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GEOLOGY

GENETIC AND EXPLORATION IMPLICATIONS OF THE ZINC RATIO [100 Zn/ (Zn + Pb)] IN THE RODRUIN PROSPECTING AREA OF THE GOLDEN TRIANGLE -EGYPT

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ABSTRACT

Rodruin Prospecting Area ($26^{o}21^{/}59^{//}$N, $33^{o}20^{/}32^{//}$ E) in the Golden Triangle -Egypt, was exploited by the Ancient Egyptian Miners. They exploited gold from gossans and gossanous gold-bearing quartz veins. Rodruin deposit is hosted by altered and bleached deeply weathered volcanoclastic-metasedimentary and metavolcanic rocks, which underlain by argillaceous metasedimentary rocks. The characteristic "zinc ratio" **[**100 Zn/ (Zn + Pb)] can be used to distinguish the Rodruin ore deposit zones. In addition, the distribution mode of zinc ratio at Aladdin’s Hill is completely different than those from North Ridge, Central Valley and Central Buttress mining working zones. The former shows bimodal distribution, while the latter show single distribution. The zinc ratio of the Aladdin’s Hill zone is wide range (6.98-99.53%) with high standard deviation (> 31.85), Spiral Pit and GF-zones is narrow (86.11-99.97%) with very low standard deviations (< 3.83), while it moderately varies (27.27-99.30%) with low standard deviations (< 12.03) in North Ridge, Central Valley, Central Buttress, and South Ridge zones. The "tail" of high lead samples with zinc ratios below 70 may be the result of leaching of zinc from the sub-outcropping mineralization. Variations in the zinc ratio between the Rodruin ore zones indicate that the mineralizing solutions were zinc saturated and Pb-under saturated rather than the volcanic source rocks that were not lead-zinc rich.

1. Introduction

Rodruin deposit is one of four gossans have been identified in the Golden Triangle area namely: Hamama, Rodruin, Miranda SE, and Waayrah (Fig.1). Mineralizations are hosted by altered and bleached deeply weathered volcanoclastics-metasedimentary, metavolcanic rocks, underlain by argillaceous metasedimentary rocks, and overlain by basaltic andesite, all belonging to the late Tonian-Cryogenian island-arc assemblage found in this part of the Nubian Shield. Present day topography can be related to the Red Sea opening during the Neogene. The morphotectonic indices show that active tectonism is present in this district, as evidenced by the rejuvenation of all ancient tectonic discontinuities.

In this paper, concentrations of trace elements and the zinc ratio [100 Zn/(Zn + Pb)] in 279 samples from the Rodruin gossan and gossanous Au-bearing quartz vein deposits are determined. Estimated trace element ratios will be used as a genetic and exploration significances to quantitative characterization of the Rodruin mineralizations.

2. Location and History

The Rodruin deposit ($26^{o}20^{/}09^{//}$N, $33^{o}31^{/}36^{//}$E) is located 102 km from Qena city on the Nile River. The Rodruin location (Figs. 1 and 2) is also 35 km from the company's Abu Marawat gold-copper vein discovery, 18 km east of the company's Hamama West mineral deposit, and 3 km east of the ancient East Eradiya processing site (Fig. 2).

Little is known about historical exploration at Rodruin. Most workings in Egypt's Eastern Desert date from the New Kingdom (1550-1070 B.C.; Klemm *et al*., 2013), Ptolemaic (300-30 B.C.) and Early Arab (800-1000 AD) periods **(Klemm and Klemm, 2013)**. Individual locations may have been worked on several times throughout the course of this time. Rodruin was a significant ancient mining site where gold was extracted from high grade gossanous formations and quartz veins. The Rodruin area is an ancient treasure that was exploited by Ancient Egyptian miners and was rediscovered in December 2017 by the Aton team.

The highly arid conditions in the Rodruin area of Egypt's Eastern Desert make it an ideal location for remote sensing research. Despite numerous geological studies for the Golden Triangle Area **(Noweir, 1968; El Ramly *et al*., 1970; Abdel Nabii *et al*., 1977; El-Kazzaz, 1999; Moghazi, 2003; Abd El-Wahed and Abu Anbar, 2009; El-Desoky, *et al*., 2015)**, there are no published work on the Rodruin area except for **Alexander Nubia Inc. (2015) and Aton (2017)**.

Recently, **Harraz *et al*., (2020)** and **Abd Ella (2021)** conducted a detail geochemical exploration and assessment to ore deposits at Rodruin area.

3. Geology of Rodruin Area

The Eradiya-Rodruin area, like most of the rocks in the central Eastern Desert, is dominated by Neoproterozoic igneous and metamorphic rocks (Fig.2). The area's main rock unit is Neoproterozoic volcanic rocks (Fig.2). Mafic and intermediate island arc metavolcanic/volcanogenic rocks, comprising foliated metabasalt intercalated with andesite tuffs and breccias, are represented by these rocks. They include basalt, dacite, and rhyodacite, as well as their volcaniclastic counterparts. Banded tuffs, lapilli tuffs, and volcanogenic greywackes and conglomerates are the diverse types of volcaniclastic rocks. Successions of purple metagreywacke, siltstone, and conglomerate (Hammamat Sediments) overlie the arc metavolcanic rocks unconformably. These sediments are distinguished by NW-SE bedding. The andesitic basalt and andesitic porphyry rocks form a NNW elongate mass that cuts across the ophiolitic and island arc rocks. These are fine-grained porphyritic rhyodacites with strong jointing. Small intrusions of diorite/quartz-diorite rocks occur parallel to the NNW–SSE Atalla Shear Zone-ASZ.

All of these rocks were metamorphosed under low-grade greenschist facies conditions, which altered the majority of their primary mineralogy but kept the igneous and sedimentary fabrics. The existence of a quartz–carbonate body, as well as shearing, marks the boundary between volcanic and volcaniclastic rocks. The volcanic rocks near the quartz–carbonate bodies have undergone extensive alteration. The presence of secondary hemimorphite/white zinc minerals also marks the contact. Dioritic rocks, quartz–diorite dykes, and andesitic dykes intrude into volcanic and volcaniclastic rocks.

The subcrops are obscured by a thin layer of unconsolidated scree and talus that covers much of the Rodruin area due to the steep slope. On the northern slope of the South Ridge, a localized mega-breccia comprising of huge blocks of re-cemented carbonate has been mapped, which has been interpreted as an in-situ mass slump or landslip feature that may mask sub-cropping mineralization **(Aton, 2018).**

4. Gossans and Mineralized Zones

The Rodruin site is situated in an isolated and mountainous area between two main roughly E-W oriented parallel mountain ridges. At most surface mineralizations are currently covered by scree and talus as well as are localized in the highly structural complexity area and complexity of the mineralized zones. The mineralization subsequently extended to the north portion of the area associated with gossanous and sheared carbonate rocks and deeply weathered volcanoclastic-metasedimentary rocks. The mineralization at the southeastern portion was terminated by cemented scree and talus cover with potential for the mineralization to extend beneath this cover. Seven mining working zones (Fig.3) may be distinguished: i) North Ridge ii) Central Valley Zone, iii) South Ridge, iv) Central Buttress Zone, and v) Spiral Pit Zone, vi) GF Zone, and vii) Aladdin’s Hill.

Oxidation and leaching extend usually to 100 m below surface at South Ridge-Aladdin's Hill, and next to South Ridge Thrust faults and other channel ways to 300 m below surface. The oxidation and leaching patterns of the Zn-Pb ore minerals generate a very varied pattern that outcrops as a lateritized plateau surface 60 m above the surrounding plains.

Hemimorphite is commonly found in great quantities in gossans. The gossans include supergene lead minerals, but only trace levels of supergene copper minerals were found. Visible gold was found in boulders of gossanous quartz from the mine workings, as well as an ancient processing site in a wadi just south-west of the South Ridge.

A significant ancient mining site where gold was extracted from high grade gossanous formations and quartz veins. The Rodruin deposit is made up of dispersed and semi-massive Au- and Ag-bearing Zn sulphides that are topped by a 40 m thick gold-rich oxide zone and, locally, a supergene silica-barite rock. The oxidized cap is 45 m wide on average, with Au grades ranging from 1.2 to 3 g/t **(Abd Ella, 2021)**.

The mineralization at Rodruin is thought to be of two distinct styles: background carbonate/gossan hosted mineralization and shear zone hosted mineralization. This gossan is linked with felsic volcanic rocks, indicating that it is Volcanic Associated; Carbonate Hosted-VMS epithermal hybrid **(Harraz *et al*., 2020; Abd Ella, 2021)**.

5. Sampling and trace-element analysis

Quantitative characterization using trace elements haloes based on 279 rock chip samples taken from surface in a 5m × 5m grid pattern, with a sampling density of ~46 samples/km^2 which corresponds to a scale of 1:10,000 (Fig.3).

All 279 orebodies/mineralized samples were crushed to a particle size of -4mm. The selected c. 250-500g powdered samples were delivered to ALS Minerals in Rosia Montana, Romania, for quantitative Zn and Pb analysis.

Analyzes were carried out at the ALS Minerals Division laboratory in Romania. Atomic absorption spectroscopy was used to determine Pb and Zn after aqua regia digestion **(Aton Resources, 2017).** Lower detection limit is 5 ppm for Pb and Zn. Details of the description of samples and chemical analyses are provided by **Abd Ella (2021)**.

6. Defining zinc-enriched Rodruin Deposits

Zn contents range from 0.1 to 37.90 wt.%. The distribution of Zn grades in Rodruin mineralization zones (Fig.4) displays strong negative skewing towards low values with ~ 45 % of the deposits with < 2.34 wt.% Zn. The log transformed data show a significantly more regular distribution, with a geometric mean of 1.04 wt.% Zn and a geometric standard deviation of 4.27. The log-transformed data are broadly consistent with cumulative probability plots; yet, it is obvious that the dataset contains numerous Zn grade populations (Fig.4). Zinc has a weak relationship with Pb (r =0.30) but a strong relationship with zinc ratio (r =0.60) (Fig.5).

7. Zinc Ratio

The 100 Zn/(Zn+Pb) ratio, hereafter referred to as the "***zinc ratio"***, is remarkably similar in samples from gossan/leaching capping that collected from orebody in the different mining working zones at Rodruin deposit (Table 1; Fig.6). However, it differs widely among samples from mineralizations along faults and those associated with quartz veins and/or carbonate alteration in mining workings zones at Rodruin area. This can be seen in a histogram as well as in the Zn-Pb and Zn-(Zn+Pb) correlations (Figs.5 and 6A).

The zinc ratio in the majority of the data was greater than 70. The zinc ratio populations for the various data groups have mean values ranging from 72.04 to 96.79 and standard deviations ranging from 3.34 to 31.85. Three groups of orebodies with Zn-ratio mean and standard deviation values in the same range can be differentiated. Mineralizations of each group were most likely formed under similar physicochemical conditions. At North Ridge, CVZ, and CBZ, the distribution of zinc ratios has two mode (Fig. 6B, C, D), with a narrow range of mean (89.63; 88.26, and 77.85%, respectively) and low standard deviation (i.e., less than 15; of 10.67, 9.71, and 14.97, respectively). At South Ridge, Spiral Pit Zone, and GF-zone (Fig. 6E, F, G), it has one mode, with a narrow range of mean (91.15; 96.79, and 93.13%, respectively) and a low standard deviation (11.81, 3.34, and 3.48, respectively). The low-grade quartz-carbonate veins at "Aladdin's Hill," on the other hand, have a much different zinc ratio distribution than the high-grade gossan deposits. The majority of samples analyzed have two mode-zinc ratios (Fig. 6H), with a low mean value of 72.04% and a high standard deviation of 31.85 (greater than 30). This suggests that sulphide remobilization has had no substantial impact on the zinc ratio. The decrease in standard deviations of Zn ratio distribution from south to western portion orebodies means that the orebody at the south section represents the orebody's top, whereas the orebody at Aladdin's Hill is located at the orebody's footwall **(Lydon, 1985, 1988; Huston and Large, 1987).**

7.1. Genetic implications of Zinc Ratio distribution

The zinc ratio in hydrothermal mineral deposits can be influenced by four factors: (i) relative Pb and Zn concentrations in source rocks, (ii) metal dissolution mechanisms in source rocks, (iii) the saturation degree of base metals and the overall chemistry of metal-bearing solutions, and (iv) metal deposition efficiency.

i) Lead and zinc concentrations in the source rock

The bimodal nature of the zinc ratio for Aladdin's Hill gossan deposit may be due to the dominant volcanics at the footwall below the deposits. The zinc ratio of the Aladdin's Hill gossan deposit was most likely regulated by the Zn and Pb contents in the source volcanic rocks, as well as the leaching mechanisms **(Solomon, 1976; Divi *et al*., 1979; and Lydon, 1985)**. This quantifies and extends observations in other orebodies from different mining working zones within and around the Aladdin's Hill. In volcanics, the expected zinc ratio, according to Lydon's (1985) model, would be the same as those of the massive sulphide deposits if the metals were leached in the same way from the volcanics. However, there may have been input from a magmatic source with a distinct Pb-Zn signature or different leaching mechanisms in the orebody at the southern portion, which has a narrow range of mean Zn ratio with a low standard deviation.

ii) Mechanisms of metal solution from the source rocks

Graf (1977) studying the Brunswick No. 6 Zn-Pb-Cu-Ag massive sulphide deposit proposed three sequential reactions of hydrothermal dissolution of elements in the source rocks, and therefore a change in the Zn ratio over time. The first reaction involves the liberation of Fe, Cu, and Zn relative to Pb from volcanic glass and/or ferromagnesian minerals, enriching the lower regions of massive sulphide deposits in the released elements. The second reaction resulted in the release of Pb and Zn, causing feldspar to alter. The iron is extensively precipitated when the source volcanics have the least alteration and content of sulphides, and when the mixing between the hydrothermal solution and seawater is increased. At the different mining working zones within Rodruin Prospecting Area the zinc ratio does not change significantly. The hydrothermal alteration hypothesis of **Graf (1977)** of secondary sulphides concentration in the VMS cannot explain the formation of the Rodruin ore because the zinc ratio does not change significantly between various portions of the ore.

Also, the "tail" of Pb-rich samples with zinc ratios below 70 in Aladdin's Hill orebody refers to the leaching of zinc from the sub-outcropping mineralization.

Therefore, sampling in oxidation zones must be done in caution, because of the extreme mobility of zinc compared to lead in the oxidized environment.

8. Conclusions and Application of Zinc Ratio to Exploration

Based on the preliminary data from the Rodruin seven mining working zones, two different mineralization styles formed during three mineralizing epochs are suggested in Rodruin Prospecting area. The three histogram parameters (distribution pattern, mean, and standard deviation) are used together to characterize the different portions of the orebodies at mining working zones.

The distribution of zinc ratios from orebody at the Aladdin's Hill zone is different from that of orebodies from the South Ridge, Spiral Pit- and GF- mining working zones. The former shows bimodal distribution, while the latter show unimodal distribution. The zinc ratio of the Aladdin's Hill zone is wide range (6.98-99.53%) with high standard deviation (> 31.85), Spiral Pit and GF-zones is narrow (86.11-99.97%) with very low standard deviations (< 3.83), while it moderately varies (27.27-99.30%) with low standard deviations (< 12.03) in North Ridge, Central Valley, Central Buttress, and South Ridge zones. The "tail" of high lead samples with zinc ratios below 70 may be the result of leaching of zinc from the sub-outcropping mineralization, and extreme care must be taken in the selection of samples from the oxidation zone.

In the Rodruin area, secondary zinc mineralization occurs in a Fe-oxide/hydroxide-rich gossan. Supergene zones can arise in VMS deposits as a result of either seafloor or subaerial weathering (Koski, 2012). The increased gold concentration in the mined working zones indicates that subaerial weathering played a part in the formation of the Rodruin prospect's gossan. This is consistent with **Barrie *et al.*, (2007)**'s finding that Tertiary to Recent weathering is critical for gossan formation in the ANS's VMS deposits. The enrichment of secondary zinc minerals in the exploited different mining working zones can be attributed to the supergene process and the high solubility of Zn sulphides by oxidizing solution with low pH values, in addition to the inheritance of primary zinc enrichment from the original mineralization **(Robb, 2005)**.

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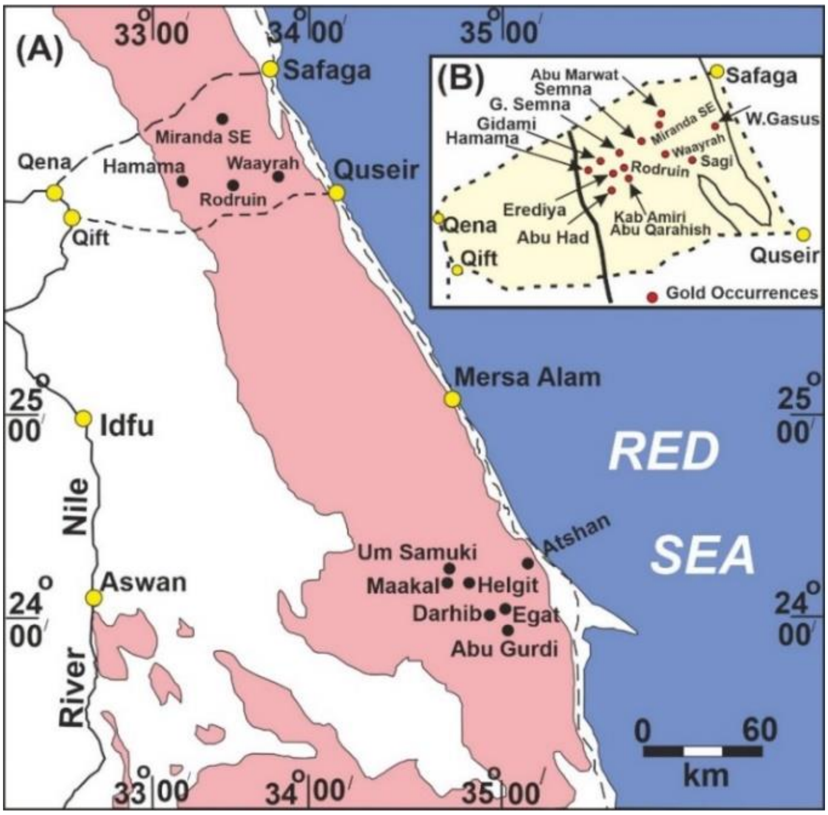

Fig.1: Location map showing the distribution of (A) massive sulphide deposits (VMS) in the Eastern Desert of Egypt., and (B) the gold occurrences and deposits in the Golden Triangle area/belt (Egypt).

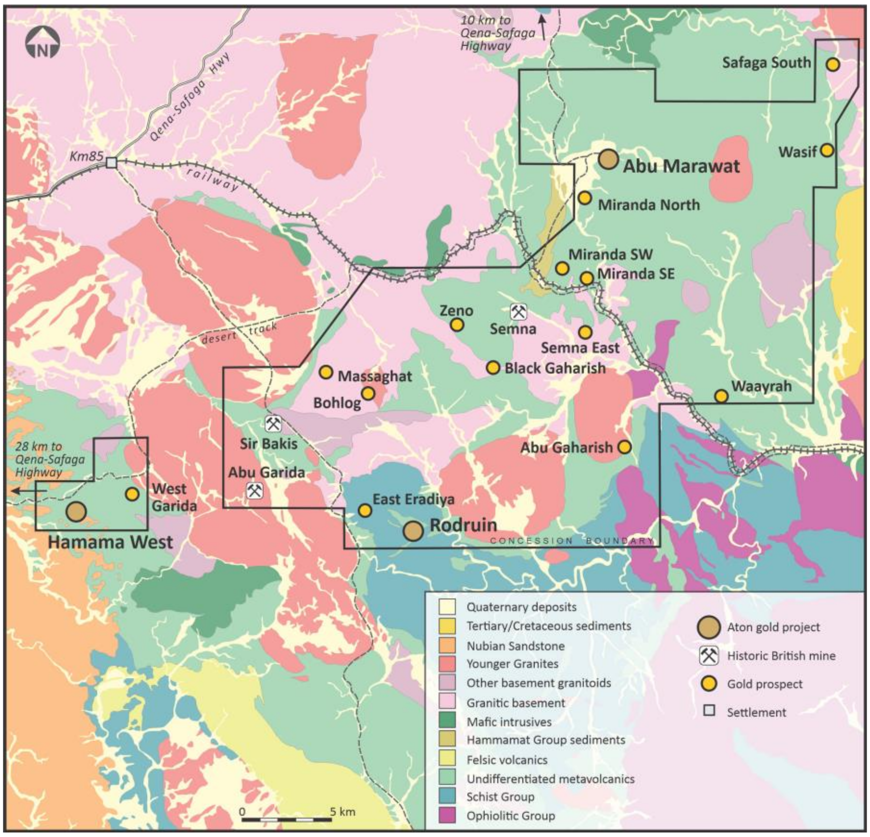

Fig.2: Regional geological setting of Rodruin Prospect Area (after Aton Company 2017).

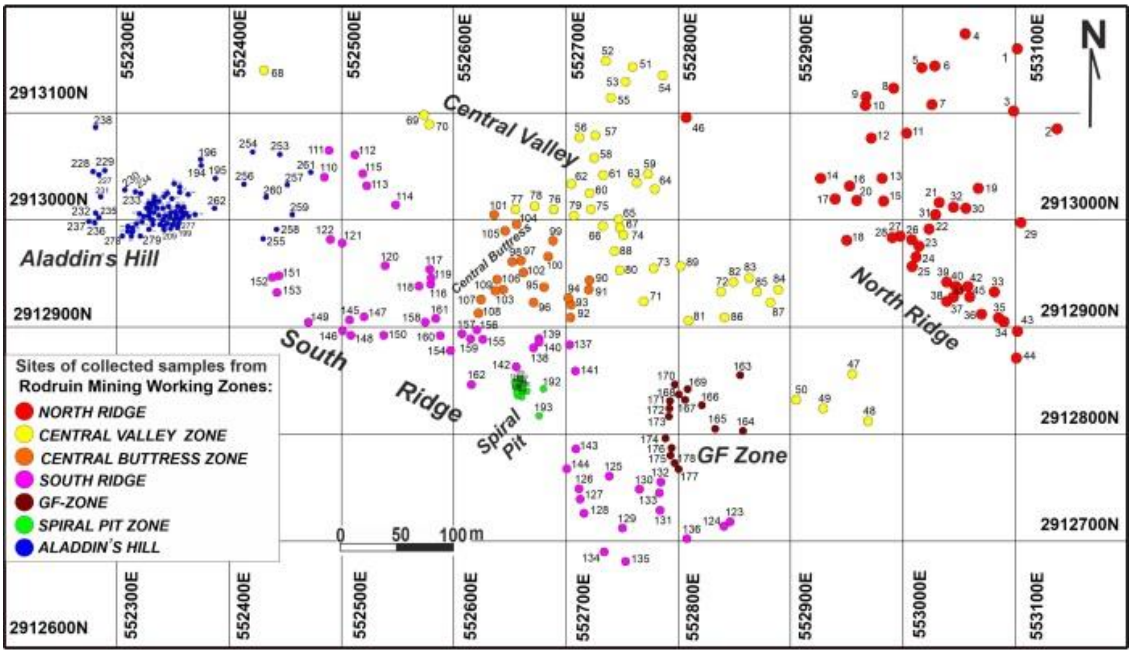

Fig.3: Longitudinal cross-section of the Rodruin Prospect in Golden Triangle area, showing sites of the analyzed samples (n = 279 samples) collected from the different mining working zones: North Ridge, Central Valley Zone (CVZ), South Ridge, Central Buttress Zone (CBZ), Spiral Pit Zone (SPZ), GF Zone, and Aladdin's Hill (The traced mining activity zones are after the Aton Company, 2018).

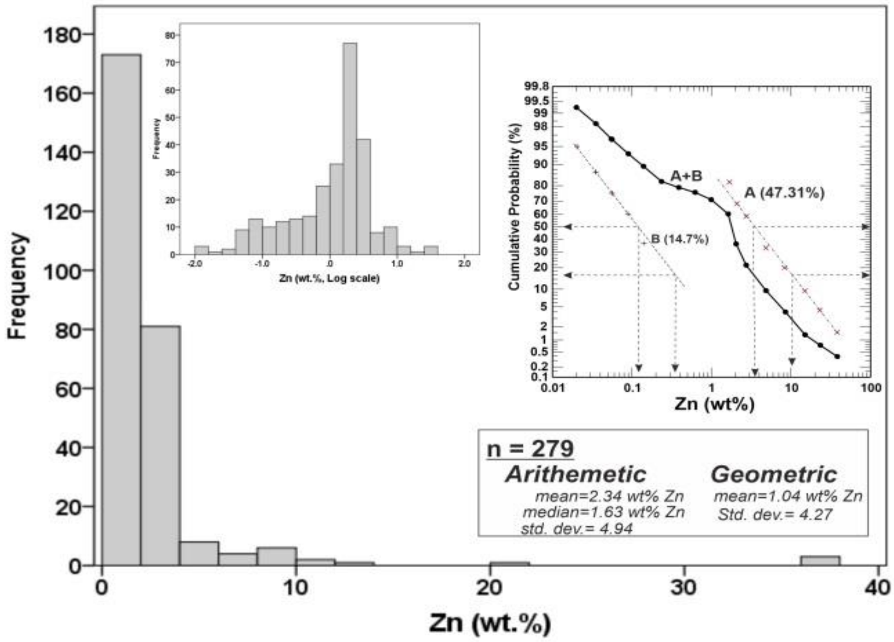

Fig.4: A. Frequency histogram of Zn content illustrating the non-normal distribution of raw data. Mean and standard deviations are shown on the plot. B. Log transformation of the content data illustrating the much closer to normal distribution of data. Geometric mean and geometric standard deviations are shown on the plot. C. Cumulative probability plot for log transformed Zn contents in Rodruin Prospect deposits.

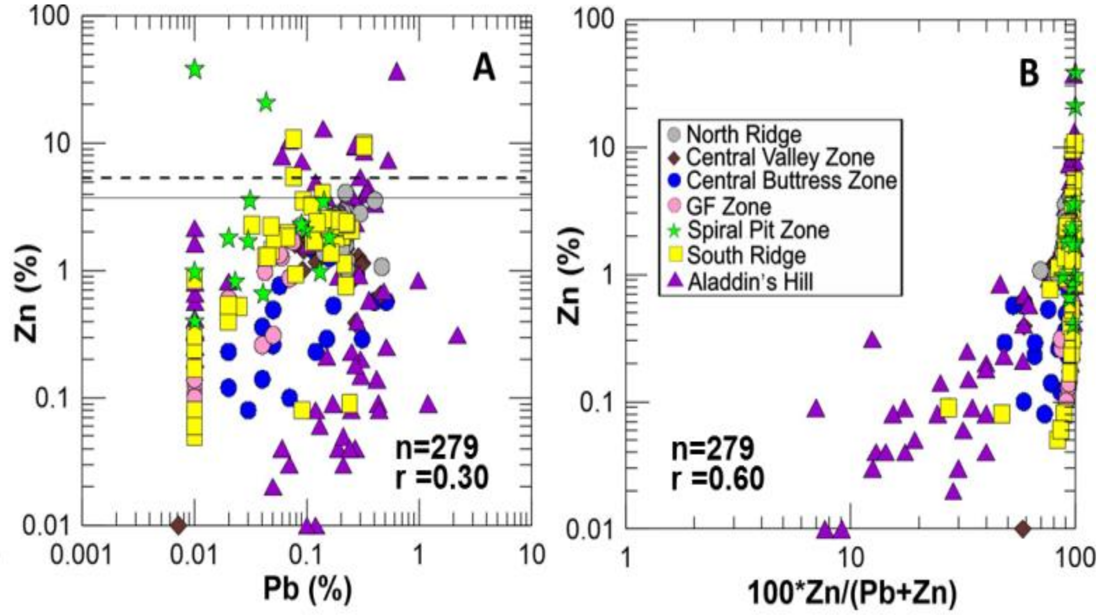

Fig.5: Bivariate plots of zinc grade (wt.%) versus (A) Pb (wt.%) and (B) Zinc ratio in the different mining working zones at Rodruin deposit area.

Table 1: Concentration ranges and statistical distribution parameters for some zinc, lead elements and zinc ratio in country rocks; quartz veins and ore materials in the different mining working zones at Rodruin Prospect - Golden Triangle area (refer to Fig. 3).

	Pb (wt.%)	Zn (wt.%)	Zinc Ratio [100*Zn/(Pb+Zn)]
		North Ridge (n=46 samples)	
min	**0.01**	**0.09**	**27.27**
max	**0.46**	**9.81**	**98.84**
Mean	**0.21**	**2.36**	**89.63**
Std	**0.07**	**1.36**	**10.67**
		Central Valley Zone (n=43 samples)	
min	**0.01**	**0.01**	**58.10**
max	**0.45**	**2.25**	**95.42**
Mean	**0.16**	**1.46**	**88.26**
Std	**0.09**	**0.50**	**9.71**
		Central Buttress Zone (n=20 samples)	
min	**0.01**	**0.08**	**48.33**
max	**0.51**	**1.47**	**97.22**
Mean	**0.14**	**0.52**	**77.85**
Std	**0.14**	**0.43**	**14.97**
		South Ridge (n=53 samples)	
min	**0.01**	**0.05**	**27.27**
max	**0.32**	**10.71**	**99.30**
Mean	**0.12**	**2.09**	**91.15**
Std	**0.09**	**2.25**	**11.81**
		GF Zone (n=16 samples)	
min	**0.01**	**0.08**	**86.11**
max	**0.09**	**2.22**	**96.77**
Mean	**0.04**	**0.66**	**93.13**
Std	**0.03**	**0.67**	**3.48**
		Spiral Pit Zone (n=15 samples)	
min	**0.01**	**0.40**	**88.10**
max	**0.16**	**37.90**	**99.97**
Mean	**0.06**	**7.80**	**96.79**
Std	**0.05**	**13.19**	**3.34**
		Aladdin's Hill (n=86 samples)	
min	**0.01**	**0.01**	**6.98**
max	**2.18**	**36.70**	**99.53**
Mean	**0.26**	**2.69**	**72.04**
Std	**0.28**	**4.62**	**31.85**
		All samples (n=279 samples)	
min	**0.01**	**0.01**	**6.98**
max	**2.18**	**37.90**	**99.97**
Mean	**0.18**	**2.34**	**84.03**
Std	**4.33**	**21.53**	**21.53**

تطبيقات نسبة الزنك[100 Zn/(Zn + Pb)] في التعرف على نشأة واستكشاف منطقة التنقيب في رودروينا في المثلث الذهبي – مصر

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استغلت منطقة استكشاف رودروينا (26°21′59″N, 33°20′32″ E) في المثلث الذهبي - مصر، من قبل عمال المناجم المصرية القديمة حيث استخرجوا الذهب من رواسب الجوسان وعروق الكوارتز المتجوسنه الحاملة للذهب. توجد رواسب رودروينا في رواسب متجويه من صخور بركانية وفتتاتية بركانية متحوله ، والتي تقع تحت صخور رسوبيه طينيه متحوله. أمكن استخدام "نسبة الزنك [100 Zn/(Zn+Pb)] لتمييز مناطق رواسب خام رودروينا. وبالإضافة إلى ذلك، فإن طريقة توزيع نسبة الزنك في تلة علاء الدين Aladdin's Hill تختلف تماما عن تلك الموجودة في مناطق التعدين في الحيد الشمالي North Ridge والوادي الاوسط Central Valley و في منطقه الدعامه المركزيه Central Buttress. الأول يظهر توزيعا ثنائيا ، في حين أن الأخير يظهر توزيع احادي. نسبة الزنك في منطقة تلة علاء الدين Aladdin's Hill لها مدي واسع (٦.٩٨-٩٩.٥٣٪) مع انحراف معياري عالي (< ٣١.٨٥)، لكن في مناطق الحفرة الحلزونية Spiral Pit و GF لها مدي ضيق (٨٦.١١-٩٩.٩ ٧٪) مع انحرافات معيارية منخفضة جدا (< ٣.٨٣)، في حين أنها تختلف بشكل معتدل (٢٧.٢٧-٩٩.٣٠٪) مع انحرافات معيارية منخفضة (< ١٢.٠٣) في الحيد الشمالي North Ridge ، والوادي الاوسط Central Valley ، منطقه الدعامه المركزيه Central Buttress ، ومناطق الحيد الجنوبي South Ridge . قد يكون "الذيل" في عينات الرصاص العالية بنسب الزنك أقل من ٧٠ نتيجة لهروب الزنك من التمعدن الاولي. وتشير الاختلافات في نسبة الزنك بين مناطق خام رودروينا إلى أن المحاليل المعدنية كانت مشبعة بالزنك وغير مشبعة بالرصاص بأقل من صخور المصدر البركانية.