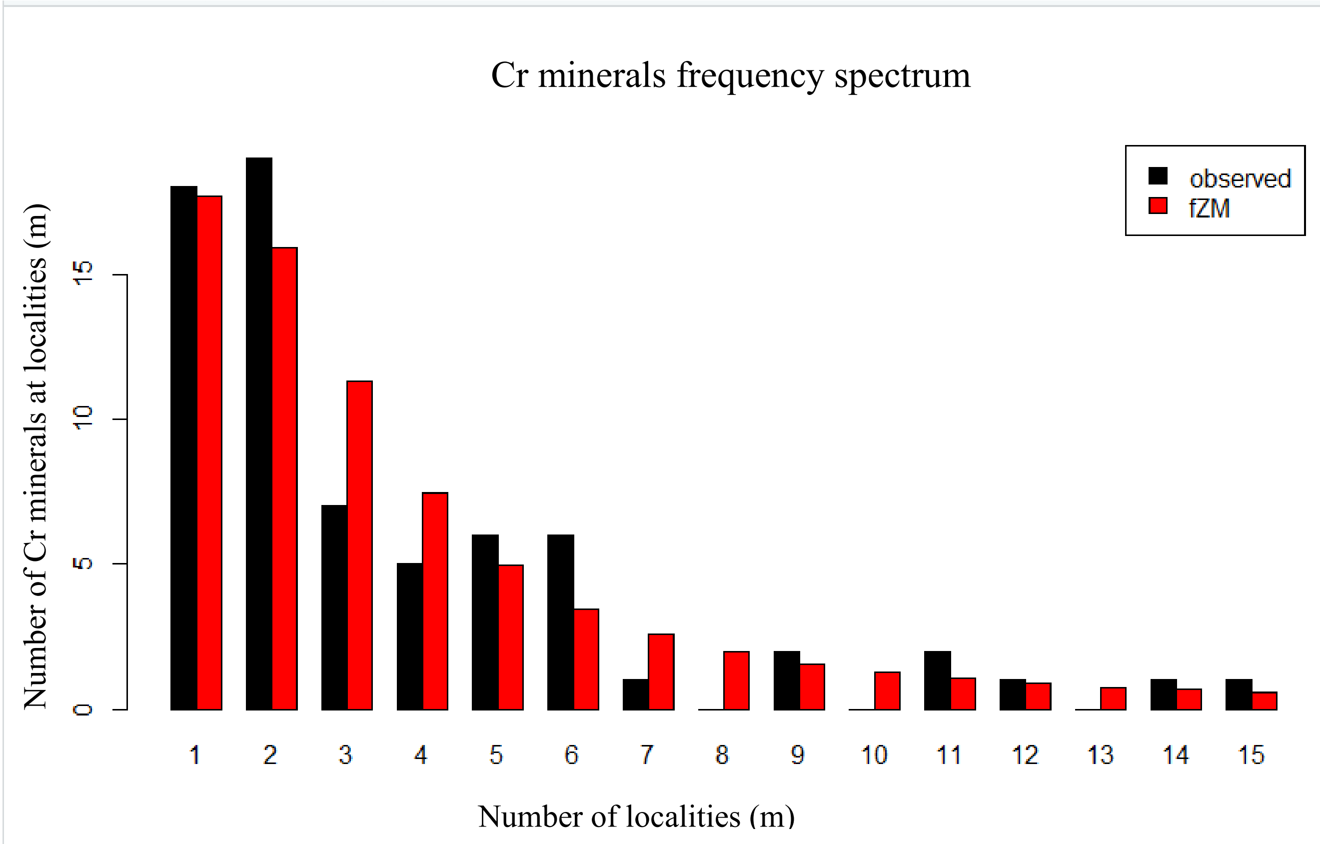

Figure 4.2: Cr frequency spectrum analysis using the fZM method. The x-coordinate labeled “m” represents the number of localities, the y-coordinate represents the number of Cr species. The observed data is in black bars whereas the bars in red were the mineral species derived from the fZM model.

Analysis of Chromium

According figure 4.2, Cr species do conform to the LNRE frequency distribution. Cr is believed to have the potential of forming 95 minerals because of the limited special geochemical conditions needed to concentrate Cr such as magma composition and, in some cases, metamorpshism (Arndt, Kesler, and Ganino, 2010). Therefore, the analysis predicts that there are 14 minerals of chromium yet to be discovered. This value will no doubt decrease as more resources are devoted to looking for these minerals.

Platinum

Platinum deposits form through processes that are similar to those that form deposits of chromium, gold and palladium deposits which are discussed as follows. Platinum deposits can form via magmatic separation, as can chromium mineralization (Reith et al., 2014). Sometimes, magmatic separation in the magma chamber is caused by wall rock contamination diffusing out platinum from wall rock. This leads to an increase in platinum concentration in the magma to the point of precipitation (Reith et al., 2014). Platinum deposits could result as a byproduct in Ni-Cu deposits that are rich in sulfur (other PGE deposits can form this way too). Deposits can also be caused by impact events that modify the temperature, pressure and composition of the melt (Reith et al., 2014). Platinum deposits are also formed as precipitates out of hydrothermal brines rich in chloride and sulfides that host PGEs, Au, Ag and Cu (Reith, 2014). Platinum deposits also arise from placer deposits. Platinum like all the other PGEs tend to accumulate/concentrate after being weathered down from a parent rock (British Geological Survey, 2009).

Research on platinum has increased over the past 20 years because of a near monopoly created in platinum trade worldwide (Reith et al., 2014). Russia and South Africa control most of the trade which has led to high prices. As a result, research was conducted improving exploration for platinum reserves other than in Russia and South Africa to create a fair-trade environment.

Mineral Ecology of Platinum

As was applied to chromium, the fZM method was also employed to visualize the frequency spectrum of platinum species. Platinum is also expected to conform to the LNRE distribution, meaning that it will tend to have a large mineral locality count with few mineral species compared to the rest of the of platinum bearing minerals (Hystad et al., 2015).

Table 4.3 Minerals of Platinum with chemical formula and their locality count.

No.	Mineral Name (No. of localities)	Chemical formula
1	Bowlesite (1)	$PtSnS$
2	Braggite (101)	PtS
3	Cooperite (124)	PtS
4	Crerarite (3)	(Pt,Pb)Bi□$(S,Se)_{4-x}$ (x = 0.4-0-8)
5	Damiaoite (2)	$PtIn_2$
6	Daomanite (5)	$CuPtAsS_2$
7	Ferhodsite (2)	$(Fe,Rh,Ni,Ir,Cu,Co,Pt)_{9-x}S_8$
8	Ferronickelplatinum (13)	Pt_2FeNi
9	Genkinite (12)	Pt_4Sb_3
10	Geversite (38)	$PtSb_2$
11	Hongshiite (27)	$PtCu$
12	Insizwaite (15)	$PtBi_2$
13	Isoferroplatinum (128)	Pt_3Fe
14	Jacutingaite (1)	Pt_2HgSe_3
15	Kharaelakhite (2)	$(Cu,Pt,Pb,Fe,Ni)_9S_8$
16	Kitagohaite (3)	Pt_7Cu

No.	Mineral Name (No. of localities)	Chemical formula
17	Lisiguangite (2)	$CuPtBiS_3$
18	Luberoite (3)	Pt_5Se_4
19	Malanite (35)	$Cu^{1+}(Ir^{3+}Pt^{4+})S_4$
20	Maslovite (23)	PtBiTe
21	Mitrofanovite (1)	Pt_3Te_4
22	Moncheite (133)	$Pt(Te,Bi)_2$
23	Niggliite (22)	PtSn
24	Orthocuproplatinum (1)	Pt_3Cu
25	Platarsite (44)	PtAsS
26	Platinum (485)	Pt
27	Rustenburgite (34)	Pt_3Sn
28	Sperrylite (337)	$PtAs_2$
29	Stumpflite (7)	PtSb
30	Sudovikovite (3)	$PtSe_2$
31	Taimyrite-I (11)	$(Pd,Pt)_9Cu_3Sn_4$
32	Tatyanaite (3)	$(Pt,Pd)_9Cu_3Sn_4$
33	Tetraferroplatinum (66)	PtFe
34	Tulameenite (48)	Pt_2CuFe
35	Yixunite (2)	Pt_3In

Data from Table 4.3 was used to obtain the frequency spectrum of platinum by using the fZM model. Platinum is reported to have 1736 mineral locality pairs over a mineral list of 34 minerals (1 omitted from the fZM for lacking accurate locality data). Table 4.4 indicates the parameter values generated from the fZM model.

Table 4.4 Platinum fZM parameters

Alpha	0.4231535
A	0.0006883136
B	0.7318165
p-value	0.2152175
Terrestrial Pt	35
Sample size	1736
Expected Pt minerals	34

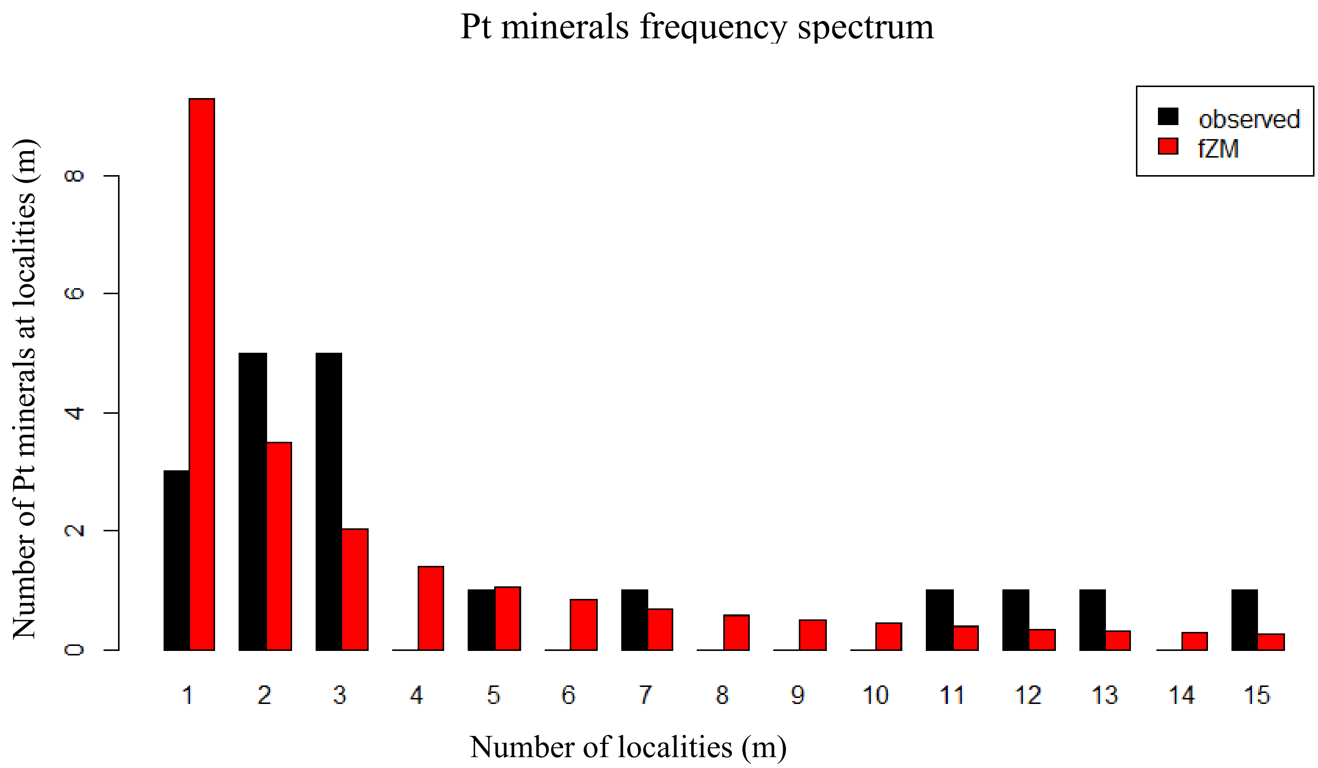

Figure 4.3: Pt frequency spectrum analysis using the fZM method. The x-coordinate labeled "m" represents the number of localities, the y-coordinate represents the number of Pt species. The observed data is in black bars whereas the bars in red were the mineral species derived from the fZM model.

Analysis of Platinum

Platinum's analysis shows that the data conforms to LNRE model and as depicted in Figure 4.3. The red on the bar graph represents the expected number of minerals in the area and the black bars represent the observed number. There are a few outliers along the graph but, these outliers hint at more minerals to be discovered in the area. That or a shift in some of the minerals positions as more of the minerals get discovered. The expected number of Platinum minerals turned out to be 34 which is less than the total number of observed platinum species. However, the sample size of platinum minerals is quite small to get very accurate readings. More data needs to be collected (or accessed) to be able to get very accurate results (Liu et al., 2017).

Palladium

Palladium deposits are formed in the same ways as platinum deposits are formed, including magmatic processes involving mafic and ultramafic rocks (British Geological Survey, 2009). Most of palladium's occurrences are with other PGEs in various possible ways of formation such as placer deposits, magmatic separation, hydrothermal fluids, metamorphic processes and as a by-product in Ni-Cu sulfide deposits (British Geological Survey, 2009).

Mineral Ecology of Palladium

Palladium has 73 terrestrial minerals with mineral locality pairs amounting to 1437. The fZM model tends to be less accurate with fewer sample sizes (Liu et al., 2017). The R programming software cited inconsistent data and few mineral samples needed to make a frequency distribution graph. R cited that with inconsistent data the sample size should be at least 2766 compared to palladium's 1437. The two problems were enough to sabotage compilation of a frequency spectrum list. In the coding, the frequency spectrum list is an essential need for the fZM analysis. Without the frequency spectrum list, an fZM graph cannot be made. The data collected was suitable for other modes of visualization, for example, the chord diagram in the mineral network analysis section.

Table 4.5 Palladium mineral list and locality count

No.	Mineral Name (No. of localities)	Chemical formula
1	Arsenopalladinite (31)	Pd_8As_3
2	Atheneite (15)	$Pd_2(As_{0.75}Hg_{0.25})$
3	Atokite (29)	Pd_3Sn
4	Borishanskiite (1)	$Pd_{1+x}(As,Pb)_2$ (x = 0.0-0.2)
5	Borovskite (7)	Pd_3SbTe_4
6	Bortnikovite (1)	Pd_4Cu_3Zn
7	Cabriite (12)	Pd_2CuSn
8	Chrisstanleyite (6)	$Ag_2Pd_3Se_4$
9	Coldwellite (2)	Pd_3Ag_2S
10	Froodite (62)	$PdBi_2$
11	Isomertieite (48)	$Pd_{11}Sb_2As_2$
12	Jagüéite (3)	$Cu^{1+}{}_2Pd^{2+}{}_3Se^{2-}{}_4$
13	Kalungaite (1)	PdAsSe
14	Keithconnite (40)	$Pd_{20}Te_7$
15	Kojonenite (1)	$Pd_{7-x}SnTe_2$
16	Kotulskite (116)	$Pd(Te,Bi)_{2-x}$
17	Kravtsovite (2)	$PdAg_2S$
18	Laflammeite (7)	$Pd_3Pb_2S_2$
19	Lukkulaisvaaraite (2)	$Pd_{14}Ag_2Te_9$
20	Majakite (22)	PdNiAs
21	Malyshevite (7)	$PdCuBiS_3$

No.	Mineral Name (No. of localities)	Chemical formula
22	Marathonite (1)	$Pd_{25}Ge_9$
23	Menshikovite (15)	$Pd_3Ni_2As_3$
24	Merenskyite (155)	$PdTe_2$
25	Mertieite-I (9)	$Pd_{5+x}(Sb,As)_{2-x}$ (x = 0.1-0.2)
26	Mertieite-II (44)	$Pd_8Sb_{2.5}As_{0.5}$
27	Michenerite (114)	PdBiTe
28	Miessiite (1)	$Pd_{11}Te_2Se_2$
29	Milotaite (1)	PdSbSe
30	Naldrettite (11)	Pd_2Sb
31	Nielsenite (4)	$PdCu_3$
32	Nipalarsite (1)	$Ni_8Pd_3As_4$
33	Norilskite (2)	$(Pd,Ag)_7Pb_4$
34	Oosterboschite (5)	$(Pd,Cu)_7Se_5$
35	Oulankaite (3)	$Pd_5Cu_4SnTe_2S_2$
36	Padmaite (3)	PdBiSe
37	Palarstanide (13)	$Pd_5(Sn,As)_2$
38	Palladinite (6)	$Pd^{2+}O$
39	Palladium (59)	Pd
40	Palladoarsenide (37)	Pd_2As
41	Palladobismutharsenide (6)	$Pd_2(As,Bi)$
42	Palladodymite (3)	Pd_2As
43	Palladogermanide (1)	Pd_2Ge

No.	Mineral Name (No. of localities)	Chemical formula
44	Palladosilicide (2)	Pd_2Si
45	Palladseite (6)	$Pd_{17}Se_{15}$
46	Paolovite (38)	Pd_2Sn
47	Pašavaite (1)	$Pd_3Pb_2Te_2$
48	Plumbopalladinite (10)	Pb_2Pd_3
49	Polarite (10)	$Pd(Bi,Pb)$
50	Potarite (25)	$PdHg$
51	Skaergaardite (10)	$CuPd$
52	Sobolevskite (44)	$PdBi$
53	Sopcheite (24)	$Ag_4Pd_3Te_4$
54	Stannopalladinite (12)	Pd_3Sn_2
55	Stibiopalladinite (75)	Pd_5Sb_2
56	Stillwaterite (24)	Pd_8As_3
57	Sudburyite (46)	$PdSb$
58	Taimyrite-I (11)	$(Pd,Cu,Pt)_3Sn$
59	Tatyanaite (3)	$(Pt,Pd,Cu)_9Cu_3Sn_4$
60	Telargpalite (18)	$(Pd,Ag)_3Te$
61	Telluropalladinite (15)	Pd_9Te_4
62	Temagamite (24)	Pd_3HgTe_3
63	Thalhammerite (1)	$Pd_9Ag_2Bi_2S_4$
64	Tischendorfite (2)	$Pd_8Hg_3Se_9$
65	Törnroosite (4)	$Pd_{11}As_2Te_2$

No.	Mineral Name (No. of localities)	Chemical formula
66	Ungavaite (3)	Pd_4Sb_3
67	Urvantsevite (4)	$Pd(Bi,Pb)_2$
68	Vasilite (11)	$(Pd,Cu)_{16}(S,Te)_7$
69	Verbeekite (2)	$PdSe_2$
70	Vincentite (17)	Pd_3As
71	Vymazalováite (1)	$Pd_3Bi_2S_2$
72	Vysotskite (53)	(Pd,Ni)S
73	Zvyagintsevite (32)	Pd_3Pb

Gold

Gold is one of the most popular precious metals in the world throughout human history. There are several ways in which gold bearing minerals can be deposited in nature, for example, placer deposits provide nearly two-thirds of all the gold mined in the world (Arndt, Kesler, and Ganino, 2010). Placer gold is not necessarily associated in the formation processes, but the deposits are rather derived from the weathering and erosion of vein deposits containing gold minerals (Evans, 1987). Alluvial gold particles are more prominent in Witwatersrand South Africa whereby through planar view, the gold deposits appear fan-like (distributing outwards like river channels). This strongly suggests that alluvial gold occupied distributary channels. Alluvial deposits are also known for having veins of quartz along with the ore (Evans, 1987). Gold deposits can result from metamorphic processes brought about by orogenic processes (Phillips and Powell, 2009). Orogenic processes contribute to the deformation of a landscape leading to the change in temperature, pressure and chemistry of the gold bearing magma bodies in the earth's crust.

Many large gold deposits, such as the Mother Lode deposits in California, are produced by lateral secretion. During lateral secretion, gold is mobilized out of the country rock and is concentrated as the ore fluids move into faults and other structures (Boyle, 1959). Deposition can be triggered by temperature drop, redox changes, or pH changes.

Deposition of gold can result from changes in the temperature or chemistry of dissolved gold-bearing hydrothermal brines. Hydrothermal brines are highly concentrated solutions that host a variable amount of economically viable minerals depending on the source of solution or minerals that diffused in from country rock (Evans, 1987). The brines are usually of sulfides and chloride concentration.

Mineral Ecology of Gold

Gold has 36 minerals but 34 had locality data and were subjected to the same treatment as the minerals preceding it in the paper. What sets gold apart from the other minerals is that gold is widely researched and therefore more is known about it. Gold has 32281 mineral locality pairs that are essential for more accurate LNRE analysis. Data from table 4.6 fit an fZM model, the parameters used are summarized in table 4.7.

Table 4.6 Gold mineral list and locality count

No.	Mineral Name (No. of localities)	Chemical formula
1	Anyuiite (10)	$AuPb_2$
2	Auricupride (24)	Cu_3Au
3	Aurihydrargyrumite (1)	Au_6Hg_5
4	Aurostibite (73)	$AuSb_2$
5	Bezsmertnovite (6)	$(Au,Ag)_4Cu(Te,Pb)$
6	Bilibinskite (12)	$PbAu_3Cu_2Te_2$
7	Bogdanovite (11)	$(Au,Te,Pb)_3(Cu,Fe)$
8	Buckhornite (13)	$(Pb_2BiS_3)(AuTe_2)$
9	Calaverite (361)	$AuTe_2$
10	Criddleite (3)	$Ag_2Au_3TlSb_{10}S_{10}$
11	Cuproauride (3)	Cu_3Au
12	Fischesserite (24)	Ag_3AuSe_2
13	Gold (30554)	Au
14	Honeaite (3)	Au_3TlTe_2
15	Hunchunite (6)	Au_2Pb
16	Jaszczakite (1)	$[Bi_3S_3][AuS_2]$
17	Jonassonite (19)	$Au(Bi,Pb)_5S_4$
18	Kostovite (21)	$AuCuTe_4$
19	Krennerite (111)	Au_3AgTe_8
20	Maldonite (88)	Au_2Bi
21	Montbrayite (19)	$(Au,Ag,Sb,Bi,Pb)_{23}(Te,Sb,Bi,Pb)_{38}$

No.	Mineral Name (No. of localities)	Chemical formula
22	Museumite (1)	$[Pb_2(Pb,Sb)_2S_8][(Te,Au)_2]$
23	Muthmannite (7)	$AuAgTe_2$
24	Nagyágite (67)	$[Pb_3(Pb,Sb)_3S_6](Au,Te)_3$
25	Novodneprite (4)	$AuPb_3$
26	Pampaloite (1)	AuSbTe
27	Penzhinite (1)	$(Ag,Cu)_4Au(S,Se)_4$
28	Petrovskaite (9)	AuAgS
29	Petzite (409)	Ag_3AuTe_2
30	Sylvanite (337)	$AgAuTe_4$
31	Tetra-auricupride (30)	CuAu
32	Uytenbogaardtite (46)	Ag_3AuS_2
33	Weishanite (3)	(Au,Ag,Hg)
34	Yuanjiangite (3)	AuSn

Table 4.7 Gold fZM parameters

Alpha	0.2689717
A	2.395885e-05
B	1.388001
p-value	0.03625169
Terrestrial Au	34
Sample size	32281
Expected Au minerals	35

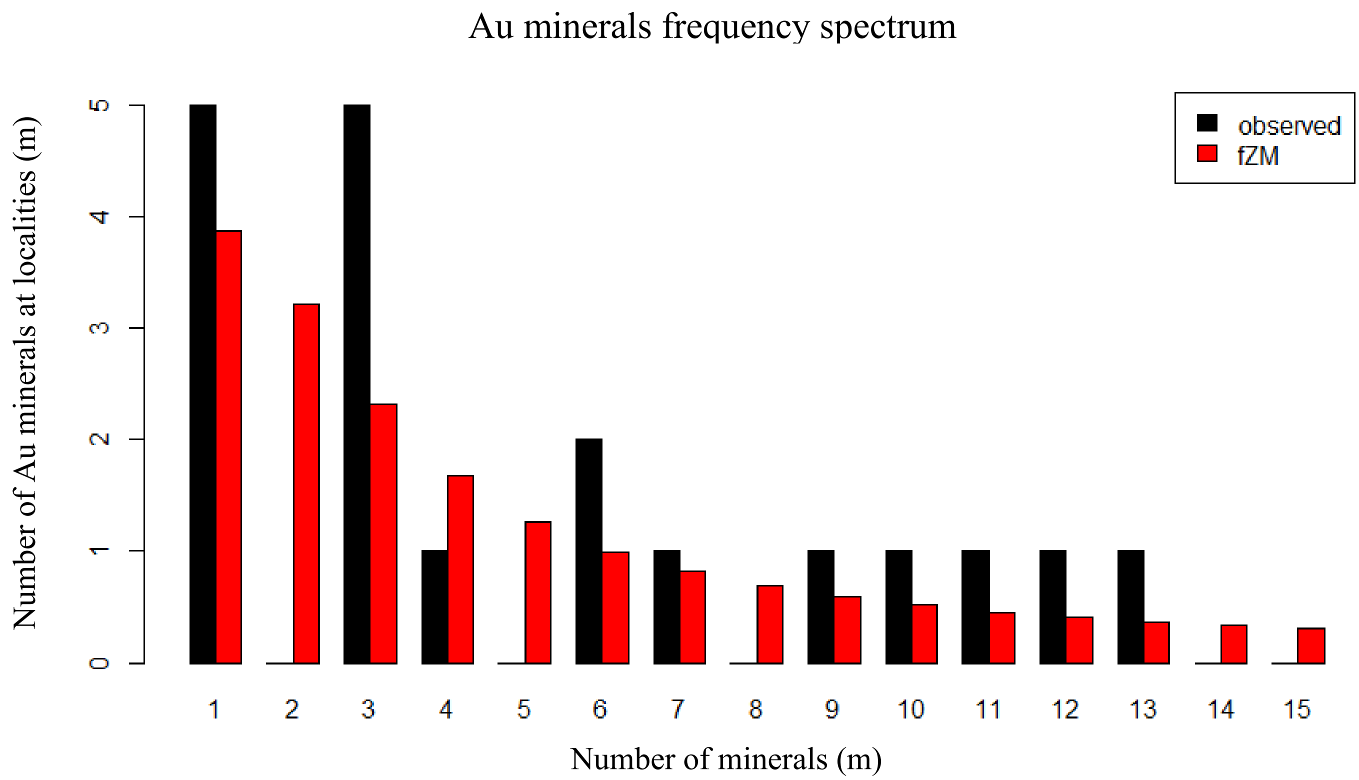

Figure 4.4: Gold frequency spectrum analysis using the fZM method. The x-coordinate labeled "m" represents the number of localities, the y-coordinate represents the number of Au species. The observed data is in black bars whereas the bars in red were the mineral species derived from the fZM model.

Analysis of Gold

Gold minerals conformed to LNRE frequency spectrum and at several points in the discovered mineral species occurring even more than the proposed value by the fZM model. An abundance of placer deposits could be the reason for having more values than those proposed by the model. Gold's erosion from a gold ore outcrop could end up anywhere leading to a branching out of multiple localities originating from one. This can exaggerate the number of localities where gold is found. Gold's appeal has motivated a wide and extensive search spanning a great number of years, and as such, the model estimated one more than the number of known minerals that were processed in the model (two mineral species were not included for lacking locality data). This goes to show that if more data on other minerals was readily available as gold is, then more minerals were to be discovered in the said localities aligning with what the model expects the number to be. Gold was estimated as having 35 mineral species by the fZM model. This is one less than the observed amount. Precious minerals have this advantage because much more money could be made from them if more is known about them.

CHAPTER 5

MINERAL COOCCURENCE NETWORK ANALYSIS OF SELECTED MINERALS

Network analysis is quite a popular section of study that is used in various fields of science that employs the use of powerful mathematical and visualization methods to analyze bulks of data (Morrison et al., 2017). The uses vary from commercial distribution, communication, physical infrastructures, water systems, terrorist networks and the spread of diseases (Morrison et al., 2017). Chord diagrams are also another way of looking into relationships between mineral species to reveal information that is not as visible by looking at bulks of data.

Chord Diagram

One such way of visualizing such data is through the chord diagrams. Chord diagrams are powerful circular graphs that in this case are quite important in visualizing mineral cooccurrence (Hazen et al., 2019). The circular graphs are accompanied by arcs that signify the importance of the connection by the arc's size (Holtz and Healy). In this research chromium, platinum, palladium and Gold were analyzed for their tendency to occur together in similar localities. A matrix table was made reflecting the probability of finding one mineral (from in table 5.1) in several other mineral's localities (to in table 5.1). Data was collected from mindat and the graph made on the r software.

Table 5.1: Probabilities of mineral cooccurrence

From/To (%)	Platinum	Palladium	Gold	Chromium
Platinum	100	37.4	34.01	13.95
Palladium	72.37	100	46.71	19.08
Gold	0.44	0.31	100	0.27
Chromium	3.59	2.54	5.34	100

Table 5.2: Mineral occurrence locality values

From/To (%)	Platinum	Palladium	Gold	Chromium
Platinum	294	110	100	41
Palladium	110	152	71	29
Gold	100	71	22695	61
Chromium	41	29	61	1142

From table 5.1 the mineral cooccurrence probabilities were displayed. The system works on a from/to scenario. The values were calculated in percentages from table 5.2 by dividing how many minerals of mineral A occurred at mineral B over the total locality count of mineral A to get the required percentage (A and B do no stand for any specific mineral but just for demonstration). For example, from platinum to chromium localities, there is a 13.95

% chance to find chromium when at a platinum deposit outcrop. From platinum to platinum, there is a 100% chance to find platinum at a platinum deposit outcrop. This data was then used to construct a chord diagram (figure 5.1) to be able to better analyze the relationship between the 4 elements/minerals. Table 5.2 is a replica of table 5.1 but with the raw locality data to display actual relationships between the minerals. Table 5.2 was used to make the chord diagram figure 5.2.

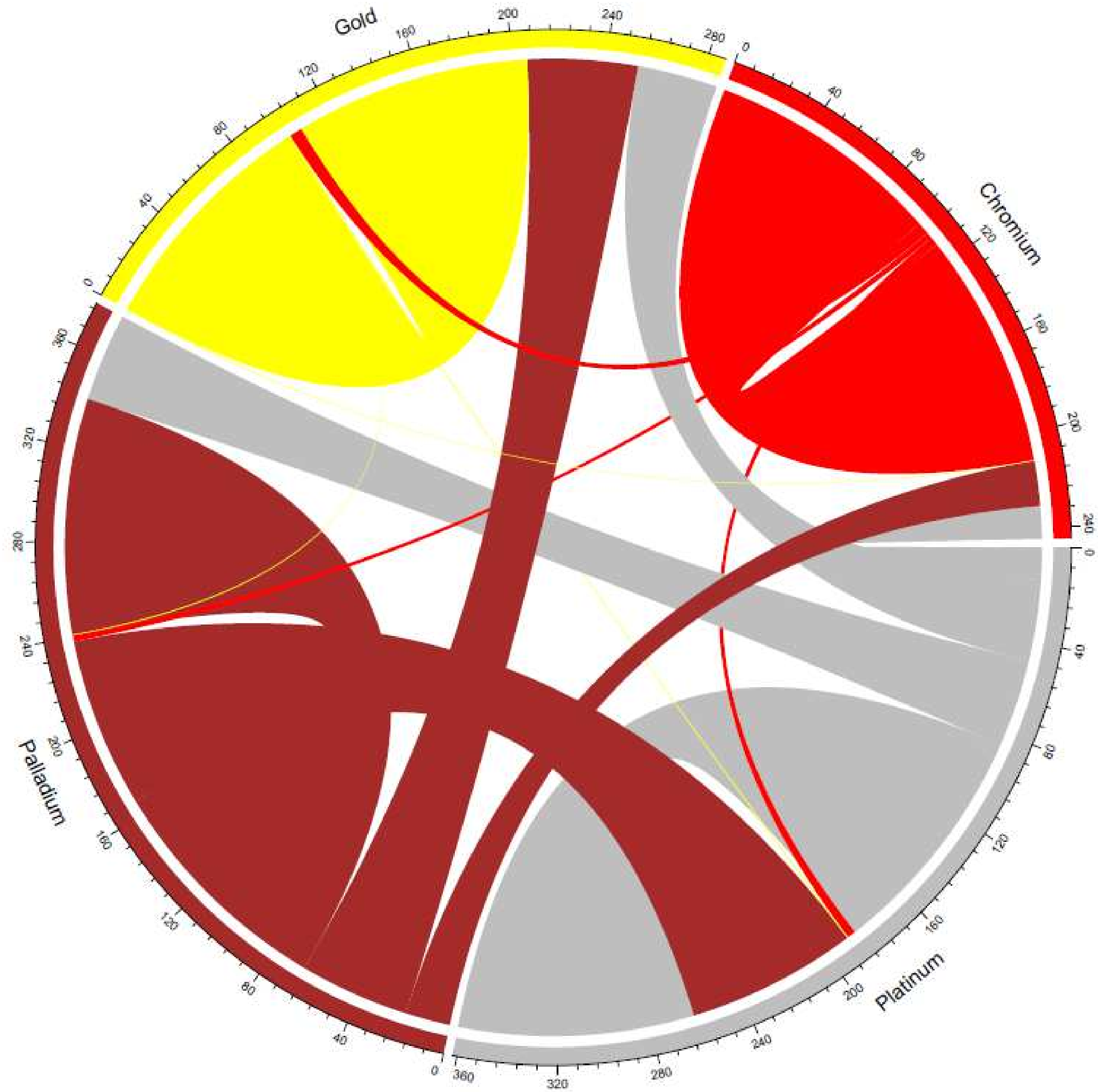

Figure 5.1: Chord diagram showing relationship between Platinum, chromium, palladium and gold in terms of the probability to find the element bearing minerals in other localities represented in percentages.

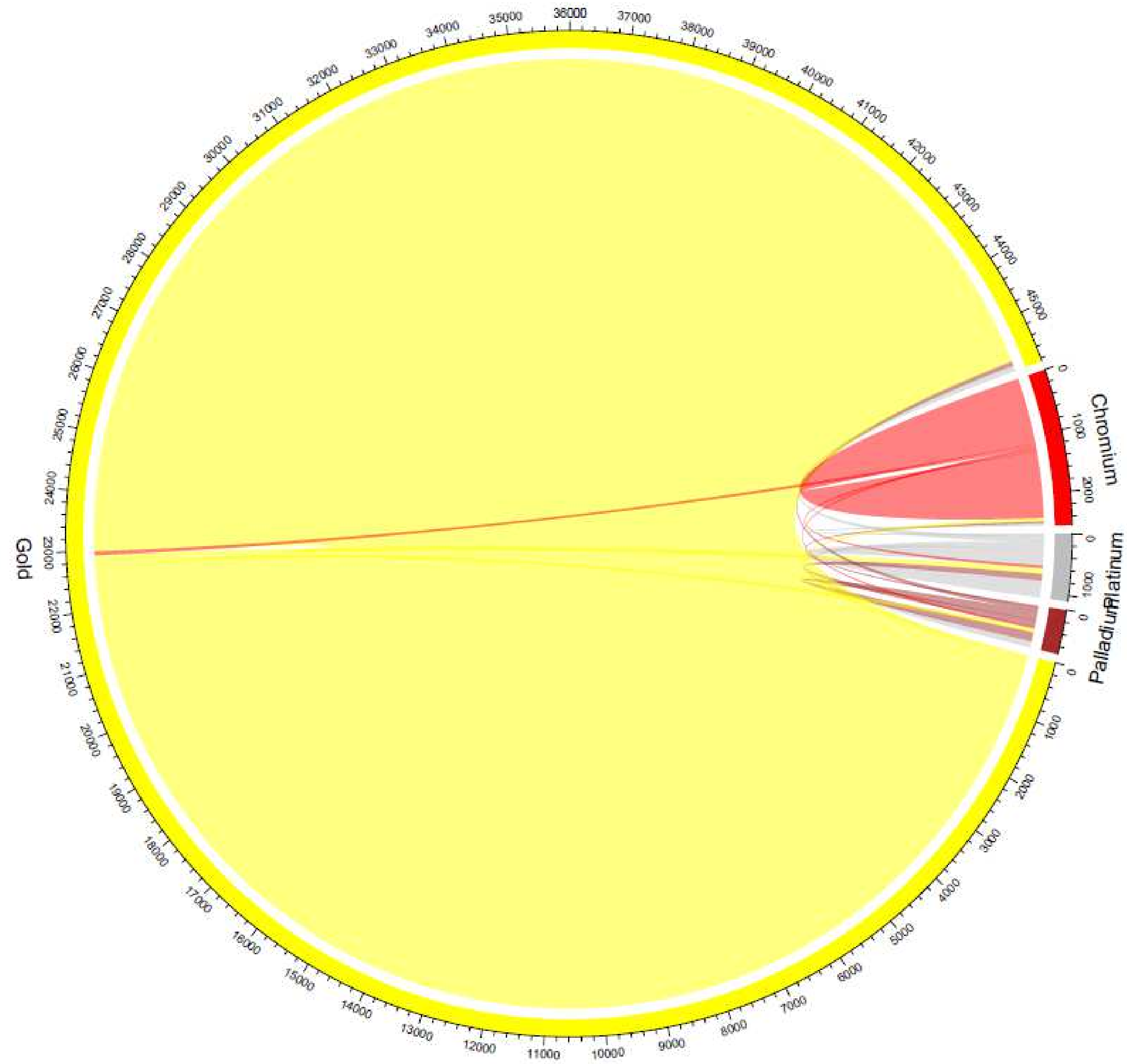

Figure 5.2: Chord diagram showing the relationship between Platinum, chromium, palladium, and gold in terms of their locality count.

Analysis of the Chord Diagram

Directly from the figure 5.1, It is quite visible that platinum and palladium have greater influence than gold and chromium. Platinum is vastly distributed but it is quite visible from the graph that it has the least relationship with chromium (compared to the other minerals). It has a greater relationship with palladium which could be explained from their relationship of being platinum group metals (British Geological Survey, 2009). Platinum and palladium form from the same ore-forming processes and the magma that forms them is most likely from the same source. Chromium, which was at first believed to have had a greater connection with platinum, is not quite clear from Figure 5.1. In the 4 sets of elements, it has a little connection to platinum (bigger only to gold). However, this could be because of how the data is represented. To make the chord diagram, the data was represented as a probability of finding one element bearing mineral at another element bearing mineral's locality. This is not indicative of the full story being told in terms of relationships between the elements.

Figure 5.2 tells a different story regarding the relationships between platinum, palladium, gold, and chromium from that told from figure 5.1. The use of raw locality values as opposed to percentage values shows the vast difference in the locality numbers between the minerals and the impact they have over one another. Chromium has a greater imprint in the figure second only to gold. It has clear ties with all the other minerals more likely with gold then followed by platinum. The chord diagram also shows that gold has strong connections with all the other minerals. But, compared with its total locality this represents quite a small number. Both platinum and palladium are almost overshadowed in the graph but, the strong relationship between palladium and platinum is still the highest value on the graph.

Mineral Network Analysis

Mineral network diagrams as discussed above are very useful. The uses range from indicating connectivity through networks of friends on social media sites such as Facebook to tracking down possible patients of COVID-19. In biology, network analysis is used to study ecosystem diversity and relationships among associated organisms (Morrison et al., 2017). The model can also be used to study co-relationships between mineral species.

Network diagrams are made up of nodes and edges. Nodes which are also called vertices will represent mineral species. Nodes can represent other attributes such as locality count and mineral pair-wise associations through the size of the nodes (Ognyanova, 2015: Morrison et al., 2017). Nodes are connected by links known as edges. The links can also be utilized to show the weight of relationships between two nodes (Morrison et al., 2017). If two nodes are connected it means they have a relationship and, in our case, it means that they occur at the same location. The weight of their cooccurrence (number of times they occur together) is indicated by the thickness of the edges.

The data used to make the network diagrams is obtained from mindat and displayed on Tables 5.3 and 5.4. The data was imported into R via lists made in excel. One of the lists was data on mineral species, locality count and mineral associations whereas the other list represented weight relationships between mineral species.

Table 5.3: Mineral Node attributes

id	minerals	Mineral.type	Type.label	Mineral.association	Locality.count
s01	Platinum	1	Platinum	251	294
s02	Palladium	2	Palladium	210	152
s03	Gold	3	Gold	232	22695
s04	Chromium	4	Chromium	131	1142

Table 5.3 was used to create nodes in R. The columns mineral association and locality count were used to create different node sizes. The mineral association column represented the number of pairwise relationships the mineral had with all the other minerals altogether. However, the locality count column brought about a problem in graphing because of the vast difference in scale between the mineral data that will be addressed further in the paper.

Table 5.4: Mineral edge attributes

From	**To**	**Weight**	**Mineral pair**
s01	s02	110	Platinum→Palladium
s01	s03	100	Platinum→Gold
s01	s04	41	Platinum→Chromium
s02	s01	110	Palladium→Platinum
s02	s03	71	Palladium→Gold
s02	s04	29	Palladium→Chromium
s03	s01	100	Gold→Platinum
s03	s02	71	Gold→Palladium
s03	s04	61	Gold→Chromium
s04	s01	41	Chromium→Platinum
s04	s02	29	Chromium→Palladium
s04	s03	61	Chromium→Gold

Table 5.4 displays important attributes used in the formation of edges. The weight column represented the number of times the two minerals occurred at the same locality. Tables 5.3 and 5.4 were used to make Figures 5.3 and 5.4, which depict different attributes discussed below.

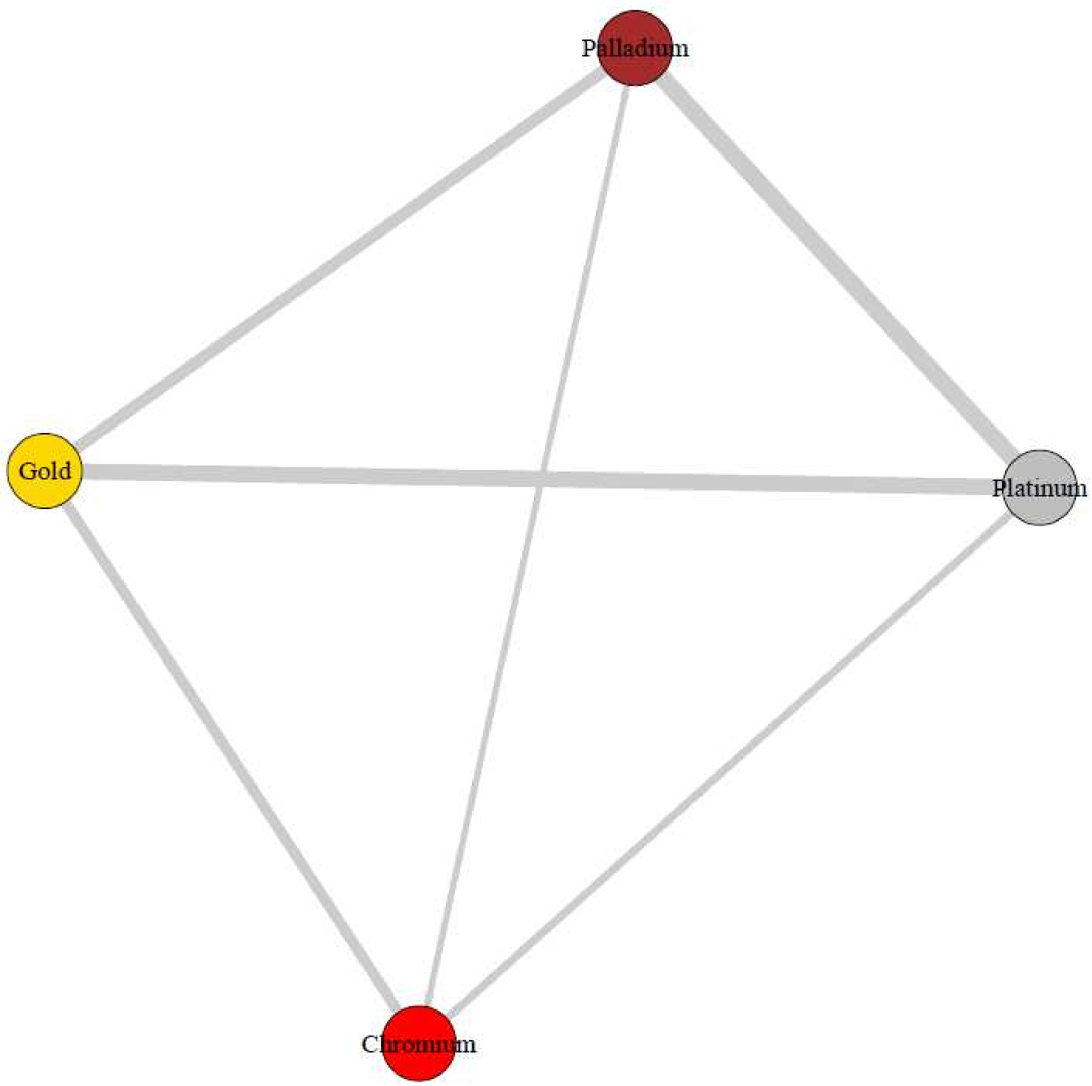

Figure 5.3: Network diagram showing the weight of relationships between minerals.

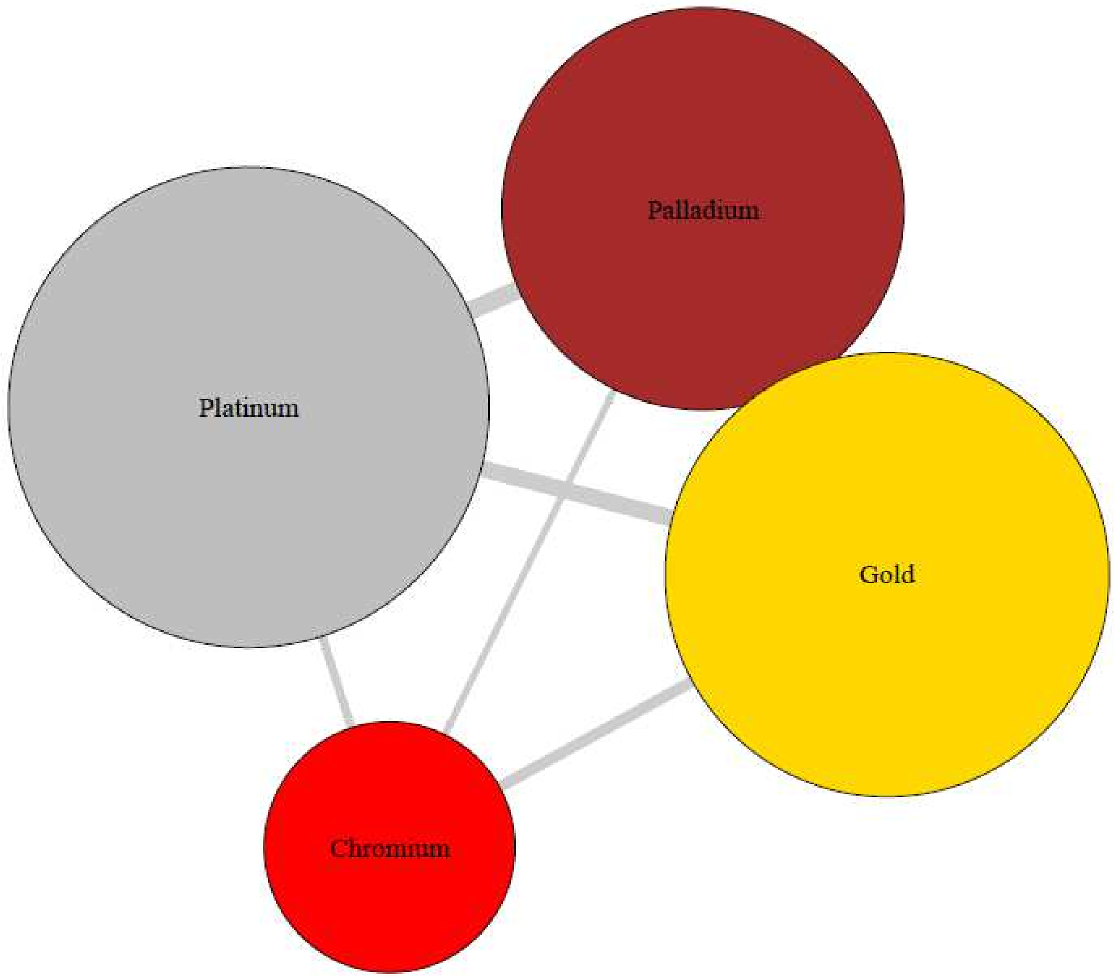

Figure 5.4: Network diagram displaying mineral associations and weight of mineral relationships.

Analysis of Network Diagrams

There are many ways to utilize network diagrams depending on the data being analyzed. In this case, the strength of a pairwise connection was an important attribute worth showing as displayed on Figures 5.3 and 4. In Figure 5.3 stronger connections have thicker edges such as platinum and palladium mainly because they are platinum group elements

(PGEs) that are chemically similar and often occur together (British Geological Survey, 2009). The second strongest connection is that of gold and platinum. The strength of the Au-Pt connection could be explained as follows

Large number of gold occurrences of different genetic types (mesothermal, epithermal, placer, etc.), some of which do not contain Pt, produces a low overall probability (0.44%) of Au coexisting with platinum minerals. The probability of Pt occurring with Au is significantly higher (34%) due to its lower number of platinum bearing localities (294 to gold's 22695). In terms of the sample sizes of the elements in the selection (chromium, platinum, palladium and gold) numbers favor gold because of its higher number of localities giving it more of a chance to have high numbers of connections compared to probability numbers. The connections between gold and palladium and gold and chromium might also be biased toward more numerous cooccurrences for the same reason discussed for Au-Pt cooccurrence.

Another reason is the formation of the ores. Gold shares similar geologic environments of deposition such as placers and hydrothermal brines with platinum, palladium, and chromium (Evans, 1987: Knopf, 1917). This improves gold's chances of cooccurrence with the other elements if they were at any point deposited in the same locality through mineralization from hydrothermal brines containing platinum and palladium, or as a placer downstream where gold can accumulate with platinum, palladium and chromium bearing elements. The Boss Mine in southern Nevada is an example that has ores rich in gold, platinum, and palladium (Knopf, 1917).

Another way of looking at the element's cooccurrence is by looking at the number of connections it has in the relationship. Figure 5.4 displays the strength of connections through edges as well as mineral associations with each other. Mineral associations with each other could be translated to the total number of times the mineral has been found at other mineral locations in this relationship. This was done by taking the total of mineral cooccurrence of that specific mineral which is displayed in table 5.5.

Table 5.5: Mineral locality counts and cooccurrence values.

From/to, Total locality counts↘	Platinum	Palladium	Gold	Chromium	Mineral association
Platinum	294	110	100	41	251
Palladium	110	152	71	29	210
Gold	100	71	22695	61	232
Chromium	41	29	61	1142	131

As seen on table 5.5 the sum along the row of the mineral (excluding the total locality counts in red) displayed the mineral association count, a measure of how "common" the mineral is in this sample size. Figure 5.4 indicates that platinum is more likely to be found with other minerals in this sample size followed by gold, palladium, and chromium, respectively.

Using the locality count as the determiner of node size proved unsuccessful because of the vast difference in locality count values. Gold's locality count (22695) is 19 times the size of the next high value of chromium (1142). Gold's value also far outweighs the least locality count mineral which is palladium (152) by 149 times its size. This made it difficult to put them in the same scaled graph and even much more difficult in addressing the connectivity of minerals according to their locality count. Figure 5.5 shows the vast differences in node size among the minerals. All the values were normalized to palladium's locality count which was the least among the group. However, the overwhelming presence of gold can be minimized by removing all of the placer locality count values for gold, that account to almost two thirds, to better view the relationships among the other elements without being dwarfed by the magnitude of gold's locality values. But it should be noted that there was not a proper distinction between the different geologic environments of formation to make such a graph.

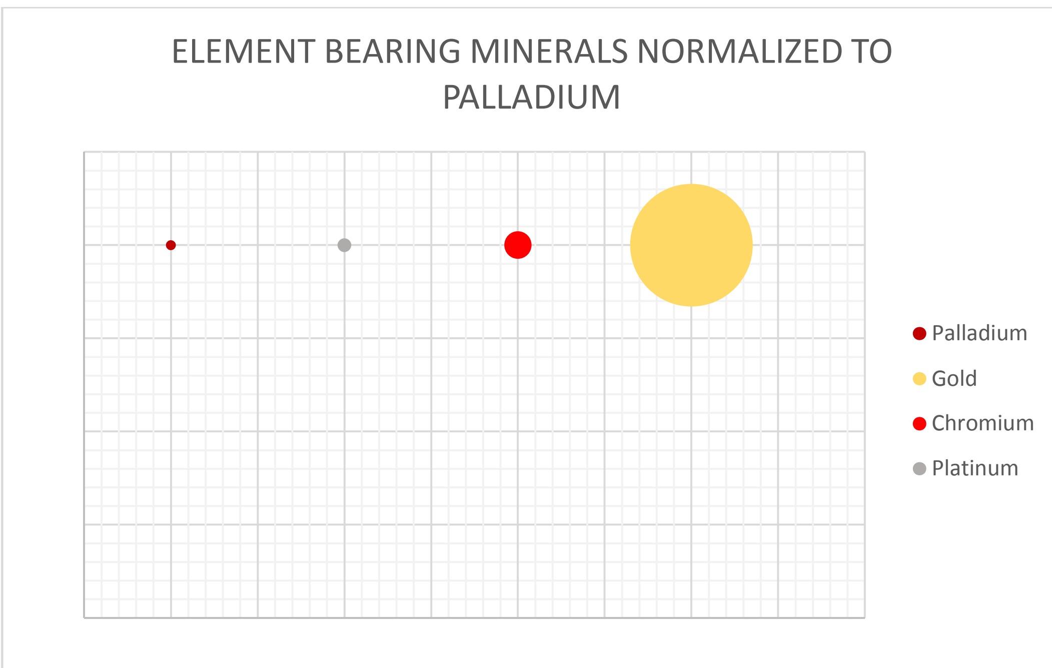

Figure 5.5: Difference in node sizes between the element bearing minerals when normalized to palladium's locality count. The grid is to be used for size comparison between palladium, gold, chromium and platinum-bearing minerals.

However, the overwhelming presence of gold can be minimized by removing all of the placer locality count values for gold, that account to almost two thirds, to better view the relationships among the other elements without being dwarfed by the magnitude of gold's locality values. But it should be noted that there was not a proper distinction between the different geologic environments of formation to make such a graph.

CHAPTER 6

DISCUSSION

The main objective of this work was to explore spatial and network relationships of minerals containing any four elements, namely, platinum, chromium, palladium and gold through the use of statistical tools. The expectation was that such tools would prove useful in the field of mineral exploration by indicating possible pathfinder elements. Pathfinder elements or indicator elements are elements that are commonly associated with the sought element and are useful in locating concealed deposits (Haldar, 2013). The pathfinder elements concentration spikes when close to the vicinity of the deposit and falls to background (normal) concentration when away from the deposit (Haldar, 2013). For example, chromium minerals chrome diopside and chrome spinel are pathfinder elements for locating diamonds (Muggeridge, 1995). Based on the results of this study, chromium can be used as a pathfinder element for locating platinum and palladium deposits. Network and fZM analyses can clearly be useful tools in identifying readily observed minor elemental indicators of ore mineralization.

In the sections that follow, the results obtained from fZM models, chord diagrams and network diagrams will be discussed in detail, emphasizing the importance of mineral ecology and network analysis in mineral exploration.

fZM

Chromium, platinum and gold bearing minerals were used to make frequency spectrum graphs through the fZM model. It was expected that the mineral groups would conform to or behave like an LNRE frequency distribution. Palladium's data was not suited for analysis by the fZM model due to inconsistent data and small sample size of 1437 mineral locality pairs. The fZM model's results tend to overestimate the expected number of mineral species with occasional instances of underestimation.

fZM analysis of chromium predicted that there should be 95 mineral species containing Cr. This means that 14 minerals were termed as "missing" or yet to be discovered. The data was collected on May 21, 2020 and as of July 14, of 2020, the number of known terrestrial Cr-bearing minerals jumped up to 83. Even though the analysis estimates the number of minerals to be discovered, the drawback is that it does not indicate where to look for such minerals. Network analysis of chromium, palladium, gold and platinum-bearing mineral associations can provide hints to where these minerals formed.

Platinum's expected number of minerals was 34, one less than the number of known platinum minerals. It should be noted that the smaller the B parameter (less than 1) the better the estimate would be for the expected minerals. Chromium's B value was 2021 that could be attributed to its overestimation. As of the July 14, 2020, the value still stands at 35 for known platinum minerals.

Gold's extensive value and varieties of occurrence led to 32,281 mineral-locality pairs, with 34 known minerals that were processed through the fZM. The fZM model predicts gold's minerals to be numbered at 35 one less than the observed value. Gold's B value was numbered at 1.388 (close to 1) hence the close estimate to the discovered value.

The fZM model has sparked several mineral hunts in recent years. The carbon mineral challenge started in 2015 and ended in 2019 (Hazen et al., 2016), with (as of July 14, 2020), 31 new carbon minerals discovered at 27 new localities (The Carbon Mineral Challenge). The missing carbon minerals were believed to be mostly hydrous carbonates that were soluble, colorless and poorly crystallized (Hazen et al., 2016).

The reasons minerals have not been previously discovered varies, some may have not been discovered because of poor crystallization, lack of preservation or misidentification. Recognition of these issues could boost numbers for the frequency of minerals occurring at certain localities, though in the case of misidentification, could decrease the frequencies of occurrence for other minerals.

Chord Diagram

Use of chord diagrams provided insight on interrelationships among chromium, platinum, palladium and gold-bearing minerals. Figures 5.1 and 5.2 clearly show mineral cooccurrence by frequency (%) and by locality count. Chromium is identified as a pathfinder element for platinum and palladium as seen in Figure 5.2 and reaffirmed by Haldar (2013). Chromium has a close geochemical relationship with platinum and palladium from the way their ores are formed. Most chromium, platinum and palladium-bearing minerals originate from mafic and ultramafic magmatic processes, which could be the reason for their cooccurrence. Chromium and gold can also be byproducts in nickel-copper deposits which are sulfur-rich (British Geological Survey, 2009). Palladium is also a pathfinder element for platinum ores (Haldar, 2013). Palladium occurs as a primary associate with platinum in ore formation (Haldar, 2013).

Table 5.6 lists several minerals used as pathfinders in the search for certain mineral deposits with chromium and palladium proving to be useful pathfinders in the search for platinum.

Table 5.6: Example pathfinder elements used in mineral exploration (Haldar, 2013).

Type of deposits	**Pathfinder elements**
Gold, silver, gold-silver-copper-cobalt-zinc and complex sulfide ores	As
Copper-zinc-lead-silver and complex sulfide deposits	Hg, Zn
Wolframite-tin deposits	Mo
Porphyry copper, barium-silver deposits	Mn, Mo, Au, Te
Platinum-Palladium in mafic-ultramafic rocks	Cu-Ni-Cr-Pd
Uranium (all types)	Rn, Cu, Bi, As
Sulfur deposits	SO_4

Network Diagrams

Network diagrams present a different way for revealing relationships among minerals. Gold bearing minerals showed strong connections with chromium, platinum and palladium-bearing minerals through node size and weight of the links. This is mainly due to the magnitude of the gold locality count among the minerals. Also, gold, platinum and palladium overlap with similar processes of ore formation in sulfide deposits (Evans, 1987; Knopf, 1917). Gold and chromium also occur as byproducts in nickel-copper deposits (British Geological Survey, 2009), further strengthening the links weight of gold to the other elements in this study. Gold's node size was 149 times larger than that of palladium, which was the mineral with the smallest locality count. The magnitude of gold's locality count can be minimized if the network diagram omits gold's placer locality values. Chromium had the weakest links and a small node size in the group, mainly because the other minerals had greater relationships with each other compared to chromium.

Platinum and palladium had the strongest link with each other because of their geochemical similarities as PGEs. They accumulate through the same processes and can occur as a solid solution whereby platinum and palladium substitute for one another in the same structural site in a disordered fashion (Peterson, 1994; Bindi et al., 2013).

Problems Associated with the Research

Several problems were encountered while analyzing the data through mineral ecology and mineral network analysis. The evaluation of mineral relationships is heavily dependent on the data collected. Some mineral species may have either been overcounted or undercounted. For example, gold placer deposits may exaggerate the number of minerals associated with gold at individual localities (many of which have no genetic relationship with gold), thereby hindering results in fZM, chord diagrams and network analysis. The undercounting of minerals can occur if the element is part of another mineral in small proportions due to solid solution or substitution. For example, the alloy of palladium and platinum may have compositions of Pt_xPd_{1-x} with x ~0.67, ~0.50 and ~0.33, respectively in its chemical formula (Bindi et al., 2013). This mineral is most likely to be labeled as a platinum mineral together with its locality. This situation is not only limited to palladium and platinum but many other minerals.

The network graphs accounted for all the minerals lumped together according to their respective element. If the network graphs discriminated individual mineral groups (sulfides and oxides among others), a much better analysis could have been made. The distinction of mineral groups in the network graphs would have made analysis easier, but, it was not possible due to the magnitude of mineral species and locality counts, as well as the lack of proper distinction of mineral groups and the localities in which they are found in. The information would provide hints as to where the minerals formed. For example, primary sulfide minerals are indicative of a sulfur-rich environment or host.

These problems only provide emphasize the need for large data repositories containing a wide variety of informative data.

CHAPTER 7

CONCLUSION

Mineral ecology has provided an insight into how minerals are spatially distributed on Earth. The results showed that chromium, platinum, gold and palladium-bearing minerals all conformed to an LNRE distribution. The fZM model also showed that there are several Cr-bearing minerals yet to be discovered in nature, this will be more apparent over time as more data is collected on the field. The mineral network analysis results revealed inter-mineral relationships, depicting strong correlations between PGEs, namely platinum and palladium. Mineral network diagrams also showed the magnitude of gold-bearing mineral locality counts that dwarfed other relationships. Even though chromium had the weakest relationships with gold, platinum and palladium-bearing minerals in the network diagram, connections were established to reaffirm it as a pathfinder element for platinum. Palladium's correlations also made it identifiable as a pathfinder element for platinum, too, as indicated by the relationship shared between the two elements on the network diagram. Advancement in observing inter mineral relationships, can be done in making distinctions between mineral groups and processing them through the network diagram. Removing placer localities from the results will provide a clearer picture on the correlation, based on similar geologic environments of accumulation. Future research can employ the eradication of placer localities to explore the limiting analysis done in this research.

Mineral ecology and network analysis are relatively new fields of research in geology and should provide new knowledge useful for understanding mineral evolution and associations, and application to development of new mineral exploration models. Such advances would be greatly aided if information that is held private by companies is released.

With such additional mineral association and locality data, mineral ecology and mineral network analyses are more likely to reach their full potential.

REFERENCES

Abel, G. J. (n.d.). Estimates of global bilateral migration flows by gender between 1960 and 2015 1. *International Migration Review*, *52*(3), 809–852. https://doi-org.proxy.library.umkc.edu/10.1177/0197918318781842

Adolph Knopf. A gold-platinum-palladium lode in southern Nevada. (1917). *The Journal of Geology*, *25*(4), 399.

Arndt, N., Kesler, S., and Ganino, C. (2010). *Metals and society: An introduction to economic geology* (2nd ed.). Springer.

Baayen, R.H. (2001). Word Frequency Distributions (Book). *Computational Linguistics*, *28*(4), 565–569. https://doi-org.proxy.library.umkc.edu/10.1162/coli.2002.28.4.565

Ball, J. W., and Nordstrom, D. K. (1998). Critical evaluation and selection of standard state thermodynamic properties for chromium metal and its aqueous ions, hydrolysis species, oxides, and hydroxides. *Journal of Chemical and Engineering Data*, *43*(6), 895–918. https://doi.org/10.1021/je980080a

Bindi, L., Zaccarini, F., Garuti, G., and Angeli, N. (2013). The solid solution between platinum and palladium in nature. *Mineralogical Magazine*, *77. 2013*(3), 269-274

Britannica. (2019, April 11). *Palladium*. Retrieved July 03, 2020, from https://www.britannica.com/science/palladium-chemical-element

Britannica. (2020, June 02). *Gold*. Retrieved July 03, 2020, from https://www.britannica.com/science/gold-chemical-element

British Geological Survey. (2009). *Platinum*. British Geological Survey, from https://www.bgs.ac.uk/downloads/start.cfm?id=1401

Carnegie Science. (n.d.). *Biography*. Retrieved April 01, 2020, from https://hazen.carnegiescience.edu/cv/biography

Danon, L., Ford, A. P., House, T., Jewell, C. P., Keeling, M. J., Roberts, G. O., Ross, J. V., and Vernon, M. C. (2011). Networks and the epidemiology of infectious disease. *Interdisciplinary Perspectives on Infectious Diseases*, 1–28. https://doi-org.proxy.library.umkc.edu/10.1155/2011/284909

Evans, A. M. (1987). *An introduction to ore geology*. Oxford: Blackwell Scientific, 37-78

Evert, S., and Baroni, M. (2008). Statistical models for word frequency distributions, Package zipfR, http://zipfr.r-forge.r-project.org/. http://www.stefan-evert.de/PUB/EvertBaroni2007.pdf.

Evert, Stefan and Baroni, Marco (2007). zipfR: Word frequency distributions in R. *In Proceedings ofthe 45th Annual Meeting of the Association for Computational Linguistics, Posters and Demonstrations Sessions*, pages 29-32, Prague, Czech Republic. (R package version 0.6-66 of 2019-09-30)

Gu, Z., Gu, L., Eils, R., Schlesner, M., and Brors, B. (2014). Circlize implements and enhances circular visualization in R. *Bioinformatics (Oxford, England)*, *30*(19), 2811–2812. https://doi.org/10.1093/bioinformatics/btu393

Haldar, S. K. (2013). Mineral exploration: Principles and applications. Elsevier, 55-56. https://www.elsevier.com/books/mineral-exploration/haldar/978-0-12-814022-2

Hazen, R. M., Hummer, D. R., Hystad, G., Downs, R. T., and Golden, J. J. (2016). Carbon mineral ecology: Predicting the undiscovered minerals of carbon. *American Mineralogist*, *101*(4), 889.

Hazen, Robert M., Downs, Robert T., Eleish, A., Fox, P., Gagné, Olivier C., Golden, Joshua J., Grew, Edward S., Hummer, Daniel R., Hystad, G., Krivovichev, Sergey V., Congrui, Li., Chao ,L., Xiaogang, M., Morrison, Shaunna M., Feifei, P., Pires, Alexander J., Prabhu, A., Ralph, J., Runyon, Simone E., and Zhong ,H. (2019). Data-driven discovery in mineralogy: Recent advances in data resources, analysis, and visualization. *Engineering*, *5*(3), 397–405. https://doi-org.proxy.library.umkc.edu/10.1016/j.eng.2019.03.006

Holtz, Y., and Healy, C. (n.d.). *Chord diagram*. Retrieved May 21, 2020, from https://www.data-to-viz.com/graph/chord.html

Hystad, G., Downs, R. T., and Hazen, R. M. (2015). Mineral species frequency distribution conforms to a large number of rare events model: Prediction of earth's missing minerals. *Mathematical Geosciences*, *47*(6), 647–661. https://doi.org/10.1007/s11004-015-9600-3

Hystad, G., Eleish, A., Hazen, R. M., Morrison, S. M., and Downs, R. T. (2019b). Bayesian estimation of earth 's undiscovered mineralogical diversity using noninformative priors. *Mathematical Geosciences*, *51*(4), 401–417. https://doi.org/10.1007/s11004-019-09795-8

Hystad, G., Morrison, S. M., and Hazen, R. M. (2019a). Applied Computing and Geosciences Statistical analysis of mineral evolution and mineral ecology: The current state and a vision for the future. *Applied Computing and Geosciences*, *1*(September), 100005. https://doi.org/10.1016/j.acags.2019.100005

IMA Mineral List with Database of Mineral Properties, n.d. https://rruff.info/ima/.

King, H. M. (n.d.). The many uses of gold. Retrieved July 03, 2020, from https://geology.com/minerals/gold/uses-of-gold.shtml

Kolaczyk, E. D. (2010). *Statistical analysis of network data: Methods and models*. New York: Springer. https://pdfs.semanticscholar.org/130d/eaff056f5c8907e8b3bed9eb62be418c53bb.pdf

Liu, C., Hystad, G., Golden, J. J., Hummer, D. R., Downs, R. T., Morrison, S. M., Ralph, J. P., and Hazen, R. M. (2017). Chromium mineral ecology. *American Mineralogist*, *102*(3), 612.

Mindat. (n.d.). *Chromium*. Retrieved May 21, 2020 from https://www.mindat.org/min-52438.html

Mindat. (n.d.). *Gold*. Retrieved May 21, 2020 from https://www.mindat.org/min-52454.html

Mindat. (n.d.). *Palladium*. Retrieved May 21, 2020, from https://www.mindat.org/min-52484.html

Mindat. (n.d.). *Platinum*. Retrieved May 21, 2020, from https://www.mindat.org/min-52485.html

MONEX. (2020, June 26). *Gold Prices Today: Live Gold Spot Price: Price Charts per Ounce/Gram*. Retrieved July 03, 2020, from https://www.monex.com/gold-prices/

MONEX. (2020, June 26). *Palladium Prices Today: Live Spot Palladium Price per Ounce*. Retrieved July 03, 2020, from https://www.monex.com/palladium-prices/

MONEX. (2020, June 26). *Platinum Prices Today: Live Spot Platinum Price per Ounce*. Retrieved July 03, 2020, from https://www.monex.com/platinum-prices/

Morrison, S. M., Liu, C., Eleish, A., Prabhu, A., Li, C., Ralph, J., Downs, R.T., Golden, J.J, Fox, P., Hummer, D.R., Meyer, M.B., Hazen, R. M. (2017). Network analysis of mineralogical systems. *American Mineralogist*, *102*(8), 1588–1596. https://doi.org/10.2138/am-2017-6104CCBYNCND

Muggeridge, M. T. (1995). Pathfinder sampling techniques for locating primary sources of diamond: Recovery of indicator minerals, diamonds and geochemical signatures. *Journal of Geochemical Exploration*, *53*(1–3), 183–204. https://doi-org.proxy.library.umkc.edu/10.1016/0375-6742(94)00061-F

Ognyanova, K. (2015). *Network visualization with R*. Retrieved March 29, 2020, from https://kateto.net/network-visualization

Peterson, J. A. (1994). *Maps showing platinum-group-element occurrences in the conterminous United States, updated as of 1993*. Reston, VA: U.S. Geological Survey. https://pubs.usgs.gov/mf/1994/2270/report.pdf

Phillips, G. N., and Powell, R. (2009). Formation of gold deposits: Review and evaluation of the continuum model. *Earth Science Reviews*, *94*(1), 1–21. https://doi-org.proxy.library.umkc.edu/10.1016/j.earscirev.2009.02.002

Reith, F., Campbell, S. G., Ball, A. S., Pring, A., and Southam, G. (2014). Platinum in Earth surface environments. *Earth-Science Reviews*, *131*, 1–21. https://www.sciencedirect.com/science/article/abs/pii/S0012825214000063

Ross, R. (2016, August 01). *Facts About Platinum*. Retrieved July 17, 2020, from https://www.livescience.com/39144-platinum.html

Ruth F. Schulte, Taylor, R. D., Piatak, N.M., and Seal II, R.R. (2012). *Stratiform chromite deposit model: Chapter E of Mineral Deposit Model for Resource Assessment*. https://permanent.fdlp.gov/gpo33788/sir2010-5070e_LR.pdf#?

The Carbon Mineral Challenge. (n.d.). *Carbon Mineral Challenge*. Retrieved July 14, 2020, from https://mineralchallenge.net/guidelinesrules/

Yedemsky, Eduard, and Leonid Varennikov. 2013. *Platinum: Compounds, Production, and Applications*. Hauppauge, New York: Nova Science Publishers, Inc, 1-2.

VITA

Charles Mwaipopo was born in the city of Dar es Salaam located in the United Republic of Tanzania. Charles Mwaipopo is a husband to a beautiful woman named Beatrice. Beatrice was and is a great inspiration for his drive to get a master's degree and pursue a career as an economic geologist. Charles obtained his bachelor's of Science in Geology at the University of Missouri-Kansas City in the year 2016 after attending Metropolitan Community College-Penn valley in Kansas City for two years.