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ABSTRACT
Mineral discoveries are a major outcome defining the success of exploration activities. It has been noticed that exploration decisions are mostly based on both, how mature is a country in terms of geological potential and institutional quality, but little empirical evidence has been made around the main determinants of exploration success. This paper attempts to develop two empirical estimates around exploration and mineral discoveries. First, an analysis of the main determinants driving mineral discoveries using data from gold and copper deposits, building on the empirical RD and innovation literature. Second, an assessment on how mature a region is for mineral exploration based on the randomness of discoveries. Main results indicate that aggregated grassroots exploration budgets in a country are not a key variable associated with discoveries, but more and larger discoveries are more likely to occur in countries with stronger protection of property rights. In terms geological maturity, the proposed approach indicates that, on average, the world is not in the more mature geological stage for gold and copper, but the average effect differs across regions.

JEL **classifications: L72, Q32, Q38**
Keywords: Non-renewable resources, Mineral exploration, Discoveries, Geological maturity.

1 Introduction

Our understanding of the natural endowment of nonrenewable resources is incomplete at any point in time. Mineral exploration creates new information that improves our knowledge about this endowment and aides decision making aimed at optimally using scarce nonrenewable resources. Exploration provides information about previously undiscovered deposits and a better classification of those already discovered (Mason, 1986). When it comes to allocate exploration effort, both institutional quality and how geologically mature is a region have been listed as relevant variables (Fraser Institute, 2020). Understanding how this variables contribute to the success of exploration activities will to play a major tole on the future availability of non-renewable resources to mitigate depletion (Tilton et al., 2018).

In this regard, the purpose of this paper is twofold. First, to provide a prime empirical analysis of main variables associated with exploration success. Second, to propose and implement a novel approach to assess if a region is more or less geologically mature. This paper contributes to the empirical analysis of non-renewable resources by relating the success of exploration activities to different variables. Additionally, a methodology to assess the perceived maturity is developed and implemented. the empirical analysis is based on a database of major copper and gold discoveries made during 1997 to 2018.

When it comes to the main determinants of resource development, the literature has widely recognize a relationship between natural resource abundance, institutions and economic growth, mostly focusing on the causal mechanism from resource abundance to institutions but not from institutions to resource abundance. Early works from Sachs and Warner (1995, 2001) indicated a negative and robust relationship between natural resource abundance and economic growth. Subsequent studies deepen on the causal mechanism for this negative relationship, arguing that resource abundance deters economic growth by a lack of investment in human capital, crowd out other growth-driven economic sectors, creating political rent-seeking behavior, conflicts, authoritarianism or corruption perception (Gylfason et al., 1999; Auty and M., 2001; Ross, 2001; Torvik, 2002; Vicente and C., 2010). Nevertheless, the apparent curse can be mostly explained by the role of institutions (Robinson et al., 2006; Mehlum et al., 2006; Brunnschweiler and Bulte, 2008). Moreover, it has been showed that resource abundance does not impact institutional quality (Alexeev and Conrad, 2009). The latter position is aligned with empirical approaches towards exploration activity, were institutions play a major role to explain how firms allocate exploration effort and mining investment (Jara et al., 2008; Jara, 2017; Tilton and Guzman, 2016, ch.5). Nevertheless, the relationship of institutions on exploration success remains to be analyzed, which is aligned with the first goal of this paper.

As previously mentioned, the success of exploration activities also depends on the geological maturity in a country. The literature on non-renewable resource exploration is usually divided into models of general equilibrium and the analysis of information spillovers (Cairns, 1990). General equilibrium approaches usually refine previous works from Hotelling (1931) and Pindyck (1978), but do not involve the dynamics of information spillovers (Arrow and Chang, 1982; Peterson, 1978; Pindyck, 1980; Quyen, 1991; Uhler, 1976). On the other other hand, information spillovers are usually modelled using game-theoretical approaches to advise policy decisions about geological information (Dodds and Bishop, 1983; Leitzinger and Stiglitz, 1984; Isaac, 1987; Hendricks and Kovenock, 1989; Polasky, 1989, 1992). Intersecting these two research lines, theoretical models have acknowledged two main opposing effects driving exploration and discoveries (Peterson, 1978; Siegel, 1985). First, an information spillover effect (due to the spatial correlation of deposits) that is expected to dominate in the early-stage of mineral development, as it occurs with gold rushes (Lynham, 2017). Second, a stock effect reducing exploration opportunities over time that should dominate as the region matures. With the exception of Mason (2014), who develops a dynamic model to analyze the behavior of exploration decisions in the U.S. uranium market, the applied literature has been scarce. Moreover, the main focus of these studies has not been to determine if a country or region is perceived to be more or less geologically mature, which is the second purpose previously mentioned.

For the first goal of this paper, the main determinants of exploration success (number of discoveries) are analyzed using multivariate regressions for count data (Pakes and Griliches, 1984; Hausman et al., 1984; Jensen, 1987), based on the similarities between mineral exploration and R&D activities (Polasky, 1992). Main variables of interests are exploration effort (measured as total grassroots budget received in a country) and three particular set of institutional variables that has been highlighted to be related to natural resource development: strength of property rights (rule of law), political stability and transparency (control of corruption) (Robinson et al., 2006; Mehlum et al., 2006; Brunnschweiler and Bulte, 2008). Results indicate that not all institutional variables affect discoveries in a consistent way. More secure property rights (as measure by the Rule of Law index) appear as relevant for the number and size of copper and gold discoveries. However, political stability shows a different sign for each mineral. For copper, political stability is positive and significant, while the variable is negative and significant for gold discoveries. This differences can be explained by the appropriability of each mineral (Boschini et al., 2007), as copper mines last, on average, twice as longer than gold mines, requiring more long-term stability. Lack of transparency (indicated by control of corruption) does appear to contribute to the number of copper discoveries but not their size. Surprisingly, exploration effort measured by total grassroots investment in a country, does not show to explain discoveries nor their size. The value is not different than zero in the long-run for both copper and gold when including two lags of previous investment.

For the second goal of the paper, it is proposed that discoveries, if assumed random conditional on a set of observables, can be used to reveal the geological maturity. This is based on the idea that each additional discovery would change the average exploration decision of firms in a predictable way. In the early-stage of geological development, each discovery would generate a positive effect on exploration decisions due to information spillovers, while this effect will be negative as exploration opportunities become more scarce. On a global level, results indicate that the world hast not yet reached a more mature geological stage for gold, and the estimate is not different than zero for copper. Nevertheless, average trends differ as the effect has been decreasing over time for gold and slightly increasing for copper. The proposed methodology can also be informative for regions in the more mature stage, encouraging to focus on determinants other than geological potential to attract mineral exploration. For copper, Latin America, the Asia-Pacific Regions and Europe are perceived to be in the more mature stage of geological potential. On the other hand, no region appears to be in the more mature stage for gold.

The rest of the paper is organized as follows. Section 2 develops the empirical approach using to analyze the main determinants of exploration success, the analysis of geological maturity and the data for this analysis. Results in Section 3 are divided in two parts. First, a multivariate regression analysis for copper and gold discoveries, analyzing main determinants of exploration success. Second, the results from using discoveries to estimate geological maturity based on discoveries. Lastly, Section 4 states the conclusions.

2 Empirical Approach

This section is divided in three parts. First, the model used towards analyzing exploration success and its main determinants. Second, a proposed theoretical approach to estimate if a region is perceived as more mature for exploration investment based on discoveries data. Third, a review of the data of copper and gold discoveries used in the analysis.

2.1 Determinants of exploration success

As in R&D and innovation literature, count data is suitable for modelling exploration success. Count data is usually characterized by a high relevance of zeros and small and discrete values of the outcome variable (Greene, 2018, p. 884 - 885). In patents literature, this condition has been usually modelled as a Poisson process after the original description presented by Hausman et al. (1984). The basic model is a semi-log regression where the log of the Poisson parameter (λ) depends on a matrix of covariates ($\mathbf{X}$) as illustrated in equation 1:

$$log(\lambda) = \beta\mathbf{X} \tag{1}$$

A common shortcoming of the Poisson specification is the inability to fit over-dispersed data, as the expectation of the outcome is the same as the variance ($E(y) = Var(y) = \lambda$). Hausman et al. (1984) and following authors present a Negative Binomial (NB) model to develop a more flexible approach to count data allowing for differences between its mean and variance. As Poisson and Negative Binomial models are nested, it is possible select a preferred estimation based on a likelihood ratio test. In both cases, including individual fixed effects (panel data) requires that at least one observation is non-zero (Greene, 2018, p. 900).

In the case of exploration success measured as number of discoveries, the previous equation if modified to include more parameters. The left-hand side of Equation 2 indicates the average number of deposits being discovered in a country i at year t. Parameters of interest include the level of contemporaneous and past exploration effort received in country i ($e_{i,t-j}$), where the long-run effect of exploration effort is given by the sum of all δ_j coefficients. Institutional quality variables related to strengthen of property rights, political stability and transparency are listed in $\mathbf{X_{i,t}}$ and the sign of β will indicate the effect of the particular institutional measure on exploration success. Additional country (α_i) and year (α_t) fixed effects control for unchanging characteristics and common yearly events to all regions. As opposed to patents data, mineral discoveries can also be characterized by their quality. In this case, the analysis change the left-hand side variable by a quality measure as total discoverable tonnage to analyze if explanatory variables affects different count and quality measures.

$$log(\lambda_{i,t}) = \alpha_i + \alpha_t + \sum_j \delta_j \cdot e_{i,t-j} + \mathbf{X_{i,t}} \cdot \beta \tag{2}$$

When it comes to counting discoveries, it can be expected that a large number of observations would be zeros. This is could be misleading if there are different data generation processes behind the zero outcome. For example, there could be zero discoveries because there was not any investment in the contemporaneous or previous years, if investment was made mainly for due diligence a not drilling. Additionally, companies can avoid disclosing their exploration results for non-significant discoveries (low quality deposit), because of strategic reasons or the discovery could be too small to be considered a discovery in the database. In this case, there are zeros not related to exploration effort biasing results towards zero. Zero-Inflated (ZI) models were to developed to fit count data in two separate ways. First, a regular count part (e.g. Poisson or NB) that can fit zero and non-zero outcomes. Second, a zero part aiming to point out zeros not generated by the regular process and likely to come from a different distribution. Despite ZI models being non-nested with Poisson or NB regressions, Vuong (1989) suggests a test to decide between ZI and non-ZI models.

These three specifications (Poisson, NB and ZI) are presented in the results and compared using the above mention tests. The likelihood ratio test indicates if NB is preferred over Poisson and the Vuong test would support the decision between ZI and non-ZI models.

2.2 Geological maturity

Mineral exploration involves two opposing external effects determining the degree of geological maturity. First, positive spillovers occur in early stages when a firm releases geological information signaling attractiveness for other firms. For example, gold rushes has been mostly explained by this mechanism, where an initial discovery provides information about the geological potential of a region. This makes the region more attractive for miners, an effects that is increased by poorly-defined property rights (Libecap, 1990). Second, a negative stock effect from decreasing remaining discoverable deposits when a region becomes more geological mature. In this case, there are negative external effects when more than one firm is making exploration decisions (Peterson, 1978). The net result from these two effects is usually modelled considering a quadratic functional form in the remaining stock of discoverable deposits (Uhler, 1976; Mason, 1989; Siegel, 1985). In early stages (high remaining stock or low accumulated discoveries), information spillovers should dominate over the stock effect. However, as more deposits are discovered, the depletion effect dominates.

In this model, the quadratic approach is considered to model dynamic exploration decisions. For simplicity, consider an exploration decision model using two firms (i and j), two periods (0 and 1) and a fixed discoverable deposit size (q). In a particular region where institutional related variables do not change, a firm i decides its exploration effort based on the expected profits presented in equation 3.

$$\begin{aligned} \max_{e_{i,0},e_{i,1}} \quad & p(e_{i,0}, R_0) \cdot V(q) - c(e_{i,0}) + \delta E(\Pi(e_{i,1})) \\ \text{subject to} \quad & R_1 = \begin{cases} R_0 & \text{if no discoveries were made (s=0)} \\ R_0 - q & \text{if either } i \text{ or } j \text{ made a discovery (s=1)} \\ R_0 - 2q & \text{if both } i \text{ and } j \text{ made discoveries (s=2)} \end{cases} \end{aligned} \tag{3}$$

Where $p(e_{i,0}, R_0)$ represents the probability of finding a deposit based on exploration effort e_i and remaining discoverable deposits R_0. Exploration costs are given by $c(e_{i,0})$ and δ represents the discount factor for future profits in each potential state of the world s. Expected profits in period 1 depend on the finding probability as shown in equation 4.

$$\sum_s [p(e_{i,1}, R_s) \cdot V(q) - c(e_{i,1})] \cdot Prob(Y = s) \tag{4}$$

The solution depends on the decided functional form. For simplicity, assume constant marginal costs of exploration and probabilities given by $p(e_i, R) = f(e_i) \cdot g(R) = \sqrt{e_i} \cdot (aR - bR^2)$, where a and b are greater than zero. This functional form combines both, a decreasing return of exploration effort and the quadratic relationship on remaining discoverable deposits used in previous studies. Then, the optimal exploration decision for each state

s in period 1 is given by equation 5.

$$e_{i,1,s}^{*}=\frac{V(q)^{2}g(R_{s})^{2}}{4w^{2}} \tag{5}$$

Replacing the optimal exploration level in the profit function for each state s, the expected profits in period 1 ($E(\Pi_1)$) are indicated in equation 6.

$$E(\Pi_1)=(1-p_{0,i})(1-p_{0,j})\cdot\Pi_{1,s=0}+\Big[p_{0,i}(1-p_{0,j})+(1-p_{0,i})p_{0,j}\Big]\cdot\Pi_{1,s=1}+p_{0,i}p_{0,j}\cdot\Pi_{1,s=2} \tag{6}$$

If we rule-out the probability of both firms finding a deposit, then $p_i \cdot p_j \sim 0$ [1] and the maximization problem from equation 3 is simplified to:

$$\max_{e_{i,0}} \;\; p_{i,0}\cdot V(q)-we_{i,0}+\delta\Big[\Pi_{1,s=0}+(p_{i,0}+p_{j,0})(\Pi_{1,s=1}-\Pi_{1,s=0})\Big] \tag{7}$$

Where equation 7 presents the intertemporal balance between profits in period 0 and the differences on profits if a discovery is made in period 1, which can be either positive or negative depending on the geological maturity and which effect dominates (stock or information spillovers). The optimal exploration decision is finally defined in equation 8.

$$e_{i,0}^{*}=\frac{g(R_{0})^{2}}{4w^{2}}\Big[V(q)+\delta(\Pi_{1,s=1}-\Pi_{1,s=0})\Big] \tag{8}$$

The relationship between the exploration decision and the remaining stock from equation 8 is better expressed graphically. As illustrated in Figure 1, every new discovery can have a different effect on exploration decisions. If a region is perceived to be in the early stages, where information spillovers dominate over stock effects, then exploration effort will increase with each additional discovery. This effect gradually decreases and exploration effort decreases as the stock effect starts to dominate and the region moves to a more mature stage.

[1] This assumption is based on the empirical fact that the probability of finding a deposit is in the order of 1 in 10,000 (Sturla et al., 2018).

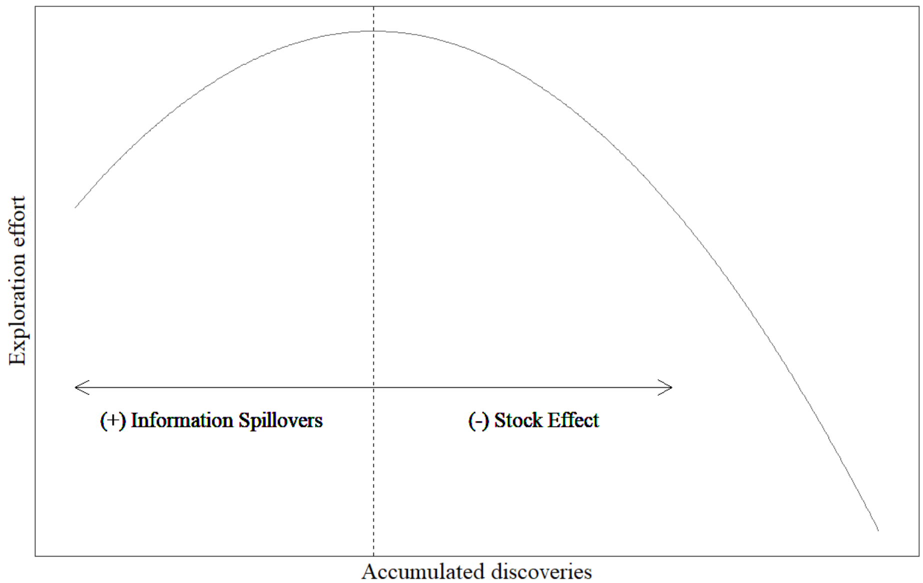

Figure 1: Relationship between exploration effort and accumulated discoveries (or decreasing remaining stock of discoverable deposits). On the left side of the dotted vertical line, information spillovers dominate over stock effects illustrating an early-stage of mineral development. The right side shows the opposite effect as the region becomes more geologically mature.

It is worth clarifying that the model assumes fixed institutional variables. Changes in institutional quality affecting the a firm's ability to appropriate mineral resources can shift the curve.

The theoretical background supports using discoveries to reveal the if a region is the more mature section conditional on institutional quality variables in a regression setting. Equation 9 regress the log of exploration effort ($e_{i,j,t}$) of firm i in country j at year t as a function of the number of discoveries ($D_{j,t}$) occurring in country j at year t and other controls ($\mathbf{X_{i,j,t}}$). Other controls include institutional quality measures, company type and country fixed effects.

$$log(e_{i,j,t}) = \delta \cdot D_{j,t} + \mathbf{X_{i,j,t}} \cdot \beta + \varepsilon_{i,j,t} \tag{9}$$

In this case, δ measures the net effect between information spillovers and stock effects. If discoveries are assummed as random conditional on the observables, then a positive sign of δ can be interpreted as an indicator that information spillovers dominate in the region of analysis. On the other hand, a negative sign will suggest that a region is becoming more mature and less attractive for exploration investment.

2.3 Data

There are three main sources of information for the analysis. First, major mineral discoveries are represented by copper and gold deposits listed in the S&P database (S&P Global Market Intelligence, 2019b, 2020). Second, country-level grassroots exploration expenditures for gold and copper comes from the S&P Global Corporate Exploration Strategies database (S&P Global Market Intelligence, 2019a). Third, institutional quality is measured by the Worldwide Governance Indicators (WGI), developed by The World Bank (2019). Grassroots exploration database only available from 1997 to 2018 and limits the period of analysis.

The discovery of a deposit needs to be further detailed as there is not a standard definition. For both, copper and gold, the discovery year refers to the year when a drill first hit a mineralized rock. In the case of copper, a major copper discovery is defined as a deposit containing at least 500,000 tonnes of copper in reserves, resources and past production where appropriate (S&P Global Market Intelligence, 2019b). A major gold discovery is defined as a potentially economic deposit containing at least 2 million ounces of gold in an inferred and/or measured and indicated resources, or at least 1 million ounces in reserves (S&P Global Market Intelligence, 2020).

The distribution of discoveries in every country-year pair is presented in Figure 2 a) and b). In the case of copper, discoveries in analyzed countries do not exceed five. In most cases, a country experiences zero discoveries in any given year, indicating that count models should be preferred in the econometric estimation. Gold discoveries follow a similar pattern, with a high percentage of zero discoveries reaching a maximum of three discoveries.

The geographical distribution of discoveries are presented in Table 1. Most copper discoveries occurred in Latin America, representing almost 51 percent of total discoveries in the 1997-2018 period. Latin America is followed by the Asia-Pacific region, concentrating 24 percent

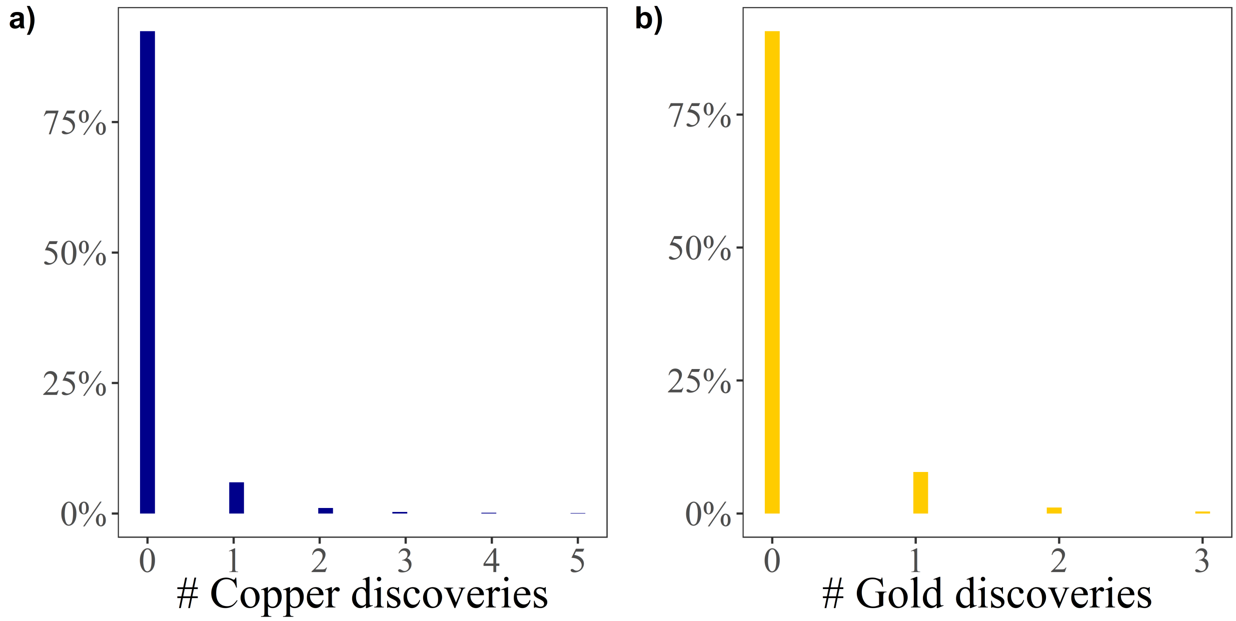

Figure 2: Histograms for copper and gold discoveries, 1997-2018. Every observation represents the number of discoveries in a country at a given year.

of total discoveries. Gold discoveries are less concentrated than copper discoveries, where most discoveries (28 percent) are in Africa, followed by Latin America (27 percent).

Table 1: Copper and gold discoveries by region, 1997-2018.

Region	Copper discoveries	Gold discoveries
Latin America and the Caribbean	67	40
Asia-Pacific	32	20
Africa	14	41
Europe	11	21
Canada-US	7	23
Middle East	1	3

Source: S&P Global Market Intelligence copper and gold database (2020; 2019b).

Over time, major copper and gold discoveries have been decreasing on average. Figure 3 a) and b) illustrate this trend. For copper, the average number of discovered deposits has been declining from 9.3 discoveries per year in the 1997-2004 period to 7.1 between years 2005 and 2011 period and reaching 1.1 discoveries per year on average during 2012 to 2018. Moreover, there were not significant discoveries in 2015, 2016 and 2017 and 2018. Gold discoveries does not follow the exact copper pattern. The average number of gold discoveries during the 1997-2004 period was 8.4, which slightly increased to 9.4 between 2005 to 2011. However, the last period (2012 to 2018) has an average of 2.1 discoveries per year, including two years (2017 and 2018) without major discoveries.

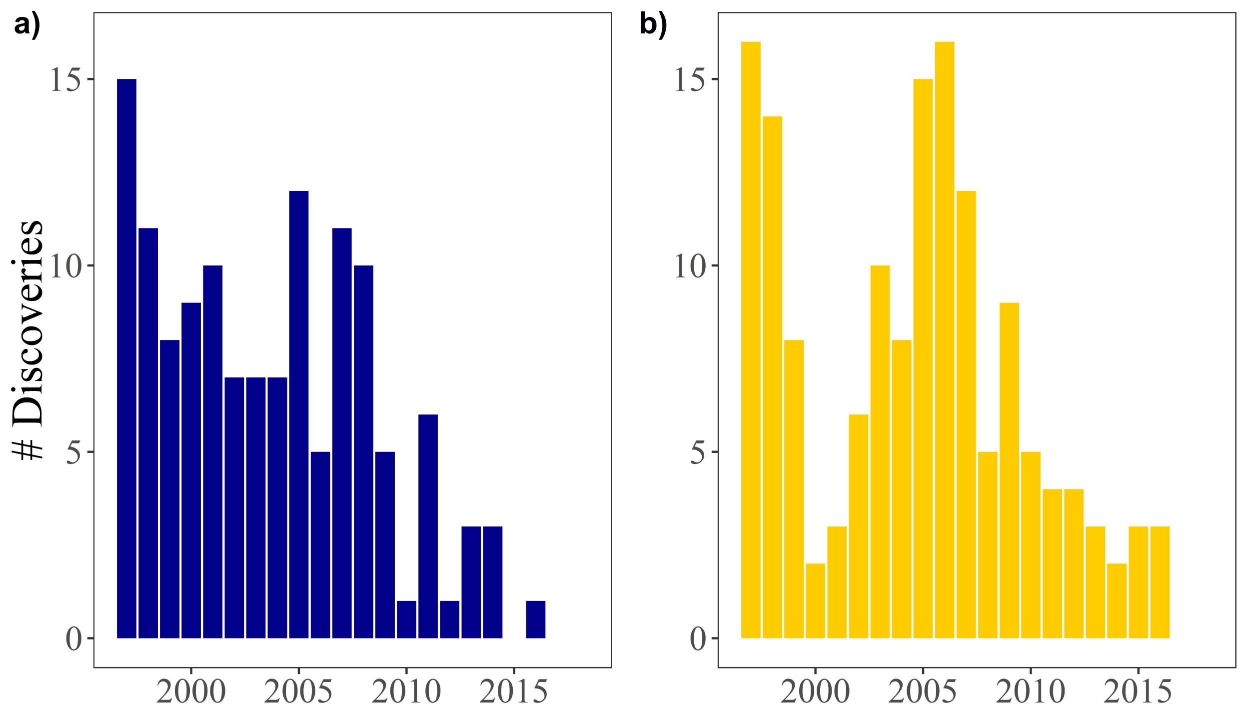

Figure 3: Number of major copper (left) and gold (right) discoveries, 1997-2018.

3 Results

This section is divided in two parts. First, an analysis of main variables associated with exploration success for gold and copper. Second, an empirical estimate of geological maturity, considering the net effect from information spillovers and stock depletion.

3.1 Determinants of exploration success

The discovery of a mineral deposit is similar to the development of a new drug or patent (Khazabi and Quyen, 2017). The most relevant characteristic for empirical purposes is to take into account the integer nature of data. In the next results, only the Poisson estimates are presented. Both the likelihood ratio test and the Vuong test support that a Poisson specification is preferred over negative binomial and zero-inflated models.

A main variable of interest is the exploration budget allocated in each country, signaling the exploration effort on discovering new deposits. Otto et al. (2006, p. 216) indicate that some institutional quality variables affect investment during the exploration stage, especially those related to property rights (land tenure and mineral ownership). The results for gold and copper discoveries are presented in Table 2 and Table 3 below.

The dependent variable in columns (1) to (6) in Table 2 is the number of copper discoveries occurring in a country at any given year. Every column includes different controls in the Poisson regression. Column one includes grassroots exploration the same year of the discovery ($Cu\ grassroots$) and up to two years prior the discovery ($Cu\ grassroots1$ and $Cu\ grassroots2$)[2]. Column two adds institutional quality variables, represented by three Worldwide Governance Indicators (WGI) developed by the World Bank (rule of law, political stability and control of corruption)[3]. Columns three, four and five include country, year and country-year fixed effects, respectively. Column six controls for linear and quadratic regional trends to take into account different levels of geological maturity. The last two columns show the OLS regression on the discovered tonnage (in million metric tonnes) as a proxy for discovery quality. Robust standard errors appear in parenthesis.

Regression estimates show mixed results in terms of total allocated grassroots budget. On one hand, investment a year prior the discovery is positively associated with discoveries. For example, the estimate in column five indicates that a one percent increase in grassroots budget is related to a 0.37 percent increase in the number of discovered deposits for the average budget (20.7 million $US). On the other hand, in column five, contemporaneous in-

[2]Lags were chosen according to information criteria. Two lags allow to take into account not only the dynamic nature of exploration investment but also the empirical limitations from a 22 years sample period.

[3]Institutional quality variable are highly colinear (pairwise R^2 ranging from 0.78 to 0.97). Nevertheless, this is mostly due to country effects. After controlling for fixed country effects, correlations halved (pairwise R^2 ranging from 0.37 to 0.49), increasing variability for the estimation.

Table 2: Regression results for copper discoveries

	Number of discoveries						Tonnage	
	Poisson	Poisson	Poisson	Poisson	Poisson	Poisson	OLS	OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cu grassroots	0.004	0.004	-0.006	0.004	-0.011^{*}	-0.010	0.005	0.005
	(0.004)	(0.004)	(0.004)	(0.006)	(0.007)	(0.007)	(0.007)	(0.007)
Cu grassroots1	0.006	0.006	0.010^{*}	0.010	0.018^{*}	0.024^{**}	-0.011	-0.010
	(0.006)	(0.005)	(0.006)	(0.008)	(0.009)	(0.010)	(0.011)	(0.010)
Cu grassroots2	-0.00003	0.0002	-0.017^{***}	0.009	-0.007	-0.011	-0.025^{***}	-0.026^{***}
	(0.004)	(0.004)	(0.006)	(0.008)	(0.008)	(0.008)	(0.009)	(0.009)
Long-run Cu grassroots	0.010^{***}	0.010^{***}	-0.013^{***}	0.022^{***}	-0.0003	0.002	-0.031^{**}	-0.032^{**}
	(0.002)	(0.002)	(0.005)	(0.004)	(0.006)	(0.007)	(0.014)	(0.014)
Rule of Law		-0.628	1.500	-0.075	2.619^{**}	1.869	2.390^{*}	2.203
		(0.482)	(1.007)	(0.492)	(1.214)	(1.443)	(1.439)	(1.603)
Political Stability		-0.080	0.770^{*}	-0.038	1.038^{**}	1.089^{**}	0.298	0.412
		(0.153)	(0.416)	(0.168)	(0.468)	(0.464)	(0.487)	(0.521)
Control of Corruption		0.696	-0.520	-0.027	-1.498^{*}	-2.299^{***}	-0.252	-0.631
		(0.428)	(0.774)	(0.417)	(0.864)	(0.877)	(1.135)	(1.214)
N obs	510	510	510	510	510	510	510	510
LL	-279.688	-278.291	-223.306	-244.057	-205.937	-194.881		
R^2							0.340	0.351
Country fixed effects	N	N	Y	N	Y	Y	Y	Y
Year fixed effects	N	N	N	Y	Y	Y	Y	Y
Regional trends	N	N	N	N	N	Y	N	Y

Note: Results indicate the Poisson regression estimates of copper discoveries (columns (1) to (6)) and discovered tonnage in million metric tonnes (columns (7) and (8)). Discoveries represent a count variable adding up all discoveries occurring in a country on any given year. Column (1) shows the basic estimate for exploration effort, column (2) adds institutional quality variables, columns (3)-(5) country fixed and year fixed effects, and column (6) includes regional trends. Column (7) considers country and year fixed effects while column (8) adds regional trends. Robust standard errors appear in parenthesis.
*p<0.1; **p<0.05; ***p<0.01

vestment has a negative coefficient. This can be explained by the fact that investment after a discoveries is shifted towards risk-reduction exploration (brownfield) and the fact that a discovery reduces available opportunities. Two years lagged investment appear with a negative but not significant coefficient. The long-run effect of budget on discoveries from adding up all three coefficients is presented at the end of Table 2. In this case, the aggregated effect seems positive but quickly becomes not different than zero when adding controls. Including year fixed effects controls for changes in prices that could drive additional investment (column four), explains the positive long-run coefficient. However, this effect goes to zero when controlling for country fixed effects as a proxy for geological potential (column five). The effect of budget on deposit size (tonnage) as shown in columns seven and eight is negative and significant at the five percent level, indicating overall that additional investment only generating smaller deposit.

In terms of the effect of institutional quality variables on copper discoveries, the strength of property rights (rule of law) mostly maintains its economic and statistical significant across the different specifications when including country fixed effects, for both the number of copper deposits discovered and their size. The effect is at least twice as important than the political stability index. The latter is positive and significant when it comes to number of deposits discovered but does not seem to have a significant effect on the size of the deposit. Lastly, control of corruption shows a negative sign, indicating that discoveries are less likely to occur in more transparent countries. However, as shown in columns seven and eight, this negative effect becomes not significant when it comes to the size of the discovery. This indicates that more deposits are found in less transparent countries but these deposits are not larger on average. These results are consistent with survey rankings on mineral exploration, where corruption or transparency does not take the leading variables driving investment (Otto et al., 2006, p. 216). Additionally, WGI indicators are normalized, so rule of law (associated with strength of property rights) is more relevant than other institutional quality indicators to explain discoveries. Interestingly, negative coefficients for indicators related to government transparency are negative. This results is not driven by non-linearities. For example, including a quadratic term for control of corruption as the coefficient of the quadratic term if small and not different than zero (0.0256, p-value of 0.95). Then, the negative coefficient could be explained by the larger unexplored lands of less transparent countries that compensate incentives for exploration companies.

Analogously to copper, Table 3 shows results for gold discoveries. Lagged grassroots budget for gold discoveries are both significant but with opposite signs. The first lag is negative while the second is positive. The long-run effect of total grassroots budget (adding up the three coefficients) is presented at the end of Table 3. The total effect is not statistically different than zero for neither the number of deposits or their size.

WGI indexes show a similar pattern than for copper discoveries when it comes to the strength of property rights. Rule of law is significant, with the expected sign and economically significant. Control of corruption does not appear as statistically significant for both the number of discoveries and the total discovered tonnage, illustrating how this variable is not relevant enough to decide where to allocate exploration effort. Nevertheless, the negative and significant sign for Political Stability is more surprising as it is sustained when adding more controls. The negative effect contrast with the positive effect from copper. Non-linearities cannot explain the negative effect. The quadratic term for Political Stability is negative (-0.1738 though not statistically significant with a p-value of 0.46), not showing a marginal effect that changes the sign within the data. Another explanation comes from differences in appropriability when comparing copper and gold. For example, gold deposits can be developed quicker than copper deposits and be profitable in a shorter term under a unstable regime. This is supported by the data. According to the S&P database, a gold mine takes about half the time between startup and closure compare to copper mines (11 years for gold and 20.4 years for copper).

As shown in copper and gold results, the Poisson specification is preferred over other models, validating previous theoretical developments using this distribution. Overall, including

Table 3: Regression results for gold discoveries

	Number of discoveries						Tonnage	
	Poisson	Poisson	Poisson	Poisson	Poisson	Poisson	OLS	OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Au grassroots	0.007***	0.005**	0.003	0.004	0.0002	−0.001	−0.001	−0.013
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.012)	(0.015)
Au grassroots1	−0.006**	−0.005*	−0.005	−0.007*	−0.007*	−0.008*	−0.003	−0.005
	(0.003)	(0.003)	(0.004)	(0.004)	(0.004)	(0.004)	(0.017)	(0.016)
Au grassroots2	0.004**	0.002	0.0002	0.006**	0.007**	0.007*	−0.003	0.003
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)	(0.019)	(0.016)
Long-run Au grassroots	0.005***	0.001	−0.002	0.003**	−0.0003	−0.002	−0.007	−0.015
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.013)	(0.016)
Rule of Law		0.146	1.414*	0.463	2.670***	2.696***	2.985***	2.674***
		(0.456)	(0.771)	(0.463)	(0.916)	(0.901)	(0.983)	(0.943)
Political Stability		−0.420**	−0.790**	−0.398**	−1.065***	−0.880***	−1.361***	−0.951**
		(0.209)	(0.323)	(0.198)	(0.313)	(0.334)	(0.499)	(0.459)
Control of Corruption		0.536	0.406	0.117	0.053	−0.248	−0.527	−0.830
		(0.445)	(0.618)	(0.460)	(0.763)	(0.795)	(1.090)	(1.176)
N obs	684	684	684	684	684	684	684	684
LL	−327.393	−320.176	−297.199	−296.623	−272.023	−260.038		
R^2							0.192	0.228
Country fixed effects	N	N	Y	N	Y	Y	Y	Y
Year fixed effects	N	N	N	Y	Y	Y	Y	Y
Regional trends	N	N	N	N	N	Y	N	Y

Note: Results indicate the Poisson regression estimates of gold discoveries (columns (1) to (6)) and discovered tonnage in million ounces tonnes (columns (7) and (8)). Discoveries represent a count variable adding up all discoveries occurring in a country on any given year. Column (1) shows the basic estimate for exploration effort, column (2) adds institutional quality variables, columns (3)-(5) country fixed and year fixed effects, and column (6) includes regional trends. Column (7) considers country and year fixed effects while column (8) adds regional trends. Robust standard errors appear in parenthesis.

*p<0.1; **p<0.05; ***p<0.01

regional linear and quadratic trends maintains the sign of the effect of variables measuring institutional quality. The low and not significant long-run effect of grassroots budget for both copper and gold discoveries indicates that the variable is not driving the number of discoveries or their size after controlling for year and country fixed effects. It appears that discoveries are not greatly driven by the net effect of current and past values of aggregated exploration effort. In terms of institutional quality, discoveries are more associated to occur in countries with stronger protection to property rights. Political stability does seem more relevant for copper than gold discoveries, and lack of transparency appear to be associated with more copper discoveries but not larger deposits.

3.2 Geological maturity

As mentioned in Section 2.2, the geological maturity depends on the net effect of two externalities associated with mineral exploration. First a positive information spillover effect that comes from the discovery of new deposits and their intrinsic spatial correlation, increasing the likelihood of finding another deposit in the area. Second, a negative depletion or stock effect that decreases the overall availability of exploration opportunities for subsequent firms. In the early-stage, spillovers dominate while the effect is reversed in more mature regions. If discoveries appear as random conditional on past exploration and other observable country-level characteristics, they can be used to estimate the effect on the average grassroots exploration budget as theorized in Section 2. A positive value suggest that information spillovers dominate (a discovery attracts more exploration) and a negative value that depletion effects are more prevalent (a discovery discourage exploration).

Regression results of copper and gold discoveries appear in Table 4 and Table 5, respectively. The dependent variable is the log of grassroots budget for the relevant mineral (copper or gold) made by an individual firm at every country-year pair. The explanatory variables include country fixed effects, year fixed effects, type of company fixed effects (junior, major or other companies) and institutional quality indexes (rule of law, political stability and control of corruption). Additionally, discoveries are defined as a count variable, adding up all discoveries that occurred in a country in year t. Two lags are included to estimate the dynamic effect of discoveries on grassroots budget. Robust standard errors appear in parenthesis and are clustered at the country level.

Table 4 presents results for copper discoveries on copper grassroots exploration budget. In this case, coefficients on contemporaneous and past discoveries are not statistically different than zero. The global long-run effect of copper discoveries is slightly positive but not different than zero at usual confidence levels. This suggest that information spillovers and stock effects for copper deposits are balanced on average during the sample period. The bottom part of Table 4 indicates the effect on three different time periods: period 1 (1997 to 2004), period 2 (2005 to 2011) and period 3 (2012 to 2018). The sign was positive in every period and slightly increasing in the most recent period. These results could indicate that information spillovers are slightly dominating over stock effects, but the statistical significance is mild.

Results for gold discoveries appear in Table 5. Contemporaneous and lagged coefficient are positive and significant. The long-run effect is positive and statistically significant. For example, in column (3) the semi-elasticity is 0.108, suggesting that an additional gold discovery in a country leads, on average, to a 10.8% increase on individual gold grassroots budget in that country. This long-run effect maintains its positive sign in the three analyzed periods as indicated at the bottom section of Table 5. Despite a decrease in the coefficient during the period 2005-2011, results suggest that information spillovers for gold discoveries are dominating stock effects, not indicating early signs of gold scarcity.

Figure 4 shows year-by-year coefficients of the long-run discovery effect for copper using two lags, company type, country and year fixed effects. The figure complements the period coefficients, showing that the net effect is mostly positive for both commodities. The decreasing trend during the period 2005-2011 for gold appear to be reversed after 2010. Additionally, lack of discoveries make estimation less clear after 2010, as the discovery of new deposits has

Table 4: Effect of new copper discoveries on copper grassroots exploration

	Log copper grassroots exploration budget		
	(1)	(2)	(3)
Cu discovery	0.012	0.012	0.012
	(0.014)	(0.013)	(0.013)
Cu discovery1		0.00001	0.0004
		(0.021)	(0.021)
Cu discovery2			−0.003
			(0.003)
Long-run effect (Cu+Cu1+Cu2)	0.012	0.012	0.009
	(0.014)	(0.028)	(0.034)
Long-run $\cdot I_{1997-2004}$	0.006	−0.005	0.010
	(0.025)	(0.031)	(0.041)
Long-run $\cdot I_{2005-2011}$	0.036	0.043	0.025
	(0.061)	(0.079)	(0.084)
Long-run $\cdot I_{2012-2018}$	−0.069	0.020	0.043
	(0.064)	(0.129)	(0.161)
N obs	10,168	10,168	10,168
R^2	0.421	0.421	0.421
Country fixed effects	Y	Y	Y
Year fixed effects	Y	Y	Y
Company type fixed effects	Y	Y	Y
Institutional Quality controls	Y	Y	Y

Note: Results indicate the regression estimates of new copper discoveries on the log of copper grassroots exploration budget. Each column includes an additional lag effect of the discovery. The aggregated long-run effect is indicated at the end of the table. Discoveries represent a count variable adding up all discoveries occurring in a country at any given year. All models include country, year and company type fixed effects (junior, major or other), and institutional quality controls. Robust standard errors appear in parenthesis and are clustered at the country level.
*p<0.1; **p<0.05; ***p<0.01

Table 5: Effect of new gold discoveries on gold grassroots exploration

	Log gold grassroots exploration budget		
	(1)	(2)	(3)
Au discovery	0.011	0.015	0.015
	(0.017)	(0.019)	(0.019)
Au discovery1		0.060^{***}	0.061^{***}
		(0.015)	(0.017)
Au discovery2			0.031^{**}
			(0.014)
Long-run effect (Au+Au1+Au2)	0.011	0.076^{**}	0.108^{**}
	(0.017)	(0.030)	(0.041)
Long-run $\cdot I_{1997-2004}$	0.074^{***}	0.145^{**}	0.163^{**}
	(0.028)	(0.064)	(0.079)
Long-run $\cdot I_{2005-2011}$	-0.038^{*}	0.021	0.046
	(0.020)	(0.034)	(0.039)
Long-run $\cdot I_{2012-2018}$	-0.005	0.023	0.078
	(0.067)	(0.088)	(0.126)
N obs	20,628	20,628	20,628
R^2	0.316	0.316	0.317
Country fixed effects	Y	Y	Y
Year fixed effects	Y	Y	Y
Company type fixed effects	Y	Y	Y
Institutional quality controls	Y	Y	Y

Note: Results indicate the regression estimates of new gold discoveries on the log of gold grassroots exploration budget. Each column includes an additional lag effect of the discovery. The aggregated long-run effect is indicated at the end of the table. Discoveries represent a count variable adding up all discoveries occurring in a country at any given year. All models include country, year and company type fixed effects (junior, major or other), and institutional quality controls. Robust standard errors appear in parenthesis and are clustered at the country level.
$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

been lower compared to other periods.

Estimated effects do not follow the inverted U-shaped theorized behavior at a global scale. This could be explained by national differences. Exploration can be at different stages in every country, each of them experiencing the inverted U-shaped pattern. Table 6 shows long-run coefficients for every region where data is available, suggesting that maturity and attractiveness are different. For example, the positive and significant coefficient for new copper discoveries in Africa suggest that spillovers are dominating while the negative and significant coefficient in the Asia-Pacific region indicates that it is already on the decreasing part of the curve. It is worth highlighting that effects need to be considered for each different commoditiy as illustrated by the differences between columns (1) and (2) in Table 6. Despite the negative sign for copper in the Asia-Pacific region, the coefficient for gold appears as positive and significant. Figure 6 illustrates regional differences for copper (left) and gold (right) in the context of the theoretical model previously presented.

Results for both copper and gold discoveries support that stock effects are not still clearly dominating exploration decisions. The empirical coefficients are illustrated in Figure 5, where copper appears closer to zero than gold. This is a positive view in the sense that new discoveries are still developing incentives to explore rather than lowering the availability of future deposits. This positive effect is not different than zero for copper, but the coefficient appears mostly stable during the sample period. On the other hand, the net effect for gold is positive and significant but year-by-year estimates show a slightly decreasing trend that was reversed after 2010. In both cases, future data can point out early signs if stock effects dominate information spillovers on mineral exploration.

4 Conclusions

The main goal of mineral exploration is to generate information. This can be done by reducing uncertainty about the quality of a previously known deposit or by discovering a

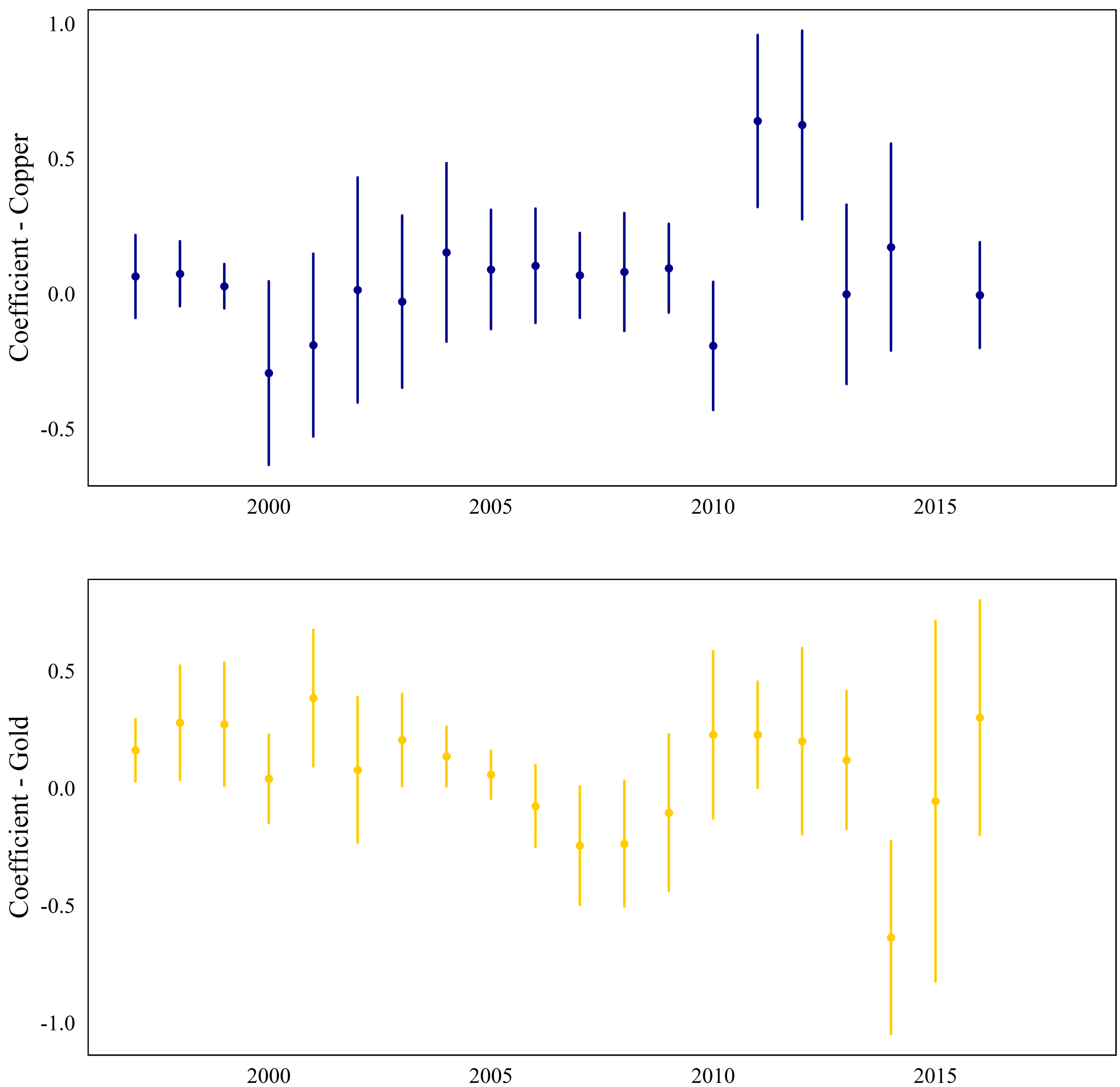

Figure 4: Effect of discoveries on copper (top) and gold (bottom) grassroots exploration, 1997-2018.
Coefficients consider discoveries lagged up to two years (model (3)), including company type, country and year fixed effects, and institutional quality controls. Bars represent robust standard errors, clustered at the country level.

Table 6: Effect of new gold discoveries on gold grassroots exploration

	Log grassroots exploration budget	
	Copper	Gold
	(1)	(2)
Long-run $\cdot Africa$	0.406***	0.026
	(0.047)	(0.170)
Long-run $\cdot Latin\,America$	-0.025	0.088
	(0.040)	(0.055)
Long-run $\cdot Asia - Pacific$	-0.149^{*}	0.283***
	(0.082)	(0.038)
Long-run $\cdot US - Canada$	0.187***	0.063**
	(0.064)	(0.028)
Long-run $\cdot Europe$	-0.450	0.418***
	(0.272)	(0.096)
Long-run $\cdot MiddleEast$	1.659***	-
	(0.272)	
N obs	10,168	20,628
R^2	0.423	0.317
Country fixed effects	Y	Y
Year fixed effects	Y	Y
Company type fixed effects	Y	Y
Institutional quality controls	Y	Y

Note: Results indicate the regression estimates of the long-run effect of discoveries on the log of gold grassroots exploration budget in different world regions. Column (1) shows estimates for copper discoveries and column (2) for gold discoveries. Discoveries represent a count variable adding up all discoveries occurring in a country at any given year. All models include country, year and company type fixed effects (junior, major or other), institutional quality controls and two lags of past discoveries. Robust standard errors appear in parenthesis and are clustered at the country level.

*p<0.1; **p<0.05; ***p<0.01

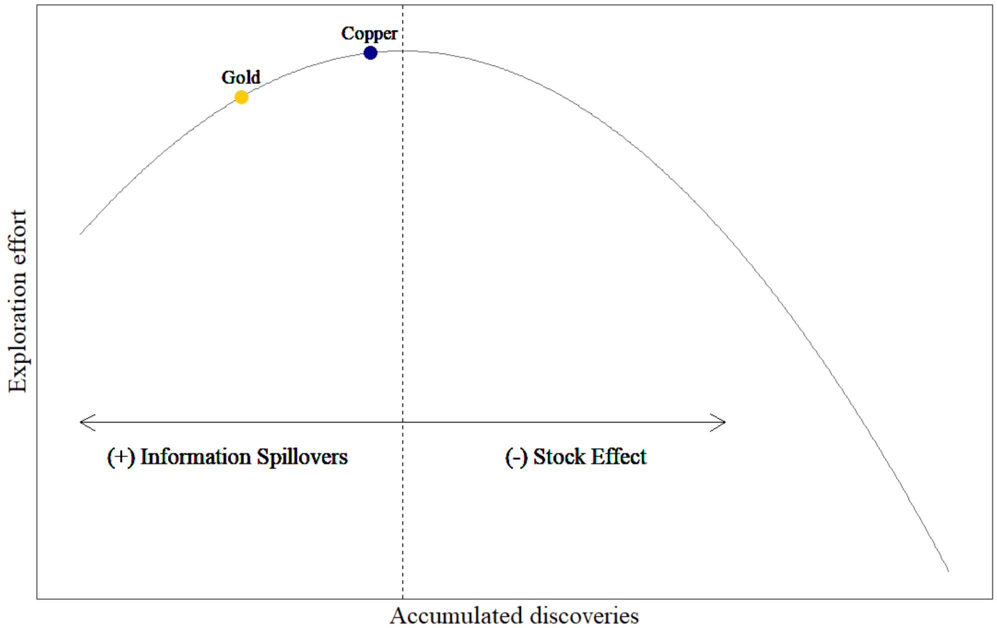

Figure 5: Illustration of the relative position for copper and gold discovery effect based on the theoretical relationship between exploration effort (vertical axis) and accumulated discoveries (horizontal axis).

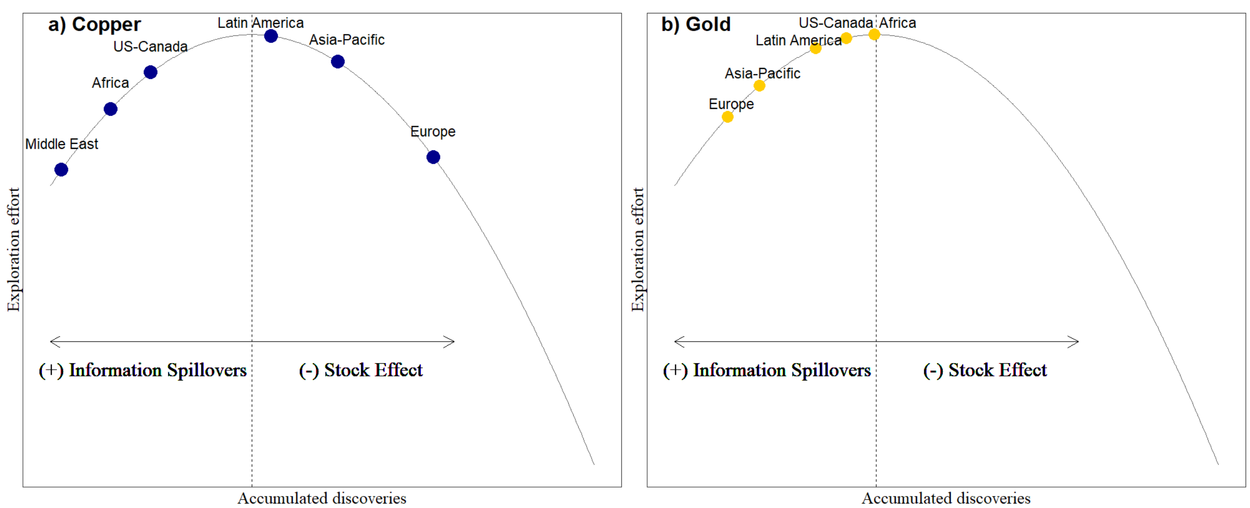

Figure 6: Illustration of the relative position of different regions based on the discovery effect for copper (left) and gold (right). The curve represents the theoretical relationship between exploration effort (vertical axis) and accumulated discoveries (horizontal axis).

previously unknown deposit. In this sense, the exploration process is similar to other industries where information is an output, like R&D and innovation processes. These similarities support reaching out empirical R&D and innovation literature to analyze main variables affecting mineral discoveries. Nevertheless, as opposed to R&D and innovation activities, exploration also faces a restriction from the stock of exploration opportunities. As exploration takes places, information about potential interesting targets is made publicly available due to spatial geological correlation among deposits. At the same time, the stock of available deposits is decreased by every additional discovery. The balance between these two effects is theoretically known but the net effect needs to be addressed empirically. The main goal of this paper has been to take a first approach approach towards empirical analysis of mineral discoveries. This expands the understanding of main variables affecting them and how these discoveries could indicate the balance between information spillovers and stock effects.

Main results of this paper are classified in two broad topics. First, exploration effort and institutional quality variables have been expected to drive the discovery of new deposits. Surprisingly, the net effect of grassroots budget on discoveries, as a proxy for exploration effort, is not statistically different than zero for both copper and gold after controlling for year and country fixed effects. On the other hand, there are consistently more and larger copper and gold deposits where property rights are stronger. However, when it comes to political stability and control of corruption there are differences across commodities. Gold discoveries are more likely to occur in less stable countries than copper discoveries and lack of transparency appear to be associated with more copper discoveries.

Second, the analysis on the net effect between information spillovers and stock effects illustrate that the world is still not facing the more mature stage for the analyzed commodities. Nevertheless, regional differences are significant and indicate that Latin America, the Asia-Pacific and Europe appear in the more mature stage for copper. There are no regions appearing as more geologically mature for gold exploration.

The previous results imply a set of policy implications. First, it highlights that countries should focus on supporting secure property rights to encourage more mineral development. However, policymakers should also be aware of the mineral potential of their own country because what different deposits might be more likely to be found with changes in other institutional measures. This is particularly important in cases where more discoveries are associated with more instability or less transparency. In this case, exploration incentives might not be entirely aligned with the improvement of political institutions. Additionally, the assessment of geological maturity indicates that countries could benefit from keeping track of changes in exploration investment that go beyond year-by-year variability. These long-term changes could provide early warnings of a decreasing geological potential and the need to focus on other variables to maintain the resource base of the country.

Lastly, results provide an initial approach to analyze mineral discoveries and indicate at least three potential areas for further research. First, the relationship between discoveries and effort still requires a reasonable explanation. If total investment is not driving discoveries there might be a structural reason for an apparent over-investment in grassroots exploration which is not leading to discoveries. Second, institutional quality variables do not have enough variability to provide consistent statistical inference and a longer time period might be needed. Third, additional commodities could be analyzed in terms of the net effect between information spillovers and stock effects. This could help to anticipate potential scarcity from commodities and to give a broader view on the geological maturity for different minerals.

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