Relationship of Mines and Calderas: A Geologic Study on the Processes of Mineralization in the San Juan Volcanic Field

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Abstract

This project covers the prospect of using calderas as sources of rare earth metals by looking at established mines within the San Juan Volcanic Field (SJVF) of southwestern Colorado. Studies in this region began in the 1960's and continues to this day covering a wide range of topics including geochronology, geochemistry, and structural geology to name a few. Current maps of the calderas within the field usually show these sixteen known calderas nested making it difficult in some cases to locate the individual caldera when looking at a map. By deconstructing these nests, a better determination on which mine belongs to which caldera and incorporating the data provided in aforementioned studies better visualizes the process needed for the mineralization of the desired ore. The types of ore bodies contained within the caldera or outside the caldera may show how certain rare earth metals are more likely to occur in one versus the other. This will also apply to the structural nature of the caldera system by showing how the mines are spatially related linearly or clustered and what the mechanism for this process may have been, i.e., fault systems. With over 3600 mines, 2921 being mined for rare earth metals, this is a prime area of study to continue into an economic viability study to determine if it is worth prospecting unmined calderas that meet conditions present in the SJVF.

Introduction

The history of Colorado was built on the pioneers moving west to become wealthy in the mineral rich areas where gold and silver were abundant beginning as early as the 1840's. Many ore deposits are spatially associated with calderas and other volcanic centers and have demonstrated that calderas provide an important setting for mineralization in the San Juan volcanic field of Colorado (Duex and Henry, 1981). Southern Colorado is home to one of the largest volcanic explosions in geologic history, the Fish Canyon eruption of the La Garita Caldera approximately 26.3 m.y.a. This explosive eruption blew out 1,500 cubic miles of rock and ash, nearly three times the amount of the Yellowstone caldera, and created a caldera so large it could be seen from space. (Bethke and Hay, 2000). This was just one of many volcanic events that, to date, have created sixteen known calderas in the San Juan volcanic field of southern Colorado.

One of the sixteen known calderas, the Creede caldera, is home to about 145 mines, both active and abandoned. These mines range in commodities but mainly extract gold and silver. Many maps today will focus on either mines or calderas and there have been papers written on the subject of these mines in the caldera but there is a lack of combining the two into a digital format, much less a visual one. The maps that exist today of the San Juan volcanic field were mainly created by the USGS in the 1960's and 1970's using aerial images and topographic maps. These maps focus more on the overall extent of the volcanic field, and it can be difficult to find maps consisting of just one caldera and even more challenging to find a digital map. The maps that are readily available usually show the calderas nested in one another (figure 1). Figure 1 shows the type of maps that are generated during this time period and which have been reused throughout various literature but and can offer a lot of information but also takes away the ability to focus on a single caldera. This is important in that we want to see where the mines are within a caldera and if we cannot separate one caldera from another then it becomes problematic to distinguish which mine is in which caldera.

This project has been designed to focus on three main goals:

1. Separate the nested calderas within the San Juan Basin to create maps of individual calderas

2. Define mines that exist within or near these calderas and their objective commodities (gold, silver, zinc, lead, etc.)

3. Define the ages of these ore bodies by comparing the available data of geochronological analysis (McIntosh and Chapin, 2004) with the mineralization of each volcanic event and any surface water sources that would have existed for hydrothermal deposition by looking at the surface and structure geology in the area (i.e., faults, fossils, minerals that form in water rich environments). This can be completed through available data analysis (Bethke and Hay, 2000)

By defining these goals in three separate components a determination was made if there is definitive correlation between volcanic events and base metal mineralization by showing the implied spatial relationships of the two defined by their age. Other structures, such as faults, were used to determine if the presence of surface water could have been transported sub-surface for hydrothermal deposition.

This project first started with the idea of digitally mapping the caldera system of the San Juan Volcanic Field. Many maps exist but these maps date from the 1960's and 1970's and are now available as PDF documents. They were created using aerial methods when available and physically examining and studying the geologic structures on the ground. All that was needed at the time was a compass, some colored pencils and a base topographic map (Keaton and Degraff, 1996). Not much has been done in the way these maps are generated since then save for a few fine-scaled areas of the field and its structure such as the Varga et al. study of the Bonanza Caldera in 1985. A description of this fine-scaled mapping would be "…applied an unconventional processing procedure that uses geologically appropriate densities for the uppermost crust and digital topography to mostly remove the effect of the low-density units that underlie the topography associated with the SJVF (San Juan Volcanic Field). This approach resulted in a gravity map that provides an improved representation of deeper sources, including reducing the amplitude of the anomaly attributed to a batholith complex" (Drenth et al., 2012). Upon closer review of the area, I noticed that there were many mines in the area, which makes sense given the hydrothermal history of the area and the way that ore deposits are mineralized. The question then became why are there so many mines located within the area of the caldera? What makes these areas more favorable to ore deposition as opposed to other areas with known hydrothermal history? Why can't we separate these on a caldera-by-caldera case to explore the mineralization process?

Many papers have been written about ore deposition and some have even focused on the ore deposition in the San Juan Basin (Barton et al., 1977; Bethke et al., 1976; Bethke and Rye, 1979; Steven and Eaton, 1975). Many well-known mines exist in the Colorado Mineral Belt (CMB) located north, north-east of the San Juan Basin. Chapin (2012) gives a good overview of the structure and possible nature of the origins of the CMB while stating that these deposits have been "a long-standing geologic enigma." Chapin's paper explains the geochronology and geochemistry of the area and helps in defining the relationship of the lithology and ore deposits.

This is a very good starter for how ores are generally thought to be deposited in igneous environments as it helps to establish a baseline for the geochemical analysis done in mineral rich areas.

Once the mechanics of ore deposition is understood, we can then analyze the ages of the rocks and ores, compositions of the rock matrix and tie these into the depositional environment and structure of the caldera complex. There are sixteen known calderas (many of these are nested calderas) within the basin and arguments exist whether there are actually more than this (Drenth et al., 2012). The peak volcanic activity forming these calderas took place during the Oligocene (30-26 m.y.a.) (Steven and Lipman, 1975) and began at about the same time as the end of the Laramide orogeny and beginning of the Rio Grande rift with overall volcanic activity dating from 40-25 m.y.a. (Bethke et al., 1976). Efforts to date these rocks has used K-Ar dating (Steven and Lipman, 1975), $^{87}Sr/^{86}Sr$ dating (Varga and Smith, 1984) and $^{40}Ar/^{39}Ar$ (Bachmann et al., 2007) of tuff deposits. K-Ar dating has been used for rocks 4.5 billion years old to as young as 20,000 years. $^{87}Sr/^{86}Sr$ dating is applicable for weathered rocks, not lunar or meteoric; strontium has a half-life of 49.23 billion years. $^{40}Ar/^{39}Ar$ dating was invented to supersede K-Ar dating and can be used for smaller sample sizes. The dating of the ore deposits yields ages 1-2 million years later than that of the youngest known volcanic event in the area (Barton et al., 1977). These are variables that help define when mineralization of ores can occur in a volcanic environment and help with exploration in other areas.

The compositions of volcanoes usually fall into one of two categories, mafic and siliceous (others do exist but are not relevant to this study and are rare). The composition of the rock matrix surrounding the ore deposits within the San Juan basin exhibit an abundance of andesite, an intermediate composition between siliceous rhyolite and mafic quartz latite (Steven and Lipman, 1975). By detailing what the mineralogy of the magma chamber was based on for the rock matrix we can then compare this against where the ore bodies are located to determine if the ore being mined is more common in a siliceous rich or intermediate siliceous environment. This can be done since we know the age and general composition of the calderas.

The final part of the puzzle is to determine the conditions that allow mineralization of the ore in these calderas. As stated earlier, there are sixteen known calderas with events occurring over millions of years. Faulting, melting, and subsequent volcanism play a big part in the transportation of hydrothermal material allowing for the mineralization of ore bodies. Lead isotopes have been used to determine the source of mineral deposits within the basin. "These regional characteristics seem mainly dependent on the particular mix of crustal rocks that underlie each area. Mechanisms for extracting the lead from the underlying rocks, transporting it and depositing it at near-surface levels probably involve a combination of magmatic process and deeply circulating convective cells of meteoric water driven by magmatic heat." (Doe et al., 1979)

What is shown here so far is a process and method of dating and recognizing the methods for ore deposition. What is missing are the ore characteristics at the individual caldera. This project was designed to separate the calderas from each other as all current maps show these structures nested making it difficult to distinguish one from the other. By doing this we can see what is being mined in each caldera, separated by age of the caldera, and integrate more structural data, such as faults, to help determine where the best locations for active mining of the desired ore have been. Based on this analysis of the San Juan volcanic field, it could help future analysts determine if a caldera structure they are interested in is suitable for prospecting. It could also be used to better understand the characteristics of the caldera itself and help determine if these conditions are present in today's super-volcanoes to better estimate the explosive potential and help hazard management planners. As there are many super-volcanic eruptions that have occurred, comparisons can be made to further validate the results. By adding fault structures to these maps, we may also be able to see if these played a significant-part in the hydrothermal transportation process and the proximity of mines to these structures.

Data and Methods

Study Region: The study area covers ~25,000 km^2 of southwestern Colorado (figure 2), and consists of multiple calderas, many successful mines and previous studies that have an abundance of data available (Cole et al., 2005; Duex and Henry, 1981; McIntosh and Chapin, 2004). While this area does have nested calderas there are calderas that stand apart and have mines present making the digitizing of these calderas a more straightforward process due to their well-defined areas. This is also important in that the mines can be looked at for each caldera which has been, at this point, drawn as a shapefile based on a georeferenced map and, based on geological and geochemical data, would help to better answer the 3rd goal of this project. The eastern side of the volcanic field is the site of an intercontinental rift, the Rio Grande rift, that has been active for the last 35-29 million years. This is an important geological event since as the rift widens there is crustal thinning and block faulting resulting in volcanic activity and can be seen in other rift areas such as the East African rift. This provides the source of our volcanism, and as mentioned, faulting which will be looked at as a source of water transport for the hydrothermal activity needed for some ore deposition. The western portion of the field is well inside the San Juan Mountain range and may provide more insight into the types of mineralogy present within the caldera since it is away from the San Luis Basin where most of today's hydrothermal activity is located such as is evident in Alamosa, Hooper, and Crestone.

Data: Data was generated into separate components for this project. First, the maps available of known calderas was georeferenced. There are abundant sources available due to the extensive research conducted across various fields of study in this area. The primary map to be used for georeferencing will be the one used in figure 1 as this map is the most commonly one referenced in various articles, papers and journals. The second component is the location of mines and their commodities. These data have been obtained from the Colorado Geological Survey and contains location, names, commodities as well as abundant other information such as ownership, structural information and years active. The final component is sourced from work previously done on the mapping, geochemical and geochronological work done in this area. The question of the water sources can be answered in these papers as well since a geochemical analysis will show minerals present if they rely on water for the mineralization process. Data is saved in three places: a hard drive, an external hard drive, and Google drive. Current data size is roughly 900 KB with available space for storing at 1 TB on external hard drive and 11 GB on Google with the option of purchasing more space thereby ensuring ample storage and backup.

Methods: Once the photos of maps were obtained ArcMap was utilized to georeference and create digital versions. Once images were georeferenced, polygon features were created for each individual caldera. Digital elevation data was used to verify the borders of the calderas. This method of creating a relief elevation map has been used in the study of Bouger anomaly values (Drenth et al., 2012). Following this the point data for the mines were added. The location of mines was used to the role of the volcanic event as exemplified by the commodities being mined. This was done by various methods depending on the concentration of mines in an area and hot spot, density, counts, etc. were used until a determination was made that the data showed a link between the two or not. Gravel pits and quarries were distinguished from mineral mines and was not included in the dataset. A line layer of faults was also added to determine the structural nature of the mine locations and determine where sources of water could seep into subsurface areas. For the purpose of this project the faults need to be in, or adjacent to, a caldera. Literature sources were used to sort the ages of calderas and ore bodies. Based on this a determination was made on if younger calderas affected the older ones for the mineralization process by determining the concentration of mines in an area along with the commodities being mined as well as any evidential structure changes of one volcanic event by the other. By showing which calderas have mines, what they are mining, the age of the calderas and whether there is evidence of water sources and/or faulting, a determination could be made whether the calderas are a good source for exploration in economic geological work. Of course, other regions in the world would need to be studied for verification to determine the economic viability of mining calderas.

Results

Since the focus of the project was on mines in calderas and the structural nature associated with them, the bulk of data was obtained from the United Geological Survey (USGS). City point data used for georeferencing was obtained from the Colorado Department of Public Health & Environment (CDPHE). All analysis was performed using ArcMap and includes cluster, hot spot and density measurements.

Results overall showed a strong relationship between the calderas, faults and mines. This is evident in figure 6 showing high density of faults within the SJVF that, when overlaid, are in areas where calderas and mines are present. The highest clustering, as seen in figure 7, is in the western portion of the SJVF. The three calderas comprising the bulk of these mines are the Silverton (365 mines), San Juan (51 mines) and Uncompahgre (66 mines) with another 471 mines outside of the calderas but still within the defined area of the volcanic field covering 462.1 square miles. Commodities being mined were copper, gold, zinc, lead, copper, molybdenum, silver, manganese, tungsten, iron, uranium and one mine with a secondary commodity of platinum. Mines located within the calderas had the same commodities with rhenium and bismuth added as a commodity for two mines in the Silverton caldera. Table 1 shows the count breakdown of primary commodities within the Silverton caldera. Mines inside calderas of the center of the study area only total 188 within 742.4 square miles. A cluster north of the central caldera system and within the field had 109 mines that listed thorium as a primary commodity showing the degree to which radioactive material is present.

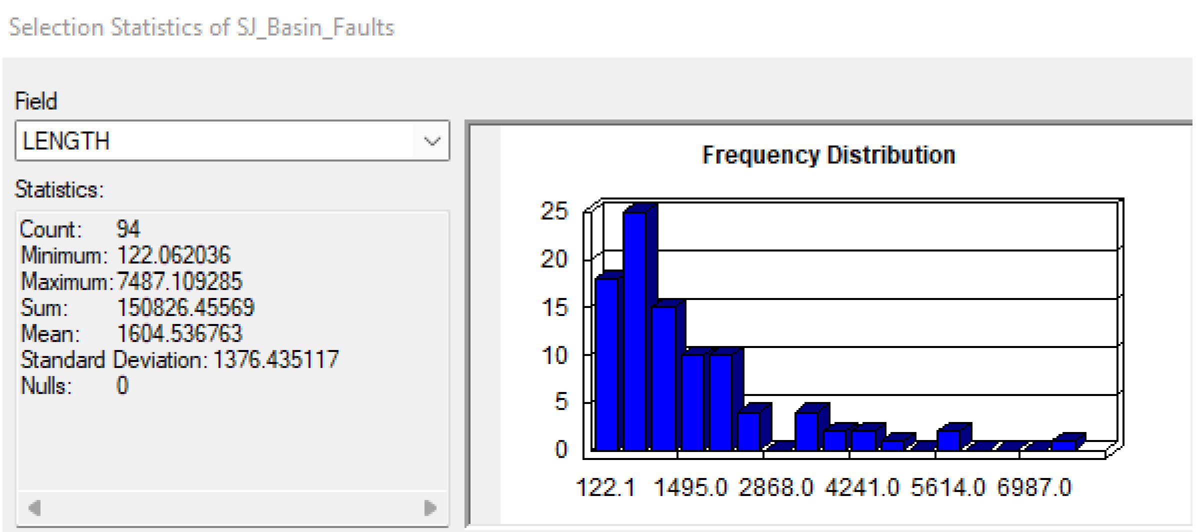
Table 1: Summary table of mines showing count for

Silverton_Mines_Summary

OID	commod1	Count_commod1
0		7
1	Bismuth	2
2	Copper	4
3	Copper, Lead, Silver	1
4	Copper, Lead, Zinc	1
5	Copper, Lead, Zinc, Silver, Gold	1
6	Copper, Silver, Gold, Lead, Zinc	1
7	Copper, Zinc, Lead	1
8	Gold	87
9	Gold, Copper, Lead, Silver, Zinc	1
10	Gold, Copper, Silver	1
11	Gold, Lead, Copper, Silver, Zinc	1
12	Gold, Silver	4
13	Gold, Silver, Copper, Lead	1
14	Gold, Silver, Copper, Lead, Zinc	1
15	Gold, Silver, Lead	1
16	Gold, Silver, Lead, Copper	3
17	Gold, Silver, Zinc, Lead	1
18	Iron	1
19	Lead	49
20	Lead, Gold, Silver	1
21	Lead, Silver	4
22	Lead, Silver, Copper	1
23	Lead, Zinc	14
24	Lead, Zinc, Copper	8
25	Lead, Zinc, Copper, Gold, Silver	1
26	Lead, Zinc, Copper, Silver	1
27	Lead, Zinc, Silver	4
28	Lead, Zinc, Silver, Copper	2
29	Lead, Zinc, Silver, Gold	1
30	Manganese	1
31	Molybdenum	4
32	Silver	36
33	Silver, Bismuth	2
34	Silver, Copper	2
35	Silver, Copper, Gold, Lead	1
36	Silver, Copper, Lead, Zinc, Gold	1
37	Silver, Copper, Zinc	1
38	Silver, Gold	4
39	Silver, Gold, Copper	1
40	Silver, Gold, Rhenium	1
41	Silver, Lead	5
42	Silver, Lead, Copper	1
43	Silver, Lead, Zinc	3
44	Silver, Lead, Zinc, Copper	1
45	Silver, Zinc, Lead	1
46	Tungsten	37
47	Uranium	1
48	Zinc	42
49	Zinc, Copper, Lead	2
50	Zinc, Copper, Silver, Gold, Lead	1
51	Zinc, Lead	6
52	Zinc, Lead, Copper	1
53	Zinc, Lead, Copper, Silver	1
54	Zinc, Silver, Copper, Lead	1
55	Zinc, Silver, Gold, Lead	1
56	Zinc, Silver, Lead	1

Structurally there is an abundance of faults located within the three mentioned calderas with a combined total of 2872 within the study area. Within the three mentioned calderas faults total 94 with a mean distance of 1604.5 m (0.99 mi) as seen in table 2. There is a dike system to the north of the calderas which show mines on the western side. Just south of these mines is a fault that trends north towards these but data shows that it does not reach this area. Mines within the calderas appear to be in these areas of faulting. The exception is the Uncompahgre caldera where the faults do not have many mines associated with it even though one of these faults runs for 7487.1 m (4.65 mi) across the center of the caldera. Faulting within the center of the study area shows them treading north-south. Along the eastern side of the study area there is a lack of faults but there is a grouping in the northeast near the Bonanza caldera. Faults in or near support the theory that water could have been transported subsurface for hydrothermal deposition of minerals.

Table 2: Statistics of faults within the Silverton, San Juan and Uncompahgre calderas



Discussion

Once data was obtained the first step was to have a map to overlay the data on. This required georeferencing a map. The map georeferenced in figure 3 was chosen due to the city points and was obtained from "*40ar/39ar and U–Pb Dating of the Fish Canyon Magmatic System, San Juan Volcanic Field, Colorado: Evidence for an Extended Crystallization History"* by Bachman et.al as it is a more modern map with many city points to reference. The city point data from the CDPHE was chosen due to the data being more accurate. The image of the SJVF was imported as a .tif file with city point data overlain in Arcmap. Problems began with city points not being on top of one another but due to the large area and not needing a high degree of accuracy was not problematic. It was noted that the city points drift apart as you travel farther north along the image. Projection WGS 1984 UTM Zone 13 was used as this did tighten up the points and scaling was much more accurate.

After the map image was georeferenced the process of creating the polygons for each caldera was started. The challenge here was by free-handing these shapes there could be errors in not tracing the rims of the caldera correctly and introduce distance errors. Due to the size of the area this error was negligible. Ages for these calderas were then assigned based on values from various sources (Cunningham et al., 1994; Doe et al., 1979; McIntosh and Chapin, 2004). By doing this I was able to complete the first of my three goals in this project by developing polygons for each individual caldera. Based on the image used by Bachman et. al, a total of 16 calderas were identified as shown in figure 4.

Mine data was brought in and sorted to exclude gravel and quarries leaving a total of 2921 mines within the study area. A closer look at the mines showed that the majority are underground and mining vein deposits. Only a few showed surface or placer mining (placer deposits are those that have managed to weather out of the rock and are typically found in stream and/or rivers). Mines, as shown in figure 5, are concentrated in the west and north either outside of the volcanic field or on the periphery. One cluster of these mines is located in the north central portion of the field itself with the majority being thorium mines which was surprising as I was personally unaware of this type of mining and did not consider it when sorting. Looking for other radioactive mines I did find that Uranium mines are scattered across with small clustering in the west and northeast outside of the field. The larger of the clusters located in the west has no faulting present and I assume this to be from ash fall. Further research would need to be conducted to conclude this. Mines were then designated by its association with a caldera, if present, as seen in figure 6. This allowed for easier and faster access to these mines data, commodities and structure. (*Data Series*, 1996)

To determine if the water needed was meteoric water, faults were added to determine their relationship to the calderas and mines as seen in figure 6. Available literature from other studies was needed to determine this and was found in numerous papers. Lead isotope dating showed that Summitville "…lead may have been locally derived by leaching of the adjacent rocks or from magmatogenic fluids". (Doe et al., 1979) This does not definitively say that the water was meteoric in nature but does show that water must be present. "Long after original volcanism has ceased, faults related to caldera collapse and/or regional extension may control later magmatic and hydrothermal episodes. The degree to which meteoric waters are heated and mixed with magmatic fluids is the prime determinant for hydrothermal ore deposition and alteration; other factors include magma type, wall-rock composition, and stress regime." (Elston, n.d.) This statement by Elston shows that meteoric water can, and does, play a part in the deposition of ore bodies within caldera systems. The only way that the water could reach these depths is through fault systems. Referring back to figure 6 and figure 9 we do see there is a strong relationship between mines and fault systems. There are a number of faults located within the central caldera system that do not have faults associated with them and are located within the older aged calderas. I had expected to see a higher degree of faulting along the eastern edge of the field as this is where the Rio Grande Rift Valley is located. This rifting does have many faults but are located outside the field and north-northeast of the field where mines are present with Uranium and Tungsten being the dominant primary commodity. The faults located near the Bonanza caldera did provide alteration by fumarolic or acid-hot spring activity showing water was present but not whether this water was meteoric in nature. Mines within the central caldera complex show “pressure from stock beneath bachelor caldera reactivated keystone graben and started a north-south-flowing, freely convecting hydrothermal system of sulfate-rich solutions that deposited ore and gangue near top of convecting cell by hypogene enrichment.”(Mason and Arndt, 1996)

Conclusion

Combination of the all the data present shows mixed results to say that calderas are good places for economic geology exploration. Factors such as chemistry, water, mineral saturation, temperature, pressure and others need to be considered which can be a lengthy and expensive process. Because most of the rare earth minerals that we do mine are hydrothermally deposited calderas do provide a good place to start for exploration if time and expenses will allow for it. The SJVF does show this as many of the mines present are located in, or close to, these caldera complexes. Because we know that subsurface magma can extend over a greater area than what we see at the surface where volcanic events occurred, we can say that hydrothermal activity can occur. We do see this in the mines outside of the calderas but within the SJVF that are mining rare earth elements.

The mineral deposition of the mines does seem to be hydrothermally deposited using meteoric water according to the data series provided by the USGS.(Mason and Arndt, 1996) The eastern side of the field shows hot spring activity, central field has convecting systems while the western side has free-flow gravity streams as sources for these depositional environments. As calderas are collapsed volcanoes these are prime areas for water to gather in the following years as evidenced by such places as Crater Lake in Oregon, Lake Toba in Indonesia and Yellowstone Lake in Wyoming.

By looking at the ages of the calderas we also see that the younger calderas within the nested systems have the bulk of the mines. This shows that the younger events could have had an impact on the older ones. Further research would be needed to see how the younger calderas impacted the older ones and to what extent, if at all. These impacts could have played on impact by remelt, destruction of ore deposits through the eruption itself or redistribution of the hydrothermal process itself as long time periods are needed for the deposition to occur. Separating the mines and calderas into individual components does provide a base to begin with for individual caldera study in the future. Geochronological and isotope data, while abundant, does not cover every caldera.

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Maps and Figures

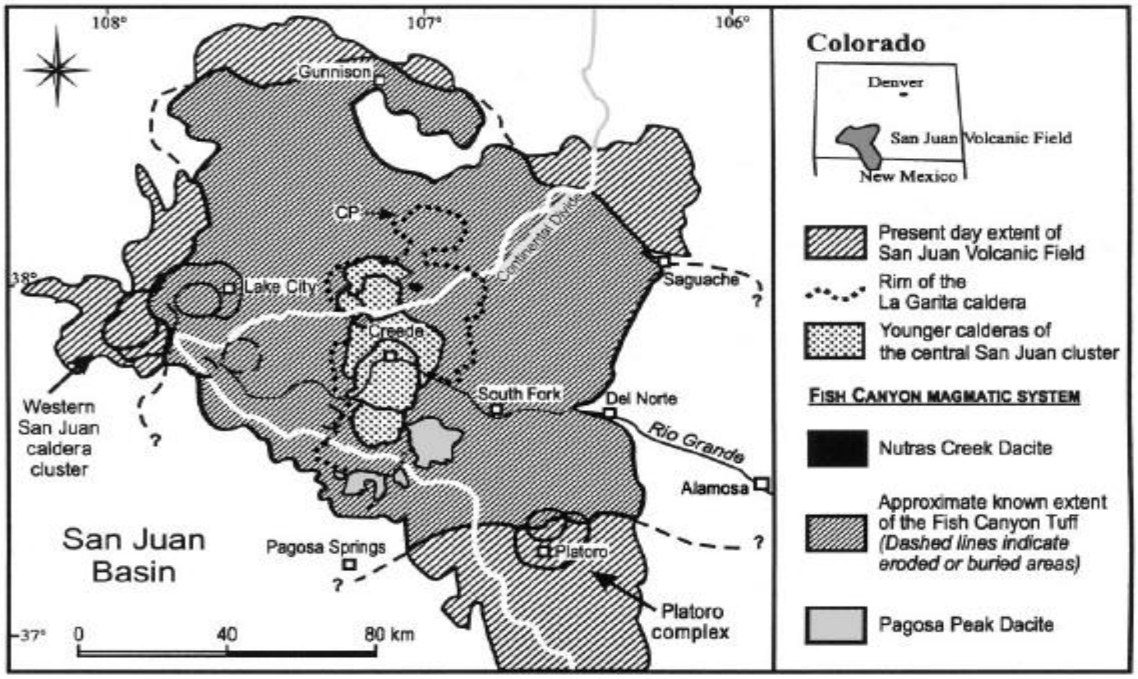

Figure 1: San Juan Volcanic Field with Nested Calderas; Source: (Bachmann et al., 2007)

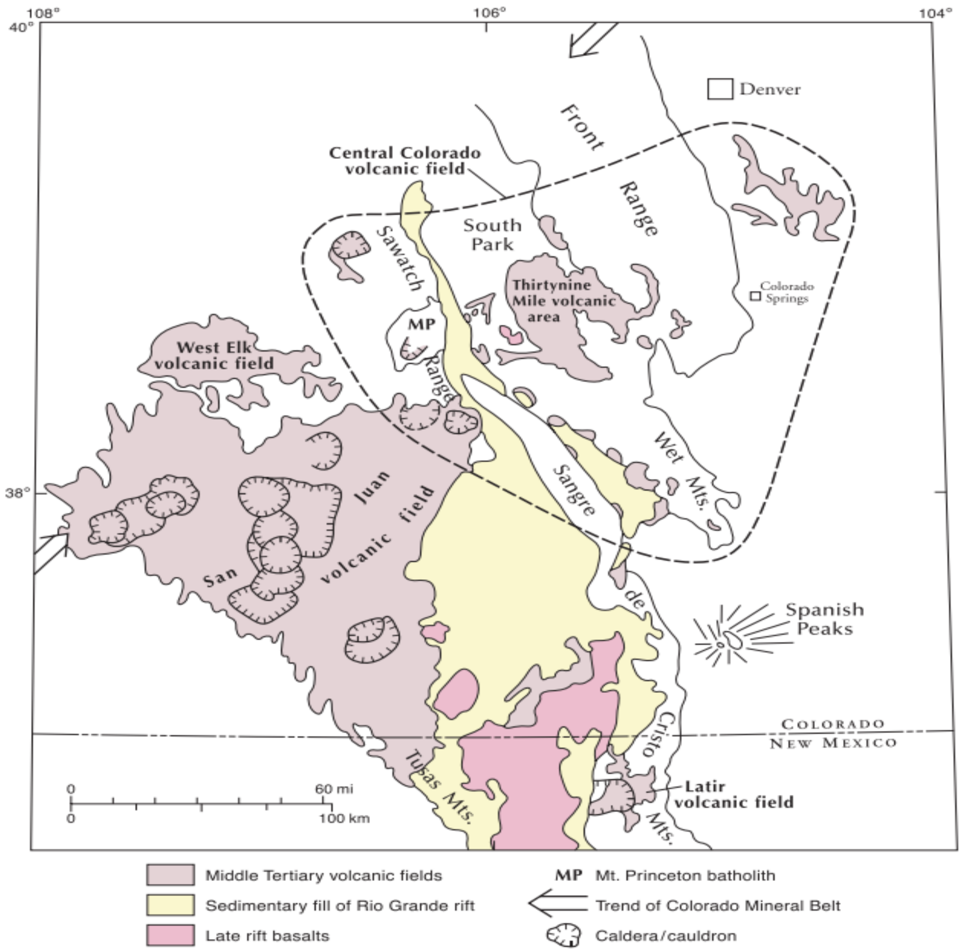

Figure 2: Study area showing SJVF in Southern Colorado; Source: (McIntosh & Chapin, 2004)

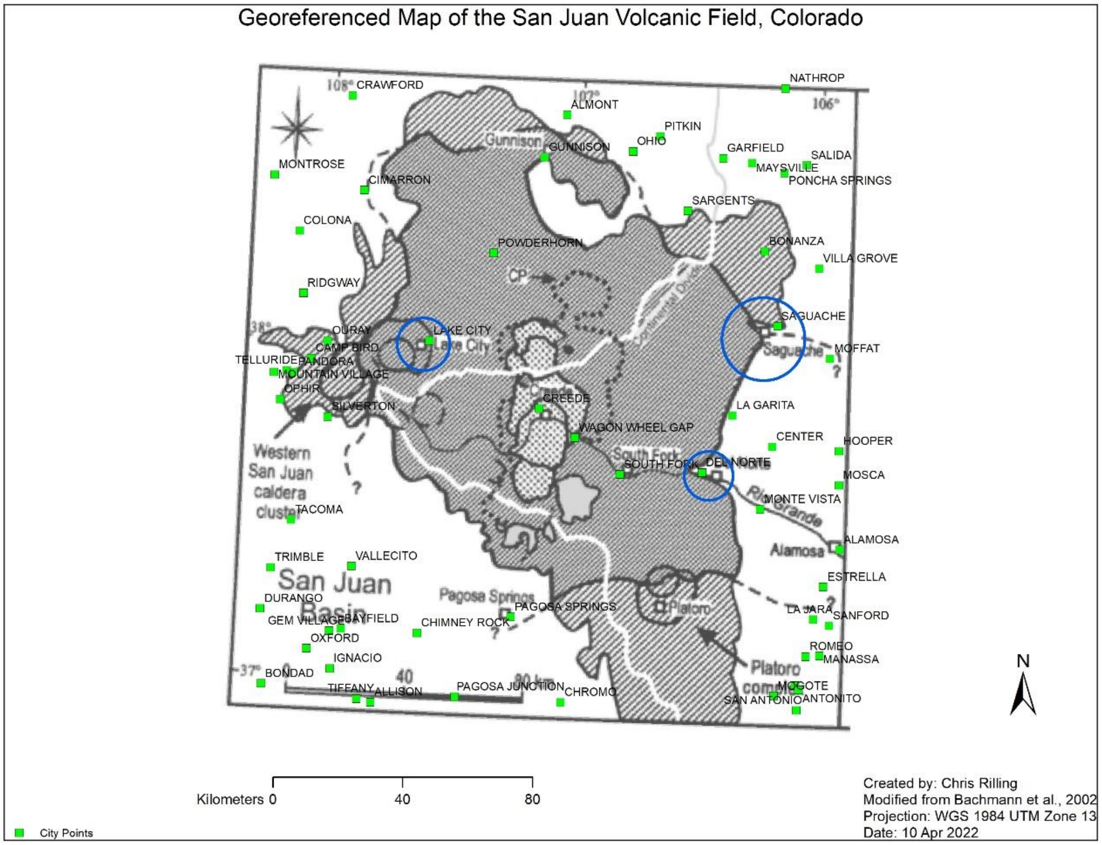

Figure 3: Map showing differences in location post georeference. Circled cities show discrepancy of plotted points from georeferenced points; modified from Bachmann et al., 2002

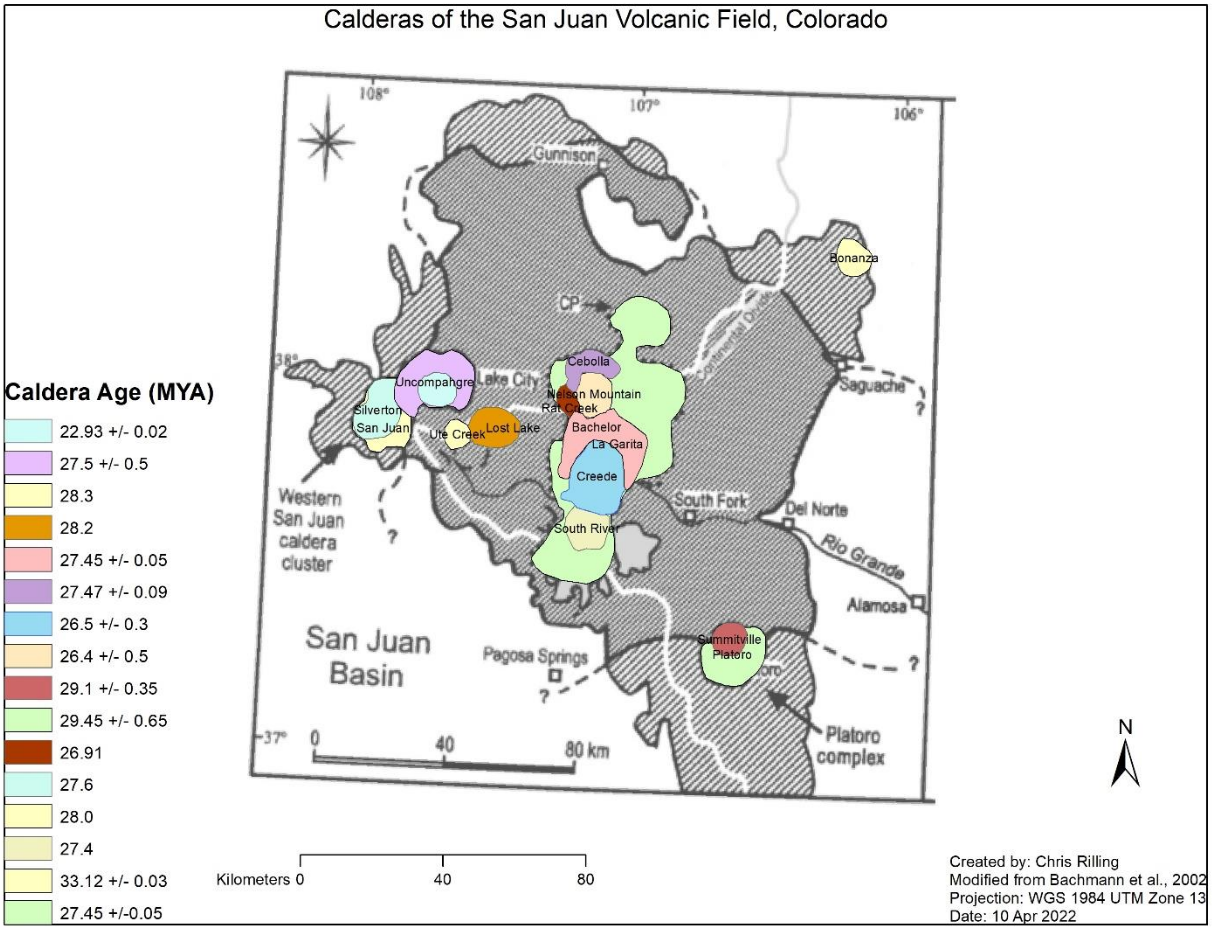

Figure 4: Sixteen calderas within the San Juan Volcanic Field with ages in millions of years; modified from Bachman et al., 2002

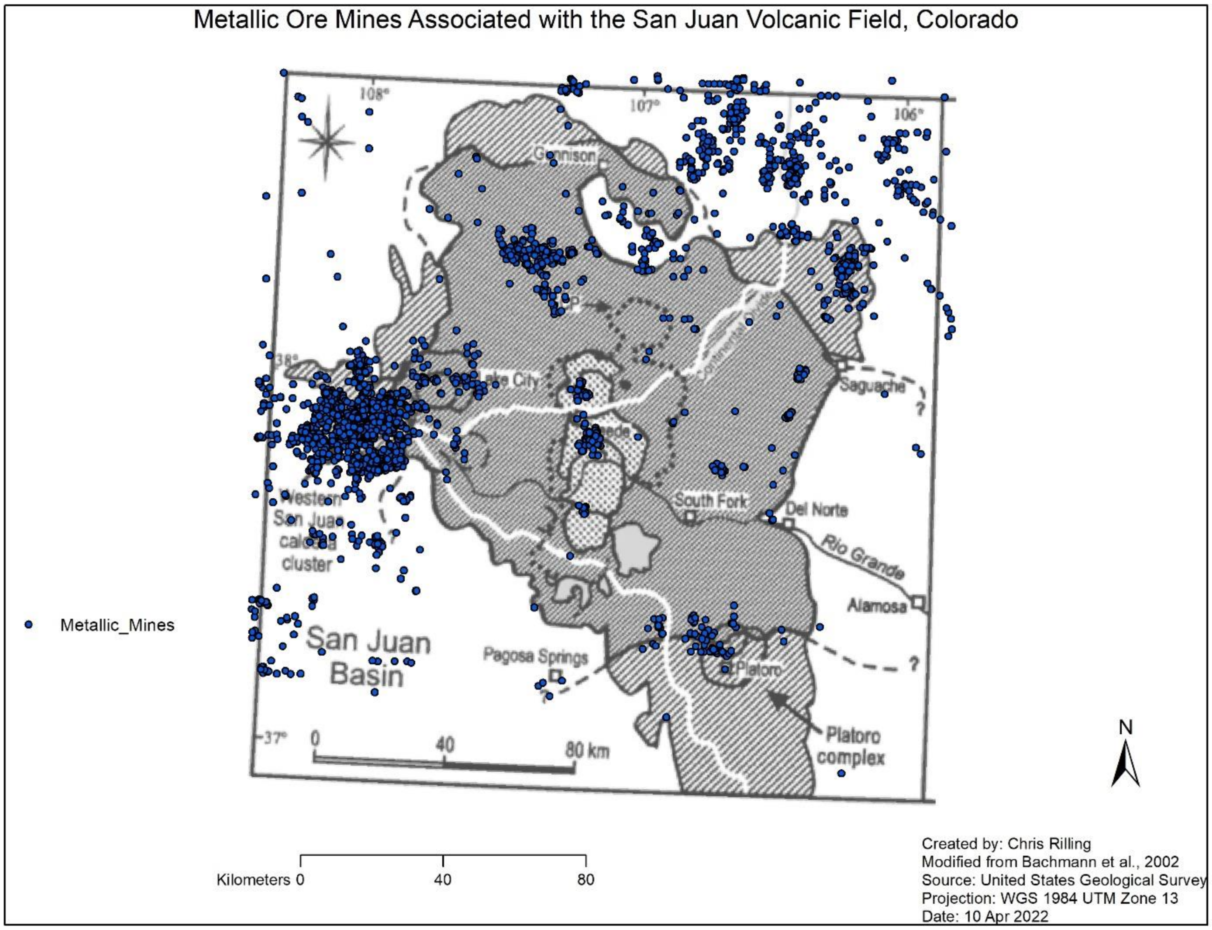

Figure 5: Mines associated with the volcanic field. These mines are non-aggregate mines and show where metal ore such as gold, molybdenum, zinc, lead, silver, etc. are produced.

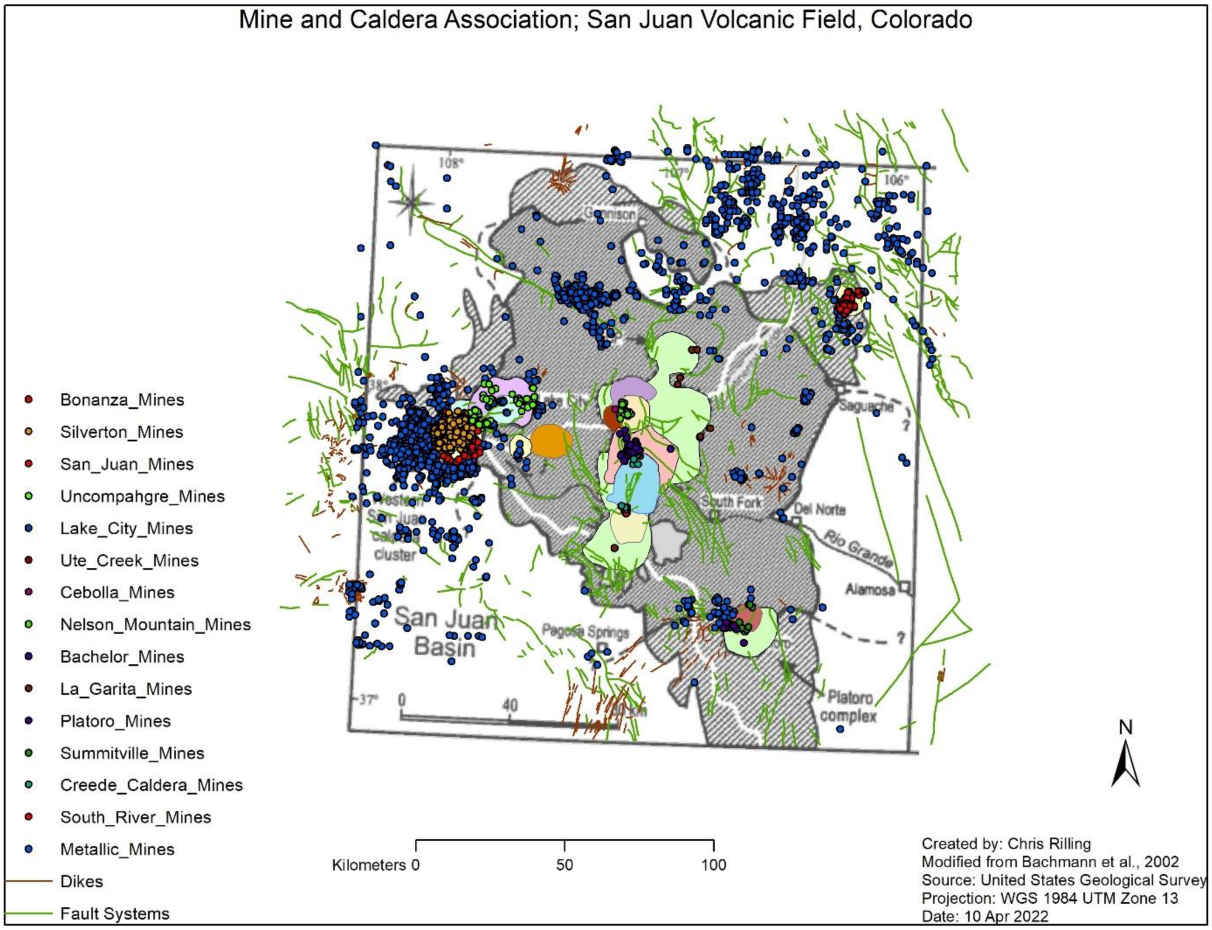

Figure 6: Mines sorted to show the association between each mine and the caldera it is associated with

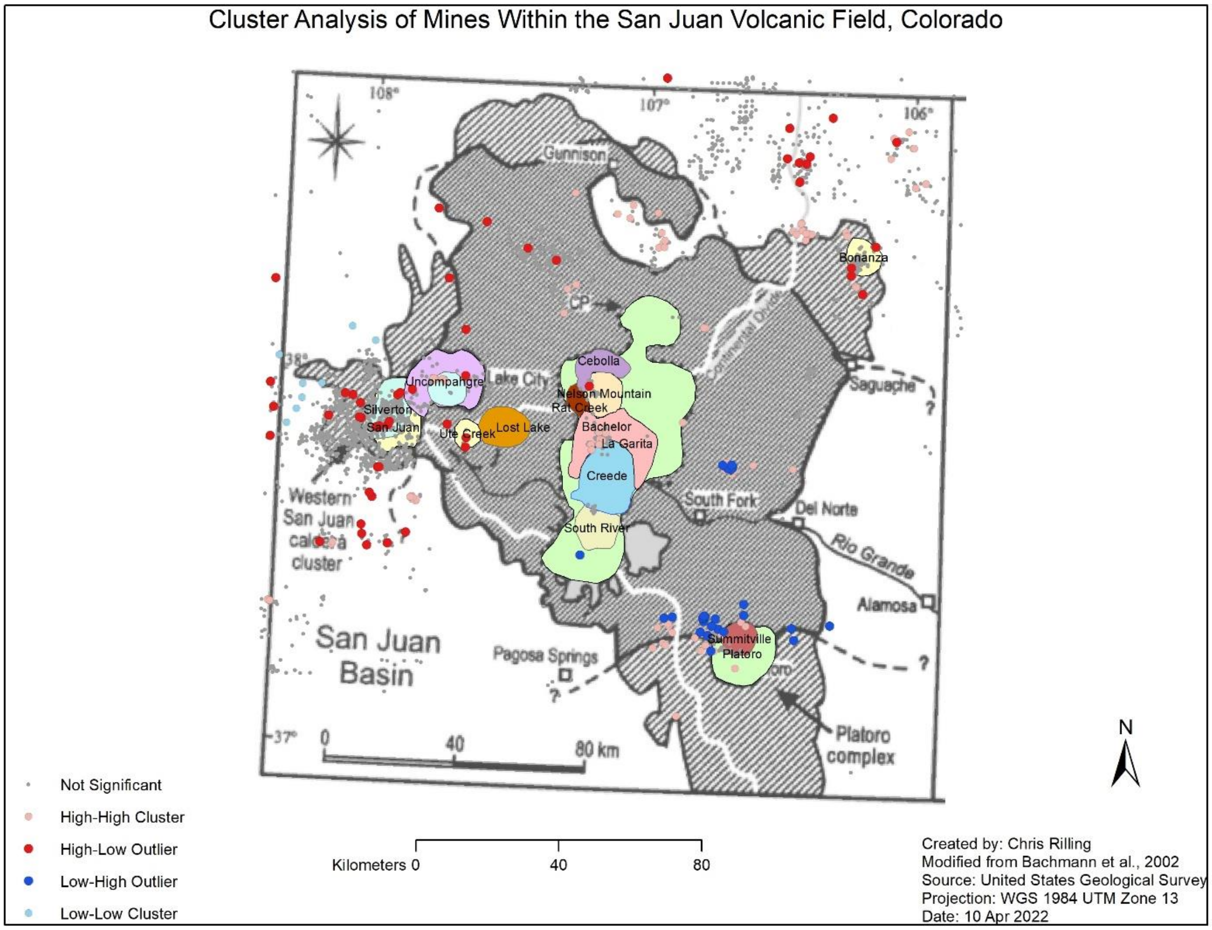

Figure 7: Cluster analysis showing high clustering in west portion of volcanic field. High-Low outliers prevalent in west to northeast while low-high in central to south.

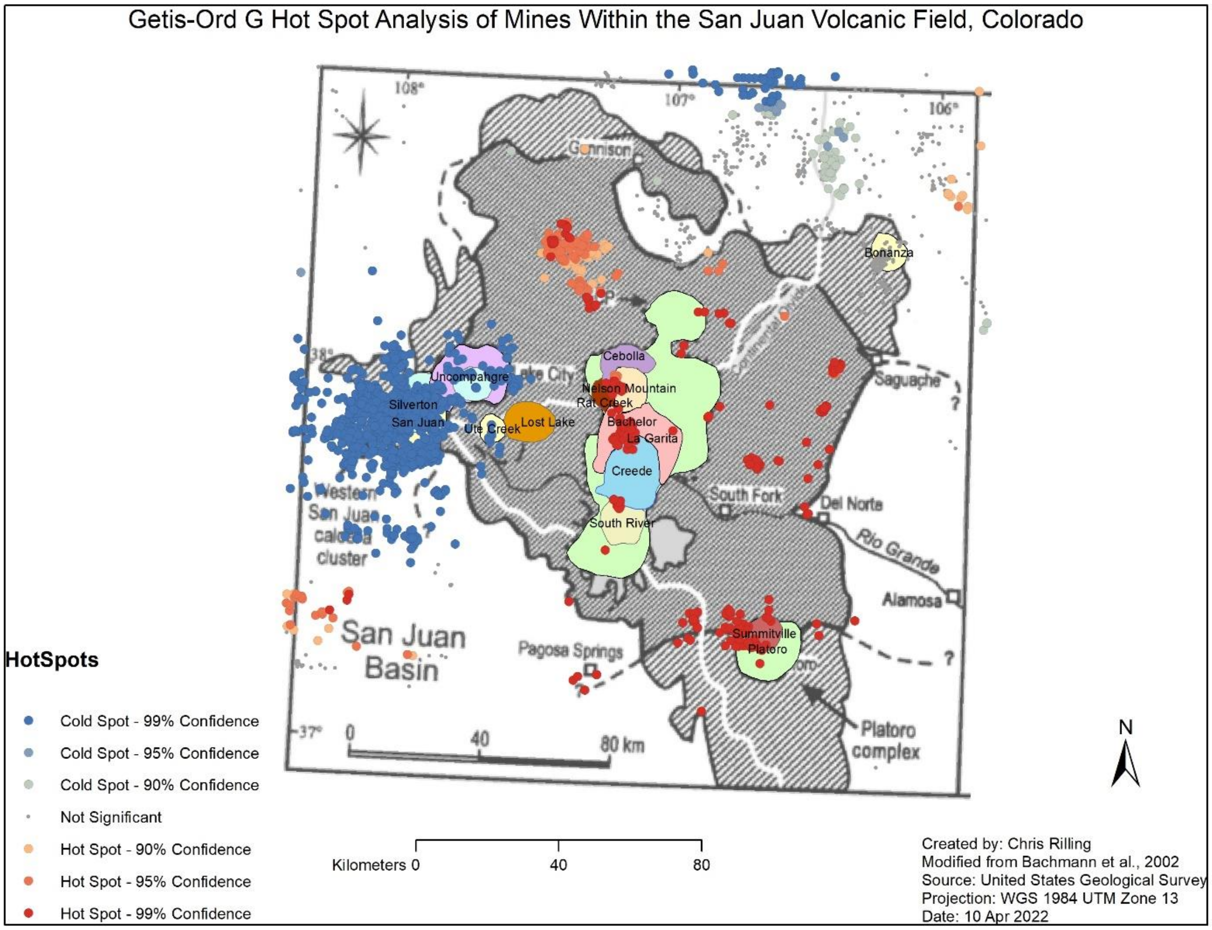

Figure 8: Hot spot analysis of mines in volcanic field. Cold spot in high clustered area in west with hot spots from central north to south and east in field.

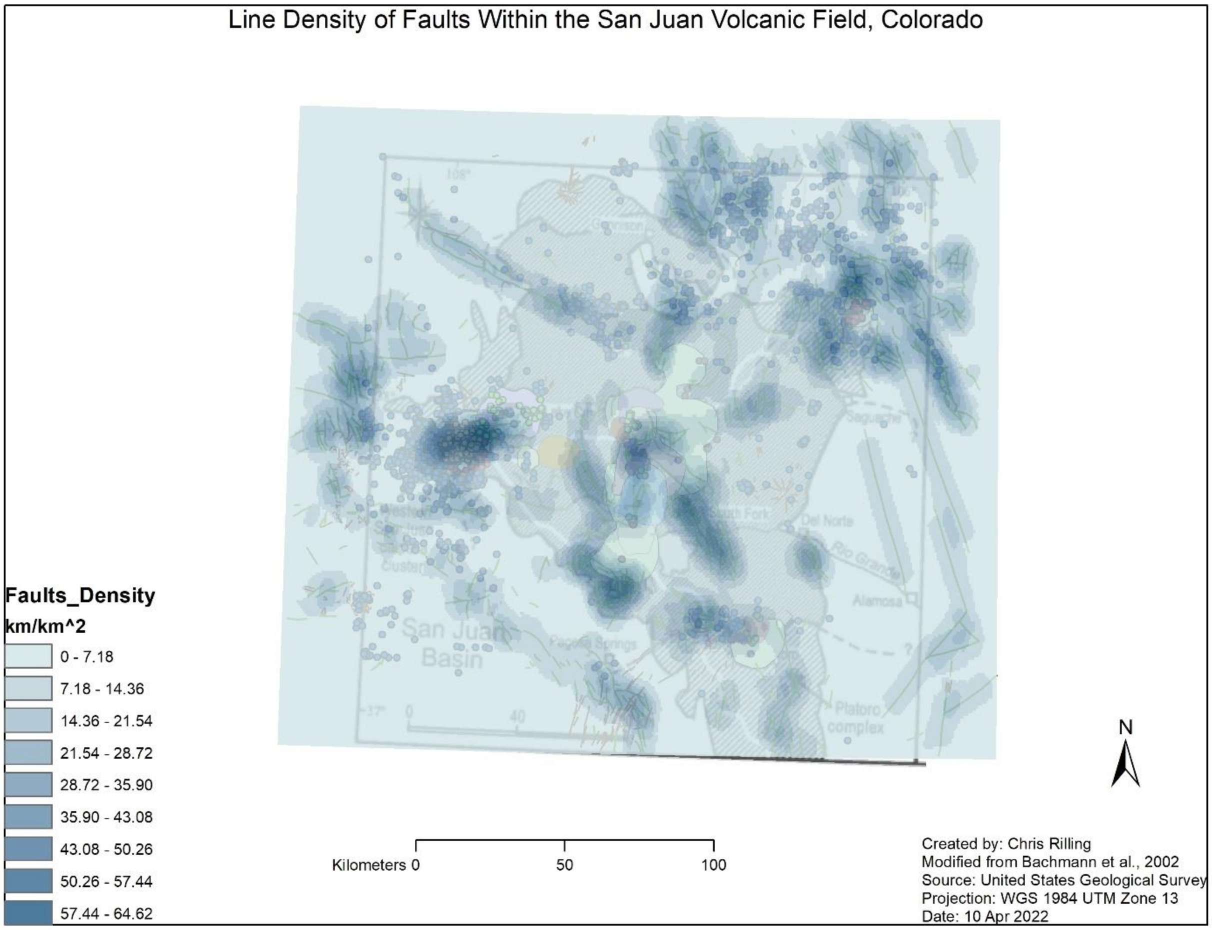

Figure 9: Line density map of fault network overlain figure 9 map. High density areas prevalent where there are heavy mining locations.