Real options and return dynamics: Gold and market exposure in gold mining firms

Determinants of gold and market betas

Master Thesis Finance

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Abstract

This thesis examines the time-varying gold and market exposure of gold mining firms, focusing on the conditions under which a firm's exposure to gold and market shifts. The analysis is based on a constructed portfolio, Adj-HUI, comprising low-hedged, revenue-generating gold producers from January 1998 to December 2024. Building on the methodology of Tufano (1998), the study extends the analysis to market exposure. This thesis evaluates different gold mining portfolios and tests for real option return dynamics through return asymmetries. Additionally, time-varying gold and market betas are estimated using unconditional rolling regressions and then regressed on macroeconomic and firm-level variables. The estimated betas are regressed in both a firm-level panel regression and a single portfolio-based regression. The study found evidence for return asymmetry, suggesting that gold miners have some downside protection similar to a call option. The results show that exposures are influenced by firm-level policies such as leverage and hedging and macro factors such as gold price variance, gold price levels, interest rates, and economic policy uncertainty (EPU). Gold beta decreases with higher gold prices and gold variance but increases with leverage. In contrast, market beta responds in the opposite direction to these variables. Increased EPU showed a negative relationship with market exposure, suggesting some weak safe-haven properties. The thesis concludes that gold miners' gold (market) exposure is higher (lower) when the value of the real option is low.

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1. Introduction

Gold has long held a special place in the global financial system, particularly during times of economic and geopolitical uncertainty. In recent years, it has regained importance among central banks as an important reserve asset. Whereas central banks were net sellers of gold for decades, viewing it as obsolete in the modern financial system, the 2008 financial crisis marked a turning point. Since then, governments and their central banks have become net buyers of gold, a trend not observed since the 1980s (O'Connor et al., 2015). According to the World Gold Council (2025), global gold reserves have risen from approximately 30,000 metric tons in Q1 2008 to 36,000 metric tons in Q4 2024. In the last few years, the price of gold has climbed steadily, surpassing its all-time high set in the aftermath of the financial crisis. Gold's reputation as a safe-haven asset, due to its inflation-hedging ability and low correlation with equities and other financial assets, continues to attract investors.

While gold itself is considered a haven, the same cannot be said for publicly listed gold mining firms. Gold mining companies are exposed to changes in the gold price and are often viewed as a leveraged proxy for gold. Tufano (1998) finds daily gold betas of these companies to be around 1.5 to 2.0, indicating that mining stocks can be significantly more volatile than gold itself. At the same time, these firms are also exposed to the overall stock market. These gold exposures are known to vary across firms and time and are influenced by macroeconomic variables and firm-specific decisions. (Tufano, 1998; Faff & Hillier, 2004).

Tufano (1998) argues that managerial decisions, such as hedging, leverage, and operational diversification, can significantly impact a firm's gold exposure. Similarly, Faff & Hillier (2004) find that macroeconomic variables, such as gold price levels, gold price volatility, and interest rates, partly influence exposure through what are called 'real options,' embedded in the gold miners' operations. Real options refer to strategic choices available to firms in the real world, which can be exercised when certain conditions are met. In the mining industry, real options capture the flexibility embedded in a firm's operations to adjust production based on commodity price levels as suggested by Brennan & Schwartz (1985). For example, a firm may choose to ramp up production when gold prices are high and suspend operations when prices fall below a certain threshold, or 'strike price,' which corresponds to the firm's marginal cost of production. Therefore, gold mines can be viewed as a call option on gold, and the gold exposure of gold miners is influenced by the decisions made by their managers. Not taking these options into account would overstate the gold exposure of gold miners.

General market exposure is known to be affected by financial leverage and the degree of operational leverage (Hamada, 1972; Gahlon, 1982). Hong & Sarkar (2007) find that higher leverage and earnings volatility increase market beta across firms. Higher interest rates, for low-leveraged firms, were found to decrease market exposure. The hedging ability of gold itself was quite strong during the global financial crisis, but it was shown to be weak in severe short-term stock market downturns, such as the COVID-19 pandemic (Burdekin & Tao, 2021). Baur et al. (2021) and Baur & Trench (2022) demonstrate that gold mining stocks do not consistently exhibit the safe-haven properties of gold during major crises, while displaying some hedging properties during smaller crises.

This research aims to investigate the relationship between gold mining firms, gold itself, and the broader market over the past 27 years. The study focuses on the gold and market beta coefficients of gold mining firms and how these exposures vary over time in response to firm-specific financial structure and macroeconomic conditions. This paper makes several contributions to the literature. First, this paper focuses on a long time period of gold mining firms at both the portfolio and individual levels between January 1998 and December 2024. Second, the paper estimates time-varying beta coefficients for both gold and the market using a rolling regression over a 27-year period. These estimated betas are then regressed on macroeconomic factors and capital structure choices to evaluate how they influence gold and market exposure. The methodology builds on Tufano (1998) and Faff & Hillier (2004), further extending their work on market exposure while also incorporating variables that resemble economic policy uncertainty and geopolitical risk. The results of the study provide information that helps investors understand when a firm becomes more exposed to gold or the broader market, highlighting the factors driving these shifts.

The central question is: What are the key determinants that drive the variation in gold and market exposure of gold mining firms over time? This question is addressed through three sub-questions: How do gold and market exposures differ across different portfolios of gold mining firms? Do gold mining firms exhibit real options in their daily returns? How do macroeconomic variables and capital structure explain the time-varying beta coefficients?

This study analyzes a set of gold mining portfolios constructed based on distinct selection criteria to evaluate how these affect exposures to gold and the broader market. The main focus is on a portfolio that excludes companies hedging over 1.5 years of future production and includes only gold mining firms with revenue-generating mines. This design enables a cleaner identification of sensitivities to gold and market fluctuations. The low-hedging, operationally active portfolio is then compared to an alternative portfolio that allows for more aggressive hedging policies and includes firms that do not operate gold mines or do not generate revenue.

The analysis proceeds in three steps. First, the gold and market exposure of three different portfolios are tested to see if they are statistically significant and different from each other. Second, the real option return effect across individual firms is tested using a positive interaction dummy. Additionally, the different portfolios are also tested using the same method across different time periods. Third, a conditional beta regression is proposed where unconditional time-varying gold and market betas are regressed on macroeconomic variables (interest rates, gold variance, and gold price), uncertainty variables (economic policy uncertainty and geopolitical risk), and a firm-level variable (leverage). All firm-level and return data are obtained from the London Stock Exchange Group (LSEG) and Wharton Research Data Services (WRDS), with macroeconomic and global risk data sourced from the Federal Reserve (FRED) and the Economic Policy Uncertainty website.

Consistent with earlier literature, this study finds that portfolios of low-hedged gold miners exhibit higher gold exposure, in line with Tufano (1998). The results consistently confirm the presence of a real option across individual firms through asymmetric returns, consistent with Baur (2014). In addition, results show the real option effect to be significant across the different portfolios and three equal periods between January 1998 and December 2024. Additionally, time-varying gold and market beta coefficients are shown to respond to both firm-level financial structure and macroeconomic conditions, as well as uncertainty variables. Specifically, high gold prices and high gold variance decrease gold exposure. Market exposure has a negative relationship with interest and economic policy uncertainty and has a positive relationship with gold variance. Leverage appears to have a positive relationship with gold exposure and a negative relationship with market exposure. This finding is contrary to the literature, as suggested in Hamada (1972). The results suggest that as gold mining firms have more flexibility and a higher real option value (e.g., high gold price, high gold variance, and low financial leverage), the gold exposure decreases, while market exposure increases.

It should be noted that this thesis does not suggest that financial leverage reduces a gold mining firm's market exposure. Rather, over time, increased financial leverage within gold mining firms is associated with sector-wide conditions that resulted in decreased market exposure, as these firms increasingly behaved like a call option on gold. In this paper, leverage acts as a proxy for broader sectoral conditions. During periods of falling gold prices and lower margins, gold miners may experience negative earnings and see their equity value decline, increasing leverage. Thus, persistently low gold prices, approaching closer to production costs, can increase operational leverage and financial leverage. Therefore, gold prices close to mining costs could have their effect through leverage. It is under these conditions that gold mining firms behave more like an option on gold, indifferent to the overall market.

The remainder of this paper is structured as follows. Part 2 presents a literature review of relevant papers on physical gold and gold mining firms as a financial asset, the exposure of gold mining firms to gold, and the theoretical foundations of market risk. Part 3 describes the data sources, construction, and constituents of the portfolios and companies of interest, as well as the macroeconomic and firm-level variables used in the analysis. Part 4 describes the hypotheses and the methodology that guide the empirical analysis. Part 5 shows and compares the empirical results of the tests and their statistical and economic significance. Part 6 summarizes the main findings, discusses their implications, and suggests future research.

2. Literature review

Gold is widely regarded as a strategic asset, valued for its role in wealth preservation and portfolio risk reduction during economic instability, particularly by reserve managers. Geopolitical risk and resulting sanctions increased the use of gold as a strategic reserve asset (Arslanalp et al. 2023). Gold mining companies, in contrast, show different properties due to their strong exposure to both commodity prices and equity markets. Tufano (1998) provides a firm-level analysis, using data from 1990 to 1994, and reports a quarterly gold beta of around 2.0 based on daily returns. He finds that hedging and metal diversification reduce a firm's exposure to gold, whereas financial leverage increases it. He also finds that gold beta tends to decline during periods of high gold prices or high gold price volatility. Faff & Hillier (2004) build further on Tufano (1998) by analyzing market-level determinants of gold exposure across gold miner portfolios in North America, Australia, and South Africa. They confirm that gold beta decreases with gold prices, volatility, and interest rates in North America but find weaker or no such relationship in Australia and South Africa. The effect of gold volatility on gold exposure reflects the real option embedded in mining operations, where higher gold volatility leads to adjustments in production by gold mining firms. The real option effect is relevant for gold mining firms because commodity firms actively use these, as suggested by Brennan &

Schwartz (1985). They hypothesized that mining companies adjust their production and have an option to open or close a mine under certain price conditions. They also suggested that if the firm does not have the option to close a mine because it would be too costly, it will have a more linear exposure to the underlying commodity. The existence of these real options is apparent in gold miners' 'gold premium,' a valuation premium over discounted cash flow (DCF) estimates, linked to an option value in mining operations. Twite (2002) studies Australian miners from 1985 to 1998, reports an average gold beta of 1.08 for weekly returns, and ties the valuation premium to firms' operational flexibility. Baur (2014) expands on this, reporting gold betas between 0.21 and 1.17 and market betas between 0.70 and 1.45, depending on daily, weekly, or monthly observations. His study reveals asymmetric return responses, with stronger reactions to increases in the gold price because of the real option to adjust production. However, Batten et al. (2017) do not find return asymmetry in the stock returns of gold miners. Baur (2014) also finds that spot prices better explain mining firm returns than lagged prices, a conclusion also supported by Nangolo & Musingwini (2011). This real option is further supported by O'Connor et al. (2016), who found that gold has a causal effect on reported production costs, rather than the other way around. So, as gold prices rise, mining companies often bring lower graded or previously unprofitable mines, or parts of those mines, into production. Thus, average production costs will follow the price of gold in the long run, but sharp increases (decreases) in gold price might increase (decrease) margins in the short term.

Mohanty and Nandha (2011) studied 40 U.S. oil and gas companies and found that these firms show significant exposure to oil prices. Additionally, it is found that exposure varies across firms and over time and that the sensitivity depends on operational characteristics and financial policies, such as hedging practices. Bartram (2005) examines not only gold but also a broader set of commodity price exposures across multiple industries and finds that only 15% of firms show significant sensitivity to commodity prices. Despite high price volatility, commodity exposure is generally less impactful than exchange rate or interest rate risk. Significant commodity exposure is concentrated in industries where commodities are outputs, such as mining and oil. The study attributes the limited exposure to the widespread use of hedging instruments, such as futures, options, and commodity-indexed debt.

The role of physical gold as an inflation hedge and safe haven is debated. Ghosh et al. (2004) and Beckmann & Czudaj (2013) find long-term cointegration with inflation. Therefore, with a long investment horizon, gold exhibits strong inflation-hedging properties. Batten et al. (2014)

disagree, noting gold's inflation hedge effectiveness varies over time and only improves in low-interest-rate and weak-dollar environments. Supporting this, Abdullah & Abu Bakar (2015) and Apergis et al. (2019) show gold rises when interest rates are low. As a safe haven, Baur & McDermott (2010) confirm gold's protective role in developed markets, especially on extreme daily stock market shocks, though Hood & Malik (2013) and Wu et al. (2019) find mixed or weaker evidence. Raza et al. (2018) and Chiang (2022) link gold demand to high Economic Policy Uncertainty (EPU) and Geopolitical Risk (GPR). Triki & Maatoug (2021) observed a changing behavior between gold and the market during periods of high GPR.

Gold also serves as a diversifier due to its low correlation with traditional assets (Hoang et al., 2015; Lucey et al., 2021). Creti et al. (2013) analyze the volatility and correlation between commodities and the S&P 500 from 2001 to 2011. They find that correlations are highly dynamic, often dropping during crises and rising afterward. Gold consistently shows low or negative correlation with equities, especially during market downturns, while other commodities tend to align more with the market. They conclude that due to increased financialization, commodities, except gold, coffee, and cacao, cannot be treated as a distinct asset class. Baur (2012) demonstrated that gold exhibits asymmetric volatility, increasing in response to significant gold price increases. While market volatility generally increases when the market declines. He suggests that increased gold volatility is due to the signal that sharp gold price increases have on market uncertainty.

Chua et al. (1990) show that gold miners, unlike physical gold, exhibit higher market exposure and correlation with the S&P 500, especially after the 1980s, making them more equity-like. The way gold mining firms are exposed to the market, specifically, has not been studied in the same manner as gold exposure has been studied, as seen in Tufano (1998). Modigliani & Miller (1958) suggested that the cost of capital increases with higher debt due to increased financial risk. Hamada (1972) argues that this increased financial risk results in higher market beta. Lev (1974) focused on operational leverage and found a positive relationship with market beta. Gahlon (1982) demonstrates that market exposure is positively correlated with the Degree of Operational Leverage (DOL) and the covariance between sales and market returns. Hong & Sarkar (2007) study determinants of equity beta across different portfolios. They find that interest rates have a negative effect on market exposure for low-leverage firms, while higher earnings volatility tends to increase market beta if earnings are correlated with the market.

The distinction between physical gold and gold mining is especially apparent during crises or periods of high market volatility. Baur et al. (2021) find that during extreme market downturns, gold mining stocks decouple from gold and follow the broader equity market, though they align more closely with gold during milder crises. Baur & Trench (2022), focusing on the COVID-19 pandemic, found that in their sample period, operating mines tended to have higher gold betas and lower market betas compared to development-stage gold firms. Despite this, sentiment-driven market dynamics caused market betas to rise sharply across all firm types during the COVID crisis, regardless of their operational activity. Burdekin & Tao (2021) compared the 2008 global financial crisis with the COVID-19 downturn and concluded that gold-related assets offered stronger hedging benefits in 2008 than during the more rapidly recovering pandemic period.

Taken together, these findings suggest that gold mining companies are exposed to both gold and the market. Research suggests that during periods of severe market stress, gold miners become more sensitive to the overall market, while their direct connection to gold becomes weaker. Meanwhile, the real option value intrinsic to mining firms remains a significant factor. Tufano (1998) and Faff & Hillier (2004) show that when the value of the real option increases (e.g., higher gold price, higher gold variance), the beta of gold mining firms to gold decreases, consistent with the model by Brennan & Schwartz (1985). Hedging and diversification decrease gold exposure, while leverage was found to increase gold exposure. Hamada (1972) and Gahlon & Gentry (1980) conclude that higher leverage, either financial or operational, increases market risk. Hong & Sarkar (2007) further support this and also find that interest rates reduce market exposure if leverage is low. While there is literature on gold mining firms' gold exposure, less attention has been paid to the market exposure of these firms. Most studies focus on static measures or single events, offering little insight into how gold miners' exposures shift over time due to macroeconomic variables and capital structure.

In contrast to past studies, this study's main focus will be on low-hedged firms that actually operate a gold mine. It compares these low-hedged firms to a portfolio that allows for more hedging. It examines the real option embedded in gold mining operations by testing for stock return asymmetry. It also estimates time-varying gold and market betas and investigates how the determinants of gold beta, as identified by Tufano (1998), also affect market exposure, while incorporating worldwide policy uncertainty and geopolitical risk. By moving beyond static or crisis-specific models, this research offers a more complete understanding of how gold mining firms are exposed over time. The findings aim to provide investors a clearer insight into the conditions under which gold mining stocks offer stronger gold-linked performance or when their exposure to the overall stock market increases. The findings also give investors a better way of understanding how to value gold mining companies under different macroeconomic conditions.

3. Data

A central observation in research on gold mining companies is that many ‘gold miners’ do not derive 100% of their revenue from gold. Prior studies often include firms with diversified operations in addition to gold, such as silver, copper, or zinc. Despite this diversification, statistically significant gold betas can still be estimated (Baur, 2014). Tufano (1998) further notes that while revenue diversification reduces a firm’s sensitivity to gold prices, other firm characteristics, such as hedging behavior and financial leverage, have an even stronger effect on gold exposure. To isolate gold-specific activities and time-varying hedging policies, this study concentrates on firms included in the NYSE Arca Gold BUGS Index (HUI). The HUI index comprises U.S.-listed gold producers that do not hedge their production beyond 1.5 years. According to Intercontinental Exchange (ICE) Data Indices (2021), constituents of the HUI must derive the majority of their revenue from gold and maintain a minimum market capitalization of $750[1] million. The companies under study are considered to be liquid gold mining firms due to their requirement to be listed in the U.S. and because of liquidity requirements necessary for inclusion in the HUI (ICE Data Indices, 2021). Historical composition data of the HUI index from October 1997 to December 2024 were obtained from the London Stock Exchange Group (LSEG), resulting in a total of 47 constituent firms. Recently, the HUI allowed for the addition of gold-exposed constituents with a different operating model than the traditional mining companies. These companies are known as royalty or streaming companies, which do not own gold mining sites but receive a percentage of their revenue by investing in gold mining operations. The first royalty company was added to the portfolio in December 2016, and subsequently, five new royalty companies were added. Among the 47 historical constituents of the HUI, 41 were classified as those owning gold mining facilities. Two gold mining companies were still in the exploration and development phase and reported no revenue, while another two lacked sufficient or available financial data.

[1] Once included, a company may remain in the index provided its market capitalization does not fall below $450 million.

To maintain analytical consistency, non-revenue companies, royalty companies, and investment entities were excluded. These excluded companies will be referred to as non-producing companies. The exclusions result in a refined portfolio of 37 producing companies, referred to as the Adjusted-HUI (Adj-HUI). Each company included was a member of the HUI for at least one full quarter between October 1997 and January 2025. The selection criteria of the Adj-HUI index result in a study that focuses on large, U.S.-listed, liquid gold mining firms that actively operate gold mines. While this selection ensures data quality and consistency, it may introduce selection bias and limit the relevance beyond these companies. The Adj-HUI preserves the original HUI weighting methodology as defined by ICE Data Indices (2021). Under these rules, the two largest constituents are each assigned a target weight of 15%, the third largest receives 10%, and the remaining 60% is distributed equally among the other constituents. An overview of the historical constituents of the Adj-HUI is provided in Appendix Figure 1.

Figure 1.

Type of constituents of the HUI

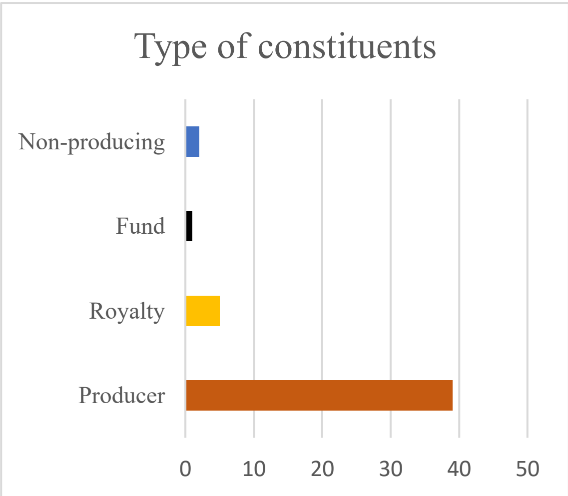
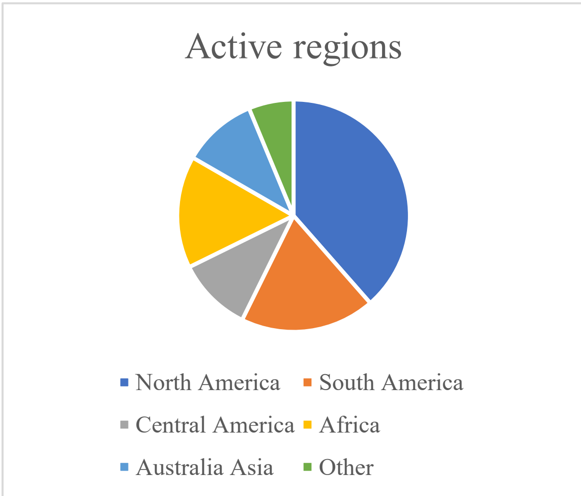


Figure 2.

Active regions of constituents of the HUI



In addition to the Adj-HUI, the analysis includes two benchmark portfolios based on the HUI index and the NYSE Arca Gold Miners Index (GDM). The GDM index is broader, including companies with more diversified operations, and it does not impose hedging constraints on index inclusion. Both the HUI and GDM indices undergo quarterly rebalancing on the third Friday of March, June, September, and December, and may adjust for corporate events such as bankruptcies, mergers, and acquisitions. The Adj-HUI, HUI, and GDM will from now on be referred to as portfolios. The number of constituents of the Adj-HUI declined due to consolidation in the mining sector. After 2003, the number of constituents stabilized around 16 firms, as illustrated in Appendix Figure 2.

Daily price data needed to calculate log returns for each firm were obtained from Wharton Research Data Services (WRDS). The portfolio returns of the Adj-HUI and HUI are calculated as the weighted sum of the constituent companies' log returns, using their respective portfolio weights. Price data for the GDM portfolio were sourced directly from LSEG, as historical constituent data were unavailable. The full dataset contains gold mining returns from October 1997 to December 2024, as this was the maximum amount of data available within the Adj-HUI portfolio.

Estimating gold exposure requires a suitable proxy for the gold price from which returns can be calculated. Baur (2014) and Nangolo and Musingwini (2011) find that spot gold prices best predict the gold mining stock returns. Thus, no leads or lags of gold returns are included in the regression models. Baur (2014) finds that Australian gold miners' gold and market coefficients decrease with higher frequency data. Appendix Table 3 shows the beta estimates based on daily, weekly, and monthly observations. It shows that there is little difference between daily and weekly estimates for these firms, likely due to higher daily liquidity in the US market compared to the Australian market. For this study, daily observations are preferred to ensure consistency with the methodology of Tufano (1998) and to enhance the statistical power of the beta estimates. Tufano (1998) uses the London afternoon gold fixing price as a proxy for daily gold and notes that asynchronous trading between gold and equity markets creates the need to adjust the gold beta using the Scholes and Williams (1977) method. However, this study uses gold price data represented by the end-of-day, 5:00 PM (ET), spot price of gold in U.S. dollars (XAU/USD), which is closely aligned with the 4:00 PM ET closing time of the exchanges on which these companies under study are listed. Because of the relatively high daily liquidity and minimal timing difference, such beta adjustments are not applied here. To calculate market exposure, the WRDS value-weighted S&P 500 index is used as a proxy for the broader equity market, consistent with standard practice in the financial literature and also employed by Tufano (1998). Market exposure, or market beta, is denoted as β, while gold exposure, or gold beta, is denoted as λ.

Daily gold return volatility is estimated using a GARCH (1.1) model consistent with the methodology employed by Faff & Hillier (2004). Prior literature employs raw gold price levels as an explanatory variable (Tufano, 1998; Faff & Hillier). However, due to the non-stationarity of gold prices over long horizons, this could lead to unreliable estimates. To solve this, a dummy variable is introduced, taking the value of 1 when the gold price is above the 252-day rolling median and 0 otherwise. The 10-year U.S. Treasury constant maturity yield, sourced from Federal Reserve Economic Data (FRED), serves as a proxy for long-term interest rates consistent with Tufano (1998), Faff & Hillier (2004), and Hong & Sarkar (2007). Leverage, defined as total debt divided by total capital, is obtained from LSEG on a quarterly basis and is chosen to reflect the capital structure for individual firms. Between quarterly observations, leverage is assumed to remain constant. In the case of the Adj-HUI portfolio's leverage, a weighted leverage ratio is constructed to align with the portfolio constituents' respective firm weights. Economic Policy Uncertainty (EPU) is a daily index based on U.S. newspaper coverage of economic policy uncertainty developed by Baker et al. (2016). Geopolitical Risk (GPR) is a daily measure of geopolitical risk based on global news sources introduced by Caldara & Iacoviello (2022). While GPR provides a direct measure of observed global geopolitical tensions, the EPU reflects uncertainty of U.S. policy. Daily data for a global EPU index is not available. Therefore, the U.S. EPU is used as a proxy. This choice is motivated by the fact that the U.S. plays a central role in the global economy, and its policy decisions often affect the whole world. Both EPU and GPR indices are publicly available at the Economic Policy Uncertainty website and have been widely adopted in gold-related studies, including Raza et al. (2018), Chiang (2022), and Triki & Maatoug (2021).

Descriptive statistics for all key variables in the main regression, including beta estimates and returns, are reported in Table 1. The rolling gold and market betas are based on 63-day windows, resembling a quarter, and are estimated in a single regression. The explanatory variables used in this study are 63-day rolling means. [2] Specifically, $\boldsymbol{VARGold_t}$ denotes the rolling mean of gold price variance; $\boldsymbol{Int_t}$ is the rolling mean of the 10-year U.S. Treasury yield; $\boldsymbol{HighGold_t}$ is the rolling mean of the 'above median' gold price dummy; $\boldsymbol{Lev_t}$ gives the rolling mean financial leverage of the firm or portfolio; $\boldsymbol{GPR_t}$ is the rolling mean of geopolitical risk; and $\boldsymbol{EPU_t}$ is the rolling mean of economic policy uncertainty. The missing observations (NA) in the dataset are a result of these rolling windows. The correlation matrix, as shown in Table 2, shows the relationships between the explanatory variables and beta estimates.

[2] Appendix Table 1 presents descriptive statistics based on unsmoothed (raw) data, before applying the 63-day rolling windows used in the main regressions.

Table 1.

This table shows the descriptive statistics for the daily values used in the conditional beta regressions. The variables are rolling means of 63 daily observations. except for $\boldsymbol{R_G}$. $\boldsymbol{R_M}$ and $\boldsymbol{R_{Adj-HUI}}$. which are daily returns. The $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$ estimates are based on the Adj-HUI returns.

Variable:	Min	1st_Q	Median	Mean	3rd_Q	Max	SD	NA
$VARGold$	4.00 E-05	7.00 E-05	9.00 E-05	1.10 E-04	1.20 E-04	6.60 E-04	7.55 E-05	62
Int	0.65	2.26	3.57	3.45	4.49	6.51	1.38	62
$HighGold$	0.00	0.24	1.00	0.70	1.00	1.00	0.42	62
Lev	0.11	0.16	0.19	0.22	0.25	0.44	0.09	62
GPR	47.49	88.00	100.74	112.28	126.01	476.38	46.63	62
EPU	39.43	68.49	95.49	108.11	129.42	463.28	55.47	62
λ	0.76	1.52	1.86	2.04	2.39	5.28	0.72	62
β	-1.20	0.19	0.45	0.45	0.71	1.97	0.45	62
R_G	-0.09	-5.00 E-03	3.00 E-04	2.72 E-04	5.76 E-03	0.10	0.01	
R_M	-0.13	-4.90 E-03	6.34 E-04	2.65 E-04	6.07 E-03	0.11	0.01	
$R_{Adj-HUI}$	-0.18	-0.02	-7.66 E-04	-3.91 E-05	0.01	0.24	0.03	

Table 2.

Below is the correlation matrix, which follows the variables used in the portfolio-based regression. The variables are rolling means of 63 daily observations. except for $\boldsymbol{R_{Gold}}$. $\boldsymbol{R_M}$ and $\boldsymbol{R_{Adj-HUI}}$. which are daily.

	$VAR Gold$	Int	$High Gold$	Lev	GPR	EPU	λ	β	R_G	R_M	$R_{Adj-HUI}$
$VARGold$	1.00										
Int	0.01	1.00									
$HighGold$	0.10	-0.18	1.00								
Lev	-0.24	0.43	-0.69	1.00							
GPR	-0.17	0.04	0.27	-0.12	1.00						
EPU	0.25	-0.46	0.27	-0.27	0.09	1.00					
λ	-0.30	0.10	-0.44	0.58	-0.02	-0.08	1.00				
β	0.26	-0.19	0.32	-0.55	-0.03	-0.09	-0.29	1.00			
R_G									1.00		
R_M									0.01	1.00	
$R_{Adj-HUI}$									0.71	0.18	1.00

Figure 3.

Gold betas individual firms

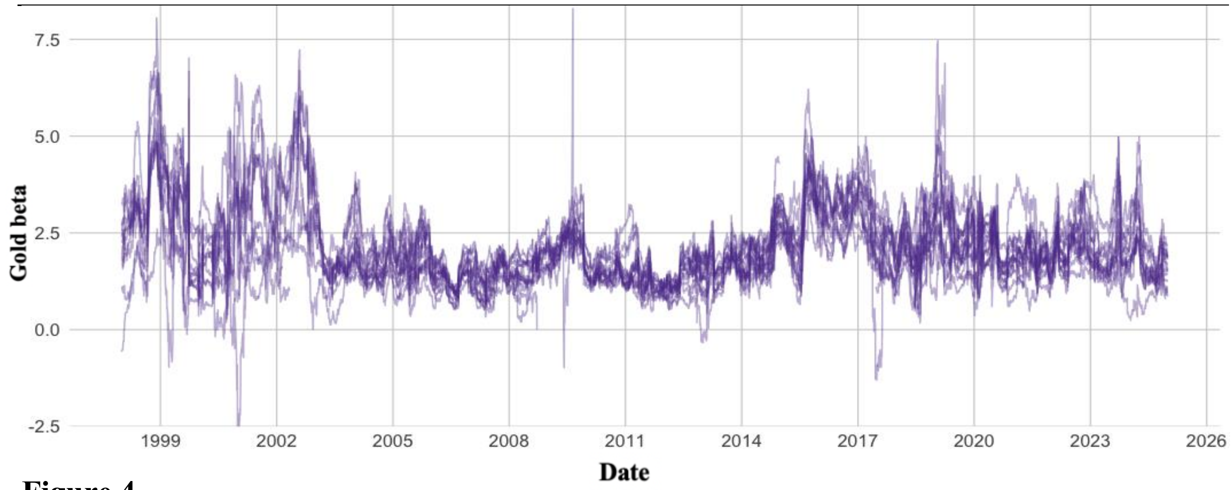


Figure 4.

Market betas individual firms

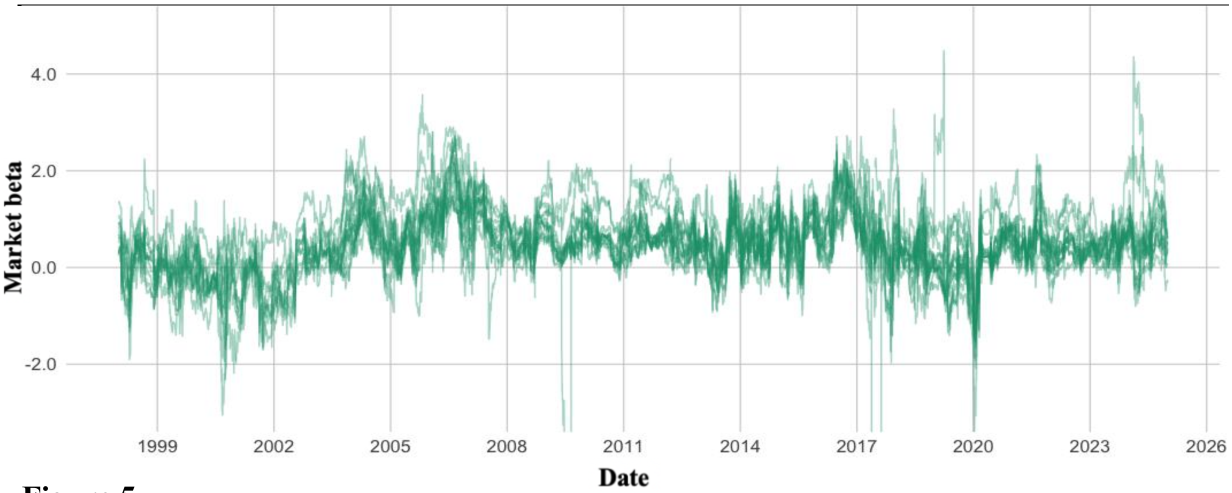


Figure 5.

Gold & Market Beta Adj-HUI

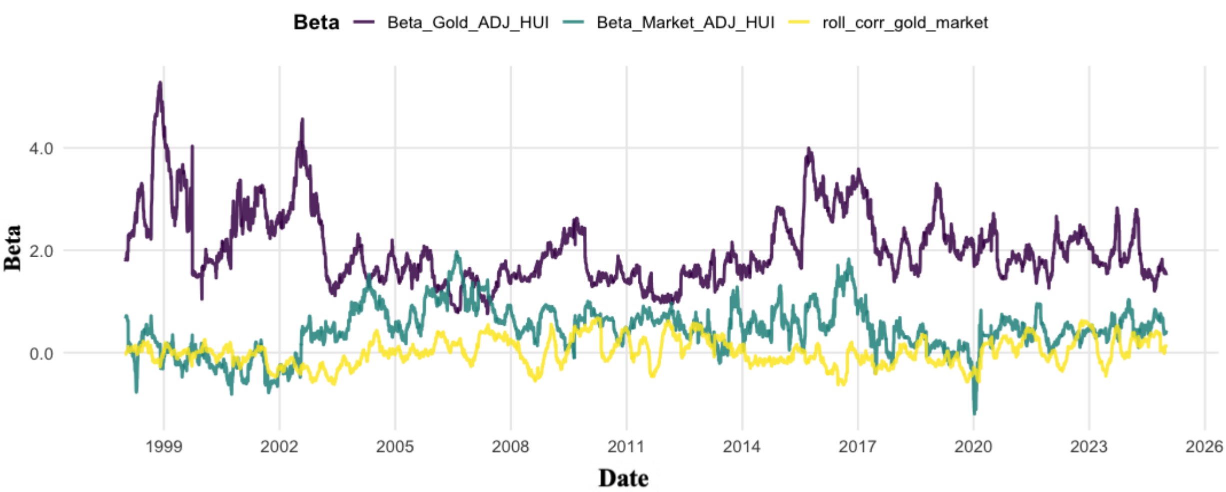


Table 3.

Gold & Market Betas for individual companies

Company	Market Beta		Gold Beta		Obs.
COEUR MINING INC	0.80	***	2.05	***	5,727
GOLD FIELDS LTD NEW	0.51	***	1.84	***	5,666
ANGLOGOLD ASHANTI LTD	0.36	***	1.96	***	4,030
BATTLE MOUNTAIN GOLD CO	0.06		3.10	***	826
LIHIR GOLD LTD	0.88	***	1.33	***	172
S S R MINING INC	0.38	***	1.96	***	1,644
HARMONY GOLD MINING CO LTD	0.57	***	1.98	***	5,030
DRD MINING	0.69	***	2.41	***	125
BARRICK GOLD CORP	0.39	***	1.66	***	5,417
GOLDCORP INC NEW	0.45	***	1.78	***	4,362
ECHO BAY MINES LTD	-0.22	**	2.82	***	1,313
MERIDIAN GOLD INC	0.53	***	1.60	***	1,363
FREEPORT MCMORAN INC	0.66	***	1.05	***	2,456
HECLA MINING CO	0.76	***	2.14	***	4,332
HOMESTAKE MINING CO	-0.08		2.07	***	1,057
NEWMONT CORP	0.36	***	1.55	***	6,855
NORTHGATE MINERALS CORP	0.05		0.47	***	216
AGNICO EAGLE MINES LTD	0.35	***	1.86	***	6,521
GLAMIS GOLD LTD	0.03		1.91	***	2,253
KINROSS GOLD CORP	0.35	***	2.08	***	6,853
BEMA GOLD CORP	-0.21	*	2.64	***	1,751
GOLDEN STAR RESOURCES LTD	0.58	***	1.97	***	1,385
COMPANIA DE MINAS BV SA	0.66	***	1.53	***	4,095
IAMGOLD CORP	0.55	***	1.90	***	5,043
ELDORADO GOLD CORP NEW	0.54	***	1.95	***	5,104
AURICO GOLD INC	0.47	***	2.20	***	510
YAMANA GOLD INC	0.53	***	2.08	***	4,162
NEW GOLD INC	0.70	***	2.16	***	2,919
FIRST MAJESTIC SILVER CORP	0.38		1.96	***	68
FORTUNA MINING CORP	0.66		1.68	***	68
PRETIUM RESOURCES INC	0.21	***	1.89	***	1,000
TAHOE RESOURCES INC	0.19		2.40	***	233
ALAMOS GOLD INC NEW	0.28	***	2.24	***	2,836
SIBANYE STILLWATER LTD	0.53	***	2.41	***	1,259
B2GOLD CORP	0.77	***	2.64	***	377
KIRKLAND LAKE GOLD LTD	0.23	***	1.94	***	1,106
EQUINOX GOLD CORP	0.48	***	2.04	***	1,262

Gold and market beta are estimated based on log portfolio returns on log gold returns and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 4.

Descriptive statistics gold & market betas

Variable	Gold Beta	Market Beta
Min	0.47	-0.22
Median	1.96	0.47
Mean	1.98	0.42
Max	3.10	0.88
SD	0.47	0.27
Insignificant	0	7
Number of companies	37	37

Lev is positively correlated with gold beta (0.57) and negatively with market beta (-0.57), suggesting that in times of increased leverage, market exposure was lower, while gold exposure was higher. In addition, Lev shows to be correlated with $HighGold$ (-0.69), indicating that during increased gold prices, equity value increases relative to debt, decreasing leverage. The correlation between gold and market returns over this sample period is 0.01, which shows the uncorrelated nature of gold with the market. Figures 3 & 4 show the time-varying gold and market betas of the individual firms over time. The graphs show that both the gold and market betas for each firm exhibit a similar trend over time, suggesting the gold mining firms' exposure responds in a similar manner to macro-wide changes.

The rolling gold and market beta of the Adj-HUI give the weighted movement of the portfolio. Comparing figures 3, 4, and 5 reveals that sharp increases in the Adj-HUI's gold or market betas are a result of sector-wide changes in return dynamics, rather than the entry or exit of heavily weighted companies in the index. Gold exposure is generally higher than market exposure throughout the sample period, except during the period from 2006 to 2007. The Adj-HUI's gold beta shows higher volatility than market beta, and while gold exposure is consistently positive and significant, market beta can be negative or statistically insignificant. The rolling correlation coefficient between gold and the market is also shown in the graph, illustrating how changes in gold's correlation with the market impact gold miners' market exposure.

Table 3 presents the estimated gold and market betas for individual firms based on daily returns.[3] Gold beta estimates show consistent estimates similar to Tufano (1998), with most firms showing strong and statistically significant exposure to gold. Market beta estimates are lower and, in some cases, statistically insignificant, possibly due to fewer observations or lower liquidity. Table 4 summarizes the descriptive statistics of beta estimates across these firms. Gold beta is consistently higher and has a higher standard deviation than market exposure. Given that these estimates are calculated over different time horizons, any direct comparison is wrong and should be interpreted with caution.

[3] A more detailed version of table 3, as well as weekly and monthly estimates can be found in Appendix Table 2 and Table 3.

4. Hypothesis and methodology

4.1 Unconditional beta

The literature reviewed and the data in the previous parts suggest that the exposure of gold mining companies to gold and the market is not constant over time. Instead, it varies conditionally on firm-level and broader macroeconomic conditions (Tufano, 1998; Faff & Hillier, 2004; Hong & Sarkar, 2007). Since gold and market returns are generally uncorrelated, this could be an interesting topic to explore. Thus, the main question is: What are the key determinants that drive the variation in gold and market exposure of gold mining firms over time? This is particularly relevant for investors seeking to understand when gold mining stocks respond more strongly to broader market movements and when they behave more like a proxy for gold, offering potential diversification or safe-haven benefits.

In this study, the unconditional exposure of gold mining firms to gold and the market is modeled in the same way as in Tufano (1998) and Faff & Hillier (2004), as shown in Equation 1. R_{GM} is the return of the gold mining portfolio or individual gold miner. A 63-day rolling regression of the unconditional model is applied to estimate the time-varying gold and market beta estimates of gold mining firms and the Adj-HUI portfolio.

Unconditional Gold and Market beta

$$R_{GM,t} = a_t + \beta_t R_{M,t} + \lambda_t R_{G,t} + \varepsilon_t \quad (1)$$

4.2 Portfolio regression

Based on the findings of Tufano (1998), diversification and hedging have negative effects on firms' gold exposure. In this study, different portfolios are evaluated that have selection criteria that, based on prior research, could affect both gold and market exposure. Companies that have a higher degree of operational risk are expected to have higher gold exposure. This is why gold mining companies that operate actual mines are more exposed to gold than non-producing companies. Exploration and development-stage mining companies experience higher market exposure, as shown by Baur & Trench (2022). It is expected that a portfolio that excludes non-revenue companies, royalty companies, or investment vehicles should have higher gold exposure. In addition, a portfolio that allows for more diversification and more aggressive hedging strategies is expected to have lower gold exposure and higher market exposure, similar to the findings of Tufano (1998). Creti et al. (2013) demonstrated that commodities other than gold have significant market exposure; therefore, more diversified mining companies should have higher market exposure. To test this, a regression model is estimated. The model is specified as Equation 2. This model compares the gold and market exposure of Adj-HUI, HUI, and GDM portfolios. The Adj-HUI portfolio consists exclusively of gold mining firms that actively operate producing mines. In contrast, the HUI includes non-producing companies, while the GDM allows for more diversified operations and longer-term hedging strategies.

$$R_{GM,t} = a_t + \beta_{1,t}R_{M,t} + \lambda_{1,t}R_{G,t} + \varphi D_{HUI} + \phi D_{GDM} + \beta_{2,t}[R_{M,t} * D_{HUI}] + \lambda_{2,t}[R_{g,t} * D_{HUI}] + \beta_{3,t}[R_{M,t} * D_{GDM}] + \lambda_{3,t}[R_{g,t} * D_{GDM}] + \varepsilon_t \tag{2}$$

$R_{GM_{it}}$ represents the return on the gold mining portfolio. The interaction terms involving the dummy variables D_{HUI} and D_{GDM} capture the different exposures of the HUI and GDM portfolios relative to the baseline portfolio, Adj-HUI. Specifically, these interactions allow the model to estimate how gold and market exposure differ for HUI and GDM compared to Adj-HUI, which serves as the reference group. The portfolios have overlapping constituents and are therefore estimated in a single regression. Because of the weighting rules of the Adj-HUI and HUI, an equal-weighted comparison between the two portfolios is also estimated for robustness.[4]

Newey-West standard errors are applied (Newey & West, 1987) with a lag of 10 based on Equation (3). Due to the relatively recent addition of non-producing companies, there will be two distinct periods. One period, from January 1998 to December 2016, and another from January 2017 to December 2024. During the first period, there is no statistically significant difference between the Adj-HUI and HUI, as they have the same constituents. After December 2016, however, it is expected that the Adj-HUI will have the highest gold exposure. GDM is expected to show lower gold exposure across both periods. Market exposure is expected to be

[4] Two of the seven companies excluded from the Adj-HUI portfolio, Wheaton Precious and Franco-Nevada, are sometimes among the three largest constituents of the HUI portfolio. Given the HUI's weighting rules of 10% to 15% for the top three firms, their inclusion could affect the index exposure characteristics. To account for this, an additional analysis is conducted using equal weighted portfolios to get a more consistent comparison.

the opposite, where GDM has the highest market exposure, as it has more metal diversification. The comparison of beta estimates follows the expected relationships outlined in Equation 4.

$$Lag = \left[4 * \left(\frac{T}{100}\right)^{2/9}\right] \tag{3}$$

$$\lambda_{Adj-HUI} > \lambda_{HUI} > \lambda_{GDM} \tag{4}$$

$$\beta_{Adj-HUI} < \beta_{HUI} < \beta_{GDM}$$

4.3 Real option test

Following Baur (2014), the existence of the real option is captured through a model that introduces a dummy variable $D_{Positive}$, which equals 1 if gold returns are positive and 0 otherwise. The interaction term $R_G * D_{Positive}$ captures the asymmetric response of mining firms to positive gold returns. A positive estimate of this interaction term indicates increased upside potential and decreased downside risk because gold mining companies might increase (decrease) production during higher (lower) gold prices. The model is shown in Equation 5.

$$R_{GM,t} = \beta R_{M,t} + \lambda R_{G,t} + \varphi D_{Positive,t} + \Pi[R_{G,t} * D_{Positive,t}] + \varepsilon \tag{5}$$

$$\Pi > 0 \tag{6}$$

This test is conducted at the individual firm level to examine how many different firms exhibit return asymmetry during their period of inclusion in the Adj-HUI. Due to differences in time period coverage and duration across firms, direct comparisons cannot be made. In order to be able to compare this model, it is estimated separately for the Adj-HUI, HUI, and GDM portfolios across three subperiods[5]. This allows for comparing real option effects within a portfolio over time. It is expected that gold mining firms and portfolios have positive gold return asymmetry due to the real option embedded in their operations, similar to Baur (2014). Thus, it is expected that the coefficient Π will be positive as shown in Equation 6.

[5] Subperiods are: 01-Jan-1998 – 01-Dec-2006; 01-Jan-2007 – 01-Dec-2015; 01-Jan-2016 – 01-Dec-2024, chosen as they conveniently give 9 years of daily data each.

4.4 Conditional gold and market beta models

Building on prior literature, it is hypothesized that both $\lambda_t^{(63)}$ and $\beta_t^{(63)}$ vary over time in response to macroeconomic and firm-specific conditions. The approach follows a two-step regression where first the 63-day rolling unconditional gold and market betas are estimated for the Adj-HUI and each firm as mentioned in Equation 1. These estimates are regressed on the 63-day rolling means of macroeconomic and firm-specific variables, as shown in Equation 7.

Conditional Gold and Market beta

$$\lambda_t^{(63)} = g_0 + g_1 VARGold_t + g_2 HighGold_t + g_3 Int_t + g_4 Lev_t + g_5 GPR_t + g_6 EPU_t + \varepsilon_t \qquad (7)$$

$$\beta_t^{(63)} = m_0 + m_1 VARGold_t + m_2 HighGold_t + m_3 Int_t + m_4 Lev_t + m_5 GPR_t + m_6 EPU_t + \varepsilon_t$$

The conditional gold and market betas are estimated in two different models: A firm-level beta panel regression model and a single portfolio-level time-varying beta regression.

The firm-level beta panel regression follows a methodology similar to that of Tufano (1998). He conducted quarterly panel regressions using firm-specific gold betas estimated from daily returns and then regressed these quarterly betas on both macroeconomic and firm-level variables. In this study, however, rolling gold and market betas are estimated for each firm using 63 daily observations, which represent one quarter, a standard research approach. These betas are then regressed on explanatory variables. The resulting panel dataset is unbalanced, as firms enter and exit the sample at different points in time based on their inclusion in the Adj-HUI portfolio. Due to this unbalanced model, it is possible firms that are included later in the dataset might respond differently to time-varying macroeconomic variables than older firms. However, as shown in Figures 3 & 4, the changes in exposure of gold mining companies' part of the Adj-HUI co-move across time. Suggesting the relationship of changes in exposure of more recently added firms to market-wide conditions is not different compared to longer-existing firms. In addition, the model includes firm fixed effects to control for variation across firms to capture diversification differences or cost structure differences. Time fixed effects are not included, as the objective is to understand how gold and market exposure within a firm evolve over time in response to macroeconomic conditions and changes in capital structure. The standard errors are two-way clustered to account for both serial correlation within firms and cross-sectional correlation across firms.

The time-varying beta regression only focuses on the Adj-HUI portfolio. Rolling gold and market betas of this portfolio are estimated, and these are regressed on the rolling 63-day average explanatory variables. To account for autocorrelation and heteroscedasticity, Newey-West standard errors (Newey & West, 1987) are applied following the same methodology as in Equation 3.

Baur (2012) showed that gold has inverted variance, increasing when gold goes up, which happens in times of increased market uncertainty. This while equity variance increases when the market goes down. Brennan & Schwartz (1985) hypothesized, and Tufano (1998) showed, that $VARGold_t$ decreases gold exposure. This is because the value of the real option to wait increases, and gold mining firms might adjust their production. Also, increased volatility of the underlying reduces the elasticity of the option, as stated by Tufano (1998). Baur et al. (2020) and Baur & Trench (2022) showed that during extreme market stress, gold mining firms act as general equities. Despite physical gold having a lower or negative correlation with the market, this suggests market exposure increases. The gold exposure is expected to be negatively affected by $VARGold_t$. Market exposure is expected to be positively affected by $VARGold_t$.

The rolling average of the above median gold price dummy variable, $HighGold_t$, serves as a proxy for short-term high or low gold price regimes. A value of 1 implies that gold has traded above its one-year median for the equivalent of a full quarter, while a value of 0 reflects a low-price environment. Higher gold prices lead to higher profitability in the short term as the real option is 'further into the money' and firms' might increase production. However, over longer periods, the mining cost of the gold industry, or 'strike price,' tends to move with the gold price level, as mentioned by O'Connor et al. (2016). That is why a window of 252 days is chosen, to reflect the short- to medium-term effect of gold price regimes. A higher gold price is expected to increase profitability and reduce gold exposure because the real option being further in the money results in lower gold exposure, as stated by Tufano (1998). Market exposure is expected to increase with a higher gold price, as gold mining firms will have access to more capital to engage in more exploration and new developments, thus being more prone to market exposure, as shown by Baur & Trench (2022).

The expected sign of Int_t is negative for market exposure of gold mining firms. Market exposure of low-leveraged, non-growth firms is expected to be negatively associated with interest, similar to Hong & Sarkar (2007). The effect of interest on gold exposure depends on an increasing or decreasing production level of a gold mining firm, as argued by Tufano (1998).

With increased production, higher corporate discount rates reduce the present value of future revenues, increasing gold beta. Brennan & Schwartz (1985) hypothesized that higher discount rates for costs should reduce gold exposure. Thus, the expected sign of Int_t is expected to be negative for gold exposure.

$\boldsymbol{Lev_t}$ is incorporated to reflect the relationship of gold and market exposure to capital structure similar to Tufano (1998) and Hamada (1972). It is expected that leverage has a positive relationship with gold exposure as sensitivity to gold price changes increases with financial and operational leverage (Tufano, 1998). Modigliani & Miller (1963) and Hamada (1972) both showed that higher leverage increases financial risk for equity holders, which should result in higher beta.

Geopolitical and macroeconomic uncertainty are captured by GPR and EPU. These variables are included to see if (expected) uncertainty has a different effect on gold and market exposure than actual crises captured by the back-looking gold variance. It hopes to capture implied volatility caused by economic or geopolitical risks, as managers act on expected gold price movements and volatility. It is expected that both GPR_t and EPU_t have a negative relationship with gold exposure, as the expectation of higher uncertainty might increase the real option value, reducing exposure, similar to the relationship with variance and gold. Market exposure is expected to be negatively affected by both GPR_t and EPU_t, as Baur et al. (2021) showed that gold mining firms had some hedging ability in 'small' crises. These smaller crises are reflected in increased uncertainty variables, and gold's hedging properties may be transmitted to gold mining firms under such conditions.

For $\boldsymbol{\lambda_t^{(63)}}$ it is hypothesized that $\boldsymbol{g_1}(VARGold_t)$, $\boldsymbol{g_2}(Int_t)$, $\boldsymbol{g_3}(HighGold_t)$, $\boldsymbol{g_5}(GPR_t)$ and $\boldsymbol{g_6}(EPU_t)$ have a negative sign. While $\boldsymbol{g_4}$ (Lev_t) is expected to have a positive sign. For $\boldsymbol{\beta_t^{(63)}}$ it is hypothesized that $\boldsymbol{m_1}(VARGold_t)$, $\boldsymbol{m_3}(HighGold_t)$, $\boldsymbol{m_4}(Lev_t)$ have a positive sign. While $\boldsymbol{m_2}(Int_t)$, $\boldsymbol{m_5}(GPR_t)$ and $\boldsymbol{m_6}(EPU_t)$ have negative signs. An overview of the expected signs is provided in Table 5.

Table 5.

Expected signs

Dependent variable: Gold Beta				
Explanatory Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
VARGold	–	–		–
HighGold	–	–	–	–
Int	–	–	–	–
Lev		+	+	+
GPR			–	–
EPU			–	–

Dependent variable: Market Beta				
Explanatory Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
VARGold	+	+		+
HighGold	+	+	+	+
Int	–	–	–	–
Lev		+	+	+
GPR			–	–
EPU			–	–

5. Results

5.1 Results: Portfolio regression

The first analysis (2) evaluated the gold and market exposures of the Adj-HUI, HUI, and GDM indices. As shown in Table 6, the estimated gold betas for these indices in period 2 range between 1.97 and 1.61, whereas the market betas are not statistically different across the portfolios. This suggests that while index construction criteria affect daily gold exposure, they do not affect daily market exposure in this setup. The HUI index shows a significantly lower gold beta than the Adj-HUI in period 2. Suggesting that the inclusion of non-producing gold stocks lowers gold exposure, thus supporting the hypothesis that firms that operate actual gold mines exhibit higher gold exposure. Furthermore, the GDM index, which includes more diversified firms and allows for more aggressive hedging strategies, confirms the hypothesis that hedging and diversification (and non-producing companies) decrease gold exposure.

Table 6

Portfolio regression

Variable	**Period 1 (1998 – 2016)**		**Period 2 (2017 – 2024)**	
Intercept	**0.00**	**	**0.00**	***
	(0.00)		(0.00)	
Gold return	**1.85**	***	**1.97**	***
	(0.04)		(0.05)	
Market return	**0.41**	***	**0.35**	***
	(0.04)		(0.08)	
HUI * Gold return	**0.00**		**-0.07**	***
	(0.02)		(0.02)	
GDM * Gold return	**-0.13**	***	**-0.36**	***
	(0.03)		(0.04)	
HUI * Market return	**0.00**		**-0.01**	
	(0.02)		(0.04)	
GDM * Market return	**0.03**		**-0.05**	
	(0.02)		(0.05)	
Observations	**4,825**		**2,016**	
R-2	**0.538**		**0.595**	
Adj R-2	**0.538**		**0.594**	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses: *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

The difference between Adj-HUI and HUI in period 2 is economically weak. This is due to the dampening effect of overlapping constituents between the two portfolios. For GDM, however, the economic significance is stronger, especially in period 2. Overall, these findings indicate that differences in gold beta are driven by the selection criteria of the portfolios. However, these differences that affect gold exposure did not result in significantly different market exposure at the portfolio level. These results are similar to those of Tufano (1998) and support Hypothesis 1 that operating gold mines have higher gold exposure than non-operating or developing gold mines. Furthermore, it confirms that more hedging and more diversification reduce gold exposure. Results of the equally weighted comparison between the Adj-HUI and HUI are shown in Appendix Table 4.

5.2 Results: Real option test

For all individual companies and portfolios, the real option embedded in their operations is tested based on their daily returns, and the results are shown in Tables 7 and 8.

Table 7.

H2: Real option effect (Firm-level)

Company Name	Market beta		Gold beta		Gold * D-Positive		Obs.
COEUR MINING INC	0.81	***	1.69	***	0.16		5,727
GOLD FIELDS LTD NEW	0.52	***	1.50	***	0.42	***	5,666
ANGLOGOLD ASHANTI LTD	0.37	***	1.59	***	0.56	***	4,030
BATTLE MOUNTAIN GOLD CO	0.08		2.67	***	0.48		826
LIHIR GOLD LTD	0.92	***	0.85	**	1.01	*	172
S S R MINING INC	0.38	***	1.68	***	0.37		1,644
HARMONY GOLD MINING LTD	0.58	***	1.57	***	0.51	***	5,030
DRD MINING	0.69	***	2.23	***	0.15		125
BARRICK GOLD CORP	0.40	***	1.47	***	0.32	***	5,417
GOLDCORP INC NEW	0.46	***	1.46	***	0.48	***	4,362
ECHO BAY MINES LTD	-0.20	*	2.28	***	0.60		1,313
MERIDIAN GOLD INC	0.55	***	1.26	***	0.27		1,363
FREEPORT MCMORAN INC	0.67	***	0.97	***	-0.04		2,456
HECLA MINING CO	0.78	***	1.79	***	0.33	**	4,332
HOMESTAKE MINING CO	-0.07		1.87	***	-0.13		1,057
NEWMONT CORP	0.36	***	1.28	***	0.35	***	6,855
NORTHGATE MINERALS CORP	0.04		0.64	*	-0.49		216
AGNICO EAGLE MINES LTD	0.35	***	1.56	***	0.34	***	6,521
GLAMIS GOLD LTD	0.06		1.24	***	0.76	***	2,253
KINROSS GOLD CORP	0.37	***	1.61	***	0.53	***	6,853
BEMA GOLD CORP	-0.19	*	2.03	***	0.97	**	1,751
GOLDEN STAR RESOURCES LTD	0.58	***	2.02	***	0.33		1,385
COMPANIA DE MINAS BV SA	0.66	***	1.29	***	0.32	***	4,095
IAMGOLD CORP	0.56	***	1.51	***	0.50	***	5,043
ELDORADO GOLD CORP NEW	0.55	***	1.60	***	0.38	***	5,104
AURICO GOLD INC	0.48	***	1.70	***	0.71	**	510
YAMANA GOLD INC	0.54	***	1.72	***	0.39	***	4,162
NEW GOLD INC	0.71	***	1.59	***	0.67	***	2,919
FIRST MAJESTIC SILVER CORP	0.41		2.01	***	0.65		68
FORTUNA MINING CORP	0.64		1.38	**	0.98		68
PRETIUM RESOURCES INC	0.22	***	1.46	***	0.73	**	1,000
TAHOE RESOURCES INC	0.23		1.61	*	1.21		233
ALAMOS GOLD INC NEW	0.29	***	1.81	***	0.55	***	2,836
SIBANYE STILLWATER LTD	0.55	***	2.21	***	0.34		1,259
B2GOLD CORP	0.77	***	1.87	***	1.13	***	377
KIRKLAND LAKE GOLD LTD	0.23	***	1.66	***	0.68	***	1,106
EQUINOX GOLD CORP	0.48	***	1.36	***	1.11	***	1,262

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses: *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 7 shows that 18 out of 37 individual firms exhibit a strong ($P < 0.01$) positive coefficient for the interaction term when gold returns are positive. The exposure to positive daily gold return ranges between 0.32 and 1.13, suggesting return asymmetry for individual gold mining companies. This suggests that the investors incorporate lower downside risk at the daily level as well. However, since firm-level observations do not span identical time frames, these estimates should not be directly compared across firms. A more detailed version of the results is shown in Appendix Table 5.

Table 8.

Real option effect Adj-HUI. HUI and GDM								
	Full period		**Period 1**		**Period 2**		**Period 3**	
Gold Betas	**1998-2025**		**1998-2007**		**2007-2016**		**2016-2025**	
Adj-HUI	**1.53**	***	**1.40**	***	**1.48**	***	**1.81**	***
	(0.07)		(0.14)		(0.11)		(0.13)	
HUI	**1.52**	***	**1.40**	***	**1.48**	***	**1.76**	***
	(0.07)		(0.14)		(0.11)		(0.13)	
GDM	**1.42**	***	**1.29**	***	**1.42**	***	**1.54**	***
	(0.06)		(0.12)		(0.10)		(0.11)	
Market Beta	**1998-2025**		**1998-2007**		**2007-2016**		**2016-2025**	
Adj-HUI	**0.40**	***	**0.09**		**0.66**	***	**0.36**	***
	(0.04)		(0.07)		(0.05)		(0.05)	
HUI	**0.40**	***	**0.09**		**0.66**	***	**0.35**	***
	(0.04)		(0.07)		(0.05)		(0.05)	
GDM	**0.40**	***	**0.14**	***	**0.65**	***	**0.32**	***
	(0.04)		(0.05)		(0.05)		(0.04)	
Gold*Positive	**1998-2025**		**1998-2007**		**2007-2016**		**2016-2025**	
Adj-HUI	**0.40**	***	**0.50**	**	**0.35**	**	**0.47**	***
	(0.11)		(0.22)		(0.14)		(0.17)	
HUI	**0.39**	***	**0.50**	**	**0.35**	**	**0.46**	***
	(0.11)		(0.22)		(0.14)		(0.17)	
GDM	**0.32**	***	**0.38**	**	**0.34**	**	**0.34**	**
	(0.09)		(0.18)		(0.13)		(0.13)	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses: *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 8 shows the real option effect at the portfolio level, which can be compared over time. Results show that both gold and market betas are significant, both statistically and economically, across all periods except for the market exposure in period 2 for both the Adj-HUI and HUI. The estimated values of the interaction term range between 0.50 and 0.34. Market beta was notably lower for the GDM in period 2 compared to periods 3 and 4. The real option, captured by the interaction term, remains positive and significant across all sub-periods for all the portfolios. A more detailed version of the portfolio-based analysis is shown in Appendix Table 6.

5.3 Results: Conditional gold and market beta models

Table 9 reports the firm-level beta panel regression for the 37 producing firms of the Adj-HUI, while Tables 10 and 11 show the portfolio-based results. The models show that gold variance significantly reduces gold beta, consistent with the hypothesis and Tufano (1998). Market exposure increases with gold variance, implying a shift in exposure from gold to market returns, which is consistent with the hypothesis. During high gold variance periods, the market often experiences strong negative shocks. Under these conditions, gold mining firms will act as general equities, increasing their market exposure. One standard deviation in gold variance reduces gold beta by 0.18, or 8.86% relative to the mean gold beta, while market beta rises by 0.14, or 34.31%[6]. These shifts are economically significant, as they indicate a notable rebalancing of risk exposure.

Interest rates have an insignificant effect on firm-level gold beta across all models, which is inconsistent with Faff & Hillier (2004) and Tufano (1998). However, interest rates exhibit a negative relationship with market exposure, similar to that observed by Hong & Sarkar (2007). A one-standard-deviation increase in interest results in a 0.13 market beta reduction, or a 34.31% decrease. At the portfolio level, interest rates show a weak and inconsistent negative relationship with market and gold exposure. One-standard-deviation increase in interest decreases gold exposure by 0.08, or 3.94%. The results for market exposure are economically significant, indicating a reduced sensitivity to the market. In contrast, the effects of gold exposure are too weak and too small in magnitude to be considered economically significant.

[6] The standard deviations of the explanatory variables and the mean gold and market betas are based on the descriptive statistics of Table 2 and Table 4. For the time varying beta regression table 2 is used. For the firm level panel beta regression, the gold and market beta of Table 4 are used.

Table 9.

Firm-level beta panel regression

	Dependent variable: Gold beta gold miner							
Independent variable:	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
VARGold	**-2,641.34**	***	**-2,255.99**	***			**-2,321.40**	***
	(427.65)		(365.33)				(447.97)	
Int	**-0.01**		**-0.02**		**-0.04**		**-0.01**	
	(0.03)		(0.03)		(0.04)		(0.04)	
HighGold	**-0.62**	***	**-0.44**	***	**-0.50**	***	**-0.51**	***
	(0.07)		(0.07)		(0.08)		(0.08)	
Lev			**1.66**	***	**1.82**	***	**1.60**	***
			(0.37)		(0.38)		(0.37)	
GPR					**2.28E-03**	***	**1.65E-03**	***
					(5.86E-04)		(6.04E-04)	
EPU					**-8.40E-05**		**8.69E-04**	
					(4.83E-04)		(5.92E-04)	
Adj R	0.2574		0.2917		0.2752		0.2982	
Within R	0.1310		0.1712		0.1519		0.1788	
Firm Fixed effects	**Yes**		**Yes**		**Yes**		**Yes**	
SE Cluster	**Yes**		**Yes**		**Yes**		**Yes**	
Observations	**93,635**		**93,635**		**93,635**		**93,635**	
Firms	**37**		**37**		**37**		**37**	

	Dependent variable: Market beta gold miner							
Independent variable:	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
VARGold	**1,578.85**	***	**1,289.67**	***			**1,896.10**	***
	(205.94)		(206.26)				(250.93)	
Int	**-0.04**	*	**-0.03**		**-0.07**	***	**-0.09**	***
	(0.02)		(0.02)		(0.02)		(0.02)	
HighGold	**0.24**	***	**0.11**	**	**0.20**	***	**0.21**	***
	(0.07)		(0.05)		(0.06)		(0.06)	
Lev			**-1.25**	***	**-1.30**	***	**-1.12**	***
			(0.30)		(0.28)		(0.27)	
GPR					**-7.81E-04**	**	**-2.68E-04**	
					(3.33E-04)		(3.20E-04)	
EPU					**-1.81E-03**	***	**-2.59E-03**	***
					(3,49E-04)		(4,19E-04)	
Adj R	0.1550		0.1934		0.1980		0.2285	
Within R	0.0599		0.1027		0.1078		0.1417	
Firm Fixed effects	**Yes**		**Yes**		**Yes**		**Yes**	
SE Cluster	**Yes**		**Yes**		**Yes**		**Yes**	
Observations	**93,635**		**93,635**		**93,635**		**93,635**	
Firms	**37**		**37**		**37**		**37**	

Gold and Market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

High gold prices have the expected negative impact on gold exposure at the firm level and also at the portfolio level. In a period where the price of gold is 63 days above its rolling median, firms' gold exposure decreases by 0.51, or 25.82%, while market exposure increases by 0.21, or 49.49%. At the portfolio level, however, this effect is weaker and inconsistent. The results are similar to Faff & Hillier (2004) and Tufano (1998), who suggest that as the 'real option' goes further into the money, the elasticity to the underlying asset decreases. The effects of the gold price level on both gold and market exposure are strong and economically significant.

Table 10.

Time series gold beta regression

	Dependent variable: Gold beta Adj-HUI							
Independent variable:	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
Intercept	**2.75**	***	**1.52**	***	**1.12**	***	**1.35**	***
	(0.10)		(0.17)		(0.17)		(0.17)	
VARGold	**-2,420.70**	***	**-1,466.20**	***			**-1,613.80**	***
	(421.16)		(421.99)				(423.29)	
Int	**0.02**		**-0.08**	***	**-0.09**	***	**-0.06**	***
	(0.02)		(0.02)		(0.02)		(0.02)	
HighGold	**-0.71**	***	**-0.12**		**-0.14**		**-0.20**	**
	(0.07)		(0.08)		(0.09)		(0.09)	
Lev			**4.69**	***	**5.15**	***	**4.53**	***
			(0.45)		(0.45)		(0.46)	
GPR					**1.27E-03**	**	**7.07E-04**	
					(5.33E-04)		(4.99E-04)	
EPU					**3.64E-04**		**1.14E-03**	**
					(3.93E-04)		(4.45E-04)	
Observations	**6,778**		**6,778**		**6,778**		**6,778**	
R-squared	0.2627		0.3863		0.3715		0.3943	
Adj. R-squared	0.2623		0.3860		0.3711		0.3937	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Leverage has a consistently significant effect on the firm level and the portfolio level of gold and market betas. Gold exposure is shown to increase over time when leverage increases. Specifically, one standard deviation increase in average leverage increases gold beta by 0.39, or 18.96%. For market exposure, however, increased leverage within a firm or portfolio is associated with lower sensitivity to market returns. This contradicts the theory of Hamada (1972), which states that market exposure increases with higher financial leverage. One standard deviation increase in leverage is associated with a reduction of 0.25, or 55.08%, in market beta. Since the regressions include firm fixed effects, the estimates reflect within-firm variation over time. The model does not identify whether firms with higher leverage at a given point in time exhibit higher market exposure. However, the results show that, within firms, periods of higher leverage are associated with reduced market exposure.

Table 11.

Time series market beta regression

	Dependent variable: Market beta Adj-HUI							
Independent variable:	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
Intercept	**0.25**	***	**1.12**	***	**1.59**	***	**1.41**	***
	0.07		0.09		0.08		0.08	
VARGold	**1426.23**	***	**750.84**	***			**1288.60**	***
	225.89		183.14				204.81	
Int	**-0.05**	***	**0.02**		**-0.01**		**-0.04**	**
	0.01		0.02		0.02		0.02	
HighGold	**0.30**	***	**-0.12**	**	**-0.04**		**0.00**	
	0.04		0.06		0.06		0.06	
Lev			**-3.32**	***	**-3.41**	***	**-2.91**	***
			0.32		0.31		0.30	
GPR					**-6.99E-04**	***	**-2.50E-04**	
					(2.09E-04)		(2.11E-04)	
EPU					**-2.16E-03**	***	**-2.78E-03**	***
					(3.51E-04)		(3.88E-04)	
Observations	**6,778**		**6,778**		**6,778**		**6,778**	
R-squared	0.1778		0.3320		0.3760		0.4121	
Adj. R-squared	0.1774		0.3316		0.3756		0.4116	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** p < 0.01. ** p < 0.05. * p < 0.1.

Leverage, being based on quarterly debt-to-capital ratios, may capture the indirect effects of these sector-wide negative earnings due to persistent low gold prices. For both gold and market exposure, leverage acts as a proxy for broader financial or operational constraints within the gold mining industry. As shown in the descriptive statistics, Table 2, gold price is negatively correlated (-0.69) with leverage. So, during high gold prices, leverage is lower, as equity valuations increase. It is under these conditions that the 'strike price' is closest to the gold price, and the elasticity of the real option is highest, thus increasing gold exposure. This is consistent with the result that the gold beta increases during lower gold price environments. Under these circumstances, the real option may become more apparent. Which causes gold mining companies to act more as a call option, moving primarily based on the underlying asset and less on market movements. Thus, the relationship between leverage and gold and market exposure may not be entirely driven by leverage itself but rather by the underlying industry conditions that leverage reflects.

EPU and GPR effects on the portfolio's gold exposure are limited and shift across models 3 and 4. At the firm-level panel regression model, higher GPR was found to positively affect gold exposure, suggesting a different relationship than gold variance. A one-standard-deviation increase in GPR leads to a 0.08, or 3.98%, rise in gold exposure. For a portfolio of gold mining firms, GPR and EPU show inconsistent effects on gold. Market exposure of gold mining firms is strongly negatively affected by EPU both within individual firms and within a portfolio. Suggesting that gold mining firms have some hedging effect, due to gold's lower or negative correlation with the market, as mentioned by Creti et al. (2013). Confirming the hypothesis that during higher levels of uncertainty, the safe-haven effects of gold work through gold mining firms' exposure to the market. One standard deviation of EPU decreases the market exposure of a portfolio by 0.15, or 34.13%, similar to individual gold mining firms. Appendix Table 7 and Table 8 give robustness checks for both models based on single quarterly observations. GPR exhibits no economically significant effect on gold exposure, whereas EPU has a relationship with an economically meaningful impact in reducing market exposure of gold mining firms.

In summary, the regressions show that gold mining firms are dynamically exposed to both gold and market movements. The first regression demonstrated that gold mining firms and portfolios exhibit significant gold exposure, and while market exposure is lower, it is often still significant. It showed that portfolios that include non-producing gold firms, firms with more diversified operations, and portfolios that allow for more aggressive hedging policies have significantly lower gold exposure. Market exposure did not show to be affected across different portfolios. The real option return effect was also found to be strongly statistically significant across 18 firms and across the portfolios. The return asymmetry was significant across all periods, while market exposure was low and insignificant during the period between 1998 and 2007. The dynamic time-varying gold and market exposures were found to be affected by several variables. Gold variance had a strong negative relationship with gold exposure while increasing market exposure. Interest showed some mixed results across models but showed a decrease in market exposure at the firm and portfolio level, while the relationship with gold exposure was weak and economically insignificant. Gold price and leverage are shown to be correlated and have some shared effects. At the firm level, higher gold prices decrease gold exposure, while market exposure increases. At the portfolio level, market exposure showed weaker effects, while gold exposure remained statistically and economically significant. Leverage was found to increase gold exposure while decreasing market exposure, which was unexpected. This relationship is probably due to leverage containing information about lower sector-wide conditions, as leverage increases when gold prices are low. The effects of GPR and EPU on gold exposure are limited. However, EPU shows a reduction in the market exposure of gold mining firms both at the firm and portfolio level. An overview of hypotheses and outcomes is shown in Table 12.

Table 12.

Beta: **Variable:**	**Gold beta (Hypothesis)**	**Gold Beta (Results)**	**Market Beta (Hypothesis)**	**Market Beta (Results)**
VARGold	−	−	+	+
Int	−	−	−	−
HighGold	−	−	+	+ / n.s.
Lev	+	+	+	−
GPR	−	+	−	n.s..
EPU	−	n.s.	−	−

6. Conclusion & discussion

6.1 Conclusion

This research investigates a portfolio of low-hedged gold mining firms from January 1998 to December 2024, constructed by following the historical constituents of the HUI index. The resulting portfolio, Adj-HUI, includes only firms that both generate revenue and operate actual gold mines. The portfolio's gold and market exposure are compared to the HUI and GDM portfolios to assess if the selection criteria affect exposures similar to theory predictions. In addition, this study tests for the existence of a real option, which is theorized to be embedded in the operations of gold mining firms and is expected to show through stock return asymmetry. Finally, the gold and market exposures of the Adj-HUI portfolio are regressed on macroeconomic variables, uncertainty proxies, and capital structure to identify key drivers of time variation. Two models are employed to analyze the effects: A firm level beta panel regression, similar to Tufano (1998), applied to individual firms, and a single time-varying beta regression applied to the Adj-HUI portfolio.

The first test reveals that Adj-HUI has a higher gold beta than the HUI after December 2016 as a result of the inclusion of non-producing gold mining companies. GDM showed statistically lower gold exposure across the whole period due to the inclusion rules that allowed for more metal diversification and stronger hedging policies. Market exposure between the portfolios was not found to be statistically different. The real option is confirmed across multiple firms, across the three portfolios, and in each of the three sub-periods. This supports the hypothesis that the real option can be observed at daily stock price changes. This suggests that investors view mining companies as a call option on gold, where there is lower downside gold risk. Time variation in gold and market exposure of gold mining firms is observed, and several macroeconomic variables are found to be significant drivers. Gold variance has a strong negative effect on gold exposure while increasing market exposure. Interest rates show some mixed results, but there is some evidence for reducing market exposure. High gold prices are found to significantly reduce gold exposure while increasing market exposure, as hypothesized. Higher GPR has a small, statistically significant positive effect on gold exposure, an unexpected result, though economically irrelevant. The expectation of uncertainty, or implied volatility, did not affect a firm's gold exposure in the way that was hypothesized. EPU did show a negative relationship with market exposure, thus showing gold mining firms have a weak hedging property during increased EPU environments. The effect of time-varying leverage is interesting because it increases gold exposure while decreasing market exposure.

The decrease in market exposure is contrary to expectations, as increased leverage should increase market exposure. This effect, however, is a result of the information that higher leverage entails. High leverage could indicate prolonged low gold prices and companies postponing or reducing production, thus exercising the real option. It is under these conditions that gold mining companies will be highly exposed to gold while indifferent to market movements. Thus, increased leverage is associated with lower market exposure within this research period. The effects proved to be robust even with quarterly regressions.

In general, and based on this research, mining companies exhibit the real option embedded in their operations through return asymmetry, affecting gold exposure. As the real option becomes more valuable, more in the money, or because of higher gold variance, gold exposure decreases similar to Tufano (1998). This paper suggests that low gold prices result in gold mining companies acting more like a call option on gold, indifferent to market conditions, thus reducing market exposure. This effect is captured by both a gold price regime dummy and by leverage. It should be noted that this study does not prove that higher firm-level leverage decreases the market risk of a gold mining company, but the conditions this higher leverage represents are associated with a decrease in market risk.

6.2 Discussion

This research follows the historical constituents of the HUI index, which follows gold mining companies that have a relatively large market capitalization, are very liquid, and therefore might have a selection bias. These findings thus only apply to relatively large, low-hedged, U.S.-listed gold mining companies that operate revenue-generating gold mines. This research does not follow total returns or performance of these companies but explains how they are exposed to gold price changes and market fluctuations as a result of market-wide variables.

Furthermore, inclusion in the HUI does not imply the absence of hedging altogether. Short-term time-varying hedging policies may still influence a firm's gold exposure, as firms might adjust their hedge ratios in response to changes in gold price. In addition, it should be noted that this research assumes the correlation of gold and the market to be equal to or close to zero. However, correlation is a time-varying measure. This means that an increase in market exposure of physical gold could increase market exposure of gold mining companies. While this is expected to be limited, due to the general low correlation and market exposure between physical gold and the market. Within a regression, a temporary changing dynamic between gold and the market could wrongly attribute these effects to the explanatory variables. This effect is minimized, however, by estimating the gold and market betas in a single regression but could still be a factor.

Leverage reflects broader industry conditions and is negatively correlated with the high gold price dummy. This suggests that part of the effect of profitability, driven by gold price levels, may be captured through leverage. Both variables remain statistically significant in the firm-level panel regression, indicating that the model is, to some extent, able to separate the effects of gold and market exposure.

For future studies, this research could be extended to non-U.S. listed firms, smaller firms, or firms that hedge their production more strongly. However, this might introduce the need for beta adjustments and requires historical hedging metrics. Also, an improved stationary metric for gold price regimes, or a variable that represents the margins made by gold mining firms, might better capture the effect than the simple high gold price dummy. It could also be interesting to study how the correlation coefficients of the gold mining firms change over time due to macroeconomic variables. Lower beta does not automatically mean lower correlation and thus better diversification benefits. Future research might focus on this correlation coefficient to see when diversification benefits of gold mining companies are stronger.

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Appendix
Figure 1.

Adj-HUI Index Historical Constituents

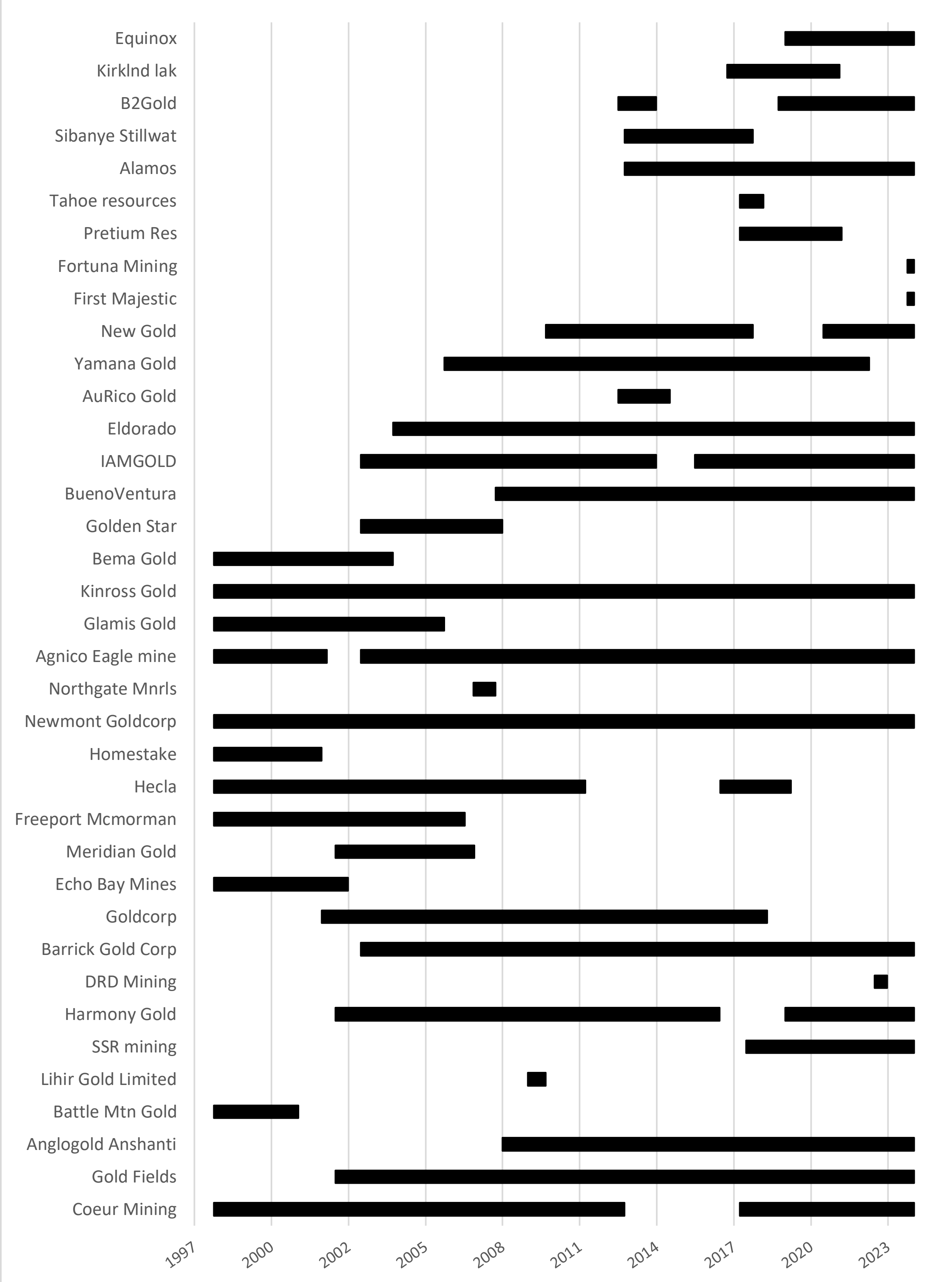

Figure 2.

Number of constituents Adj-HUI

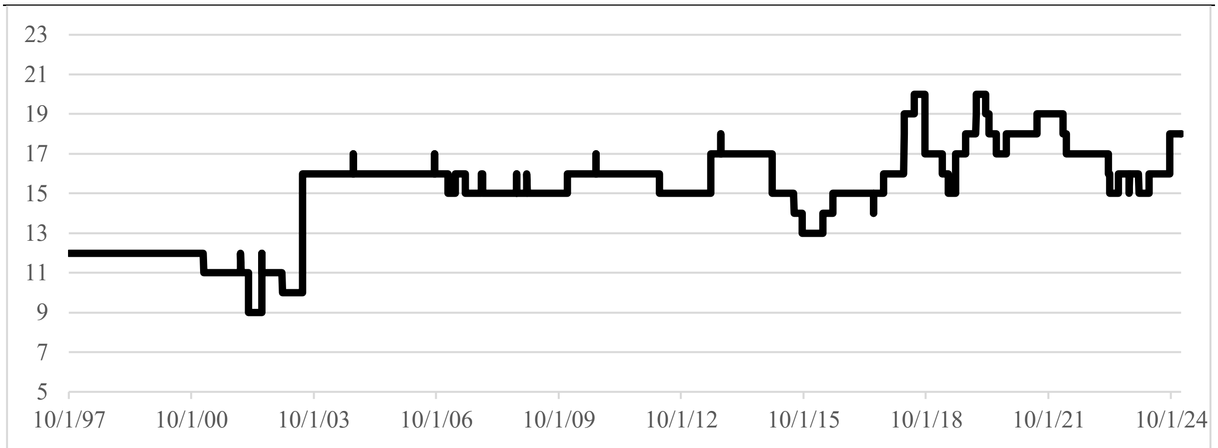

Table 1.

Descriptive statistics

Variable:	Min	1st_Q	Median	Mean	3rd_Q	Max	SD	NA
Gold_Variance	3.57 E-05	6.31 E-05	8.60 E-05	1.11 E-04	1.22 E-04	8.55 E-04	8.71 E-05	
Ten_yield	0.52	2.27	3.51	3.44	4.51	6.79	1.39	50
High Gold	0.00	0.02	0.49	0.47	0.90	1.00	0.50	62
Leverage	0.11	0.15	0.21	0.23	0.27	0.45	0.09	
GPR	9.49	75.39	99.93	112.76	134.13	1045.60	66.09	
EPU	3.32	56.77	87.76	108.60	136.16	1026.38	80.75	
Gold Beta (Adj-HUI)	0.75	1.53	1.84	2.03	2.39	5.27	0.72	62
Market Beta (Adj-HUI)	-1.28	0.20	0.47	0.46	0.72	1.97	0.46	62
Returns Gold	-0.09	-4.97 E-03	3.50 E-04	2.90 E-04	5.79 E-03	0.10	0.01	
Return Market	-0.13	-4.90 E-03	6.30 E-04	2.70 E-04	6.05 E-03	0.11	0.01	
Returns Adj-HUI	-0.18	-0.02	-6.80 E-04	1.00 E-05	0.02	0.25	0.03	

Table 2.

Gold & Market Betas (Firm based) & SE

Company	Market Beta		Gold Beta		Obs.
COEUR MINING INC	**0.80**	***	**2.05**	***	5,727
	(0.05)		(0.06)		
GOLD FIELDS LTD NEW	**0.51**	***	**1.84**	***	5,666
	(0.03)		(0.03)		
ANGLOGOLD ASHANTI LTD	**0.36**	***	**1.96**	***	4,030
	(0.03)		(0.04)		
BATTLE MOUNTAIN GOLD CO	**0.06**		**3.10**	***	826
	(0.12)		(0.16)		
LIHIR GOLD LTD	**0.88**	***	**1.33**	***	172
	(0.15)		(0.18)		
S S R MINING INC	**0.38**	***	**1.96**	***	1,644
	(0.06)		(0.08)		
HARMONY GOLD MINING CO LTD	**0.57**	***	**1.98**	***	5,030
	(0.03)		(0.04)		
DRD MINING	**0.69**	***	**2.41**	***	125
	(0.26)		(0.26)		
BARRICK GOLD CORP	**0.39**	***	**1.66**	***	5,417
	(0.02)		(0.02)		
GOLDCORP INC NEW	**0.45**	***	**1.78**	***	4,362
	(0.03)		(0.03)		
ECHO BAY MINES LTD	**-0.22**	**	**2.82**	***	1,313
	(0.10)		(0.16)		
MERIDIAN GOLD INC	**0.53**	***	**1.60**	***	1,363
	(0.06)		(0.06)		
FREEPORT MCMORAN INC	**0.66**	***	**1.05**	***	2,456
	(0.05)		(0.05)		
HECLA MINING CO	**0.76**	***	**2.14**	***	4,332
	(0.05)		(0.06)		
HOMESTAKE MINING CO	**-0.08**		**2.07**	***	1,057
	(0.07)		(0.10)		
NEWMONT CORP	**0.36**	***	**1.55**	***	6,855
	(0.02)		(0.02)		
NORTHGATE MINERALS CORP	**0.05**		**0.47**	***	216
	(0.17)		(0.15)		
AGNICO EAGLE MINES LTD	**0.35**	***	**1.86**	***	6,521
	(0.02)		(0.03)		
GLAMIS GOLD LTD	**0.03**		**1.91**	***	2,253
	(0.06)		(0.07)		
KINROSS GOLD CORP	**0.35**	***	**2.08**	***	6,853
	(0.03)		(0.04)		
BEMA GOLD CORP	**-0.21**	*	**2.64**	***	1,751
	(0.11)		(0.15)		
GOLDEN STAR RESOURCES LTD	**0.58**	***	**1.97**	***	1,385
	(0.09)		(0.09)		
COMPANIA DE MINAS BV SA	**0.66**	***	**1.53**	***	4,095
	(0.03)		(0.04)		
IAMGOLD CORP	**0.55**	***	**1.90**	***	5,043
	(0.03)		(0.04)		
ELDORADO GOLD CORP NEW	**0.54**	***	**1.95**	***	5,104
	(0.04)		(0.05)		
AURICO GOLD INC	**0.47**	***	**2.20**	***	510
	(0.17)		(0.12)		

Company	Market Beta		Gold Beta		Obs.
YAMANA GOLD INC	**0.53**	***	**2.08**	***	4,162
	(0.03)		(0.03)		
NEW GOLD INC	**0.70**	***	**2.16**	***	2,919
	(0.06)		(0.06)		
FIRST MAJESTIC SILVER CORP	**0.38**		**1.96**	***	68
	(0.47)		(0.35)		
FORTUNA MINING CORP	**0.66**		**1.68**	***	68
	(0.44)		(0.33)		
PRETIUM RESOURCES INC	**0.21**	***	**1.89**	***	1,000
	(0.07)		(0.11)		
TAHOE RESOURCES INC	**0.19**		**2.40**	***	233
	(0.23)		(0.39)		
ALAMOS GOLD INC NEW	**0.28**	***	**2.24**	***	2,836
	(0.04)		(0.05)		
SIBANYE STILLWATER LTD	**0.53**	***	**2.41**	***	1,259
	(0.12)		(0.11)		
B2GOLD CORP	**0.77**	***	**2.64**	***	377
	(0.23)		(0.15)		
KIRKLAND LAKE GOLD LTD	**0.23**	***	**1.94**	***	1,106
	(0.05)		(0.08)		
EQUINOX GOLD CORP	**0.48**	***	**2.04**	***	1,262
	(0.06)		(0.08)		

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 3.

Gold & Market Betas (Firm based) & SE

	Gold beta			Market beta		
	D	W	M	D	W	M
COEUR MINING INC	2.05	2.16	5.20	0.80	1.03	1.16
GOLD FIELDS LTD NEW	1.84	1.93	2.87	0.51	0.36	0.31
ANGLOGOLD ASHANTI LTD	1.96	2.21	2.80	0.36	0.39	0.41
BATTLE MOUNTAIN GOLD CO	3.10	2.97	4.58	0.06	-0.31	1.41
LIHIR GOLD LTD	1.33	1.75		0.88	1.21	
S S R MINING INC	1.96	1.99	2.53	0.38	0.27	0.59
HARMONY GOLD MINING CO LTD	1.98	2.05	2.91	0.57	0.46	0.20
DRD MINING	2.41			0.69		
BARRICK GOLD CORP	1.66	1.73	2.81	0.39	0.39	-0.33
GOLDCORP INC NEW	1.78	1.80	2.07	0.45	0.41	0.49
ECHO BAY MINES LTD	2.82	2.97	7.51	-0.22	-0.46	-1.82
MERIDIAN GOLD INC	1.60	1.60	3.03	0.53	0.57	1.40
FREEPORT MCMORAN INC	1.05	1.10	3.44	0.66	0.59	-0.60
HECLA MINING CO	2.14	1.96	4.04	0.76	0.72	-0.06
HOMESTAKE MINING CO	2.07	1.99		-0.08	-0.12	
NEWMONT CORP	1.55	1.51	2.17	0.36	0.31	-0.13
NORTHGATE MINERALS CORP	0.47	0.12		0.05	0.37	
AGNICO EAGLE MINES LTD	1.86	1.85	3.30	0.35	0.28	0.22
GLAMIS GOLD LTD	1.91	2.02	4.18	0.03	-0.11	0.23
KINROSS GOLD CORP	2.08	2.09	3.54	0.35	0.19	-0.34
BEMA GOLD CORP	2.64	2.74	9.07	-0.21	-0.42	1.82
GOLDEN STAR RESOURCES LTD	1.97	1.90		0.58	0.91	
COMPANIA DE MINAS BV SA	1.53	1.54	2.97	0.66	0.45	-0.52
IAMGOLD CORP	1.90	1.95	2.53	0.55	0.69	0.01
ELDORADO GOLD CORP NEW	1.95	1.89	2.57	0.54	0.82	-0.79
AURICO GOLD INC	2.20	2.27		0.47	0.51	
YAMANA GOLD INC	2.08	2.07	3.32	0.53	0.56	-0.57
NEW GOLD INC	2.16	2.02	2.22	0.70	0.85	-1.22
FIRST MAJESTIC SILVER CORP	1.96			0.38		
FORTUNA MINING CORP	1.68			0.66		
PRETIUM RESOURCES INC	1.89	1.85		0.21	0.14	
TAHOE RESOURCES INC	2.40	2.89		0.19	0.24	
ALAMOS GOLD INC NEW	2.24	2.30	3.48	0.28	0.29	-0.21
SIBANYE STILLWATER LTD	2.41	2.24		0.53	0.42	
B2GOLD CORP	2.64	2.11	2.80	0.77	0.57	0.34
KIRKLAND LAKE GOLD LTD	1.94	1.99		0.23	0.25	
EQUINOX GOLD CORP	2.04	2.10		0.48	0.68	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$. Missing values were a result of estimates with observations lower than 30.

Table 4.

Robustness check equal weighted Adj-HUI vs HUI portfolio

Variable	Period 1 (1998 – 2016)		Period 2 (2016 – 2024)		Period 2 (EW) (2016 – 2024)	
Intercept	**0.00**	**	**0.00**	***	**0.00**	**
	(0.00)		(0.00)		0.00	
Gold return	**1.85**	***	**1.97**	***	**2.10**	***
	(0.04)		(0.05)		0.06	
Market return	**0.41**	***	**0.35**	***	**0.38**	***
	(0.04)		(0.08)		0.09	
HUI	**0.00**		**0.00**		**0.00**	
	(0.00)		(0.00)		(0.00)	
GDM	**0.00**		**0.00**		**0.00**	
	(0.00)		(0.00)		(0.00)	
HUI * Gold return	**0.00**		**-0.07**	***	**-0.06**	**
	(0.02)		(0.02)		0.03	
GDM * Gold return	**-0.13**	***	**-0.36**	***	**-0.49**	***
	(0.03)		(0.04)		0.04	
HUI * Market return	**0.00**		**-0.01**		**-0.01**	
	(0.02)		(0.04)		0.05	
GDM * Market return	**0.03**		**-0.05**		**-0.08**	
	(0.02)		(0.05)		0.06	
Observations	**4,825**		**2,016**		**2,016**	
R-2	0.538		0.595		0.582	
Adj R-2	0.538		0.594		0.581	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 5.

Real Option (Firm based) & SE

Company Name	Market Beta		Gold Beta		Gold * D_Positive		Obs.
COEUR MINING INC	**0.81**	***	**1.69**	***	**0.16**		5727
	(0.05)		(0.12)		(0.17)		
GOLD FIELDS LTD NEW	**0.52**	***	**1.50**	***	**0.42**	***	5666
	(0.03)		(0.06)		(0.10)		
ANGLOGOLD ASHANTI LTD	**0.37**	***	**1.59**	***	**0.56**	***	4030
	(0.03)		(0.07)		(0.11)		
BATTLE MOUNTAIN GOLD CO	**0.08**		**2.67**	***	**0.48**		826
	(0.12)		(0.36)		(0.45)		
LIHIR GOLD LTD	**0.92**	***	**0.85**	**	**1.01**	*	172
	(0.15)		(0.37)		(0.55)		
S S R MINING INC	**0.38**	***	**1.68**	***	**0.37**		1644
	(0.06)		(0.16)		(0.24)		
HARMONY GOLD MINING CO LTD	**0.58**	***	**1.57**	***	**0.51**	***	5030
	(0.03)		(0.07)		(0.11)		
DRD MINING	**0.69**	***	**2.23**	***	**0.15**		125
	(0.26)		(0.66)		(0.81)		
BARRICK GOLD CORP	**0.40**	***	**1.47**	***	**0.32**	***	5417
	(0.02)		(0.04)		(0.06)		
GOLDCORP INC NEW	**0.46**	***	**1.46**	***	**0.48**	***	4362
	(0.03)		(0.06)		(0.09)		
ECHO BAY MINES LTD	**-0.20**	*	**2.28**	***	**0.60**		1313
	(0.11)		(0.34)		(0.44)		
MERIDIAN GOLD INC	**0.55**	***	**1.26**	***	**0.27**		1363
	(0.06)		(0.12)		(0.18)		
FREEPORT MCMORAN INC	**0.67**	***	**0.97**	***	**-0.04**		2456
	(0.05)		(0.10)		(0.14)		
HECLA MINING CO	**0.78**	***	**1.79**	***	**0.33**	**	4332
	(0.05)		(0.11)		(0.16)		
HOMESTAKE MINING CO	**-0.07**		**1.87**	***	**-0.13**		1,057
	(0.07)		(0.21)		(0.26)		
NEWMONT CORP	**0.36**	***	**1.28**	***	**0.35**	***	6,855
	(0.02)		(0.05)		(0.07)		
NORTHGATE MINERALS CORP	**0.04**		**0.64**	*	**-0.49**		216
	(0.17)		(0.34)		(0.45)		
AGNICO EAGLE MINES LTD	**0.35**	***	**1.56**	***	**0.34**	***	6,521
	(0.02)		(0.05)		(0.08)		
GLAMIS GOLD LTD	**0.06**		**1.24**	***	**0.76**	***	2,253
	(0.06)		(0.14)		(0.20)		
KINROSS GOLD CORP	**0.37**	***	**1.61**	***	**0.53**	***	6,853
	(0.03)		(0.07)		(0.10)		
BEMA GOLD CORP	**-0.19**	*	**2.03**	***	**0.97**	**	1,751
	(0.11)		(0.31)		(0.41)		
GOLDEN STAR RESOURCES LTD	**0.58**	***	**2.02**	***	**0.33**		1,385
	(0.09)		(0.17)		(0.25)		
COMPANIA DE MINAS BV SA	**0.66**	***	**1.29**	***	**0.32**	***	4,095
	(0.03)		(0.07)		(0.11)		
IAMGOLD CORP	**0.56**	***	**1.51**	***	**0.50**	***	5,043
	(0.03)		(0.07)		(0.10)		
ELDORADO GOLD CORP NEW	**0.55**	***	**1.60**	***	**0.38**	***	5,104
	(0.04)		(0.09)		(0.14)		
AURICO GOLD INC	**0.48**	***	**1.70**	***	**0.71**	**	510
	(0.17)		(0.23)		(0.34)		

Company Name	Market Beta		Gold Beta		Gold * D-Positive		Obs.
YAMANA GOLD INC	**0.54**	***	**1.72**	***	**0.39**	***	4,162
	(0.03)		(0.07)		(0.10)		
NEW GOLD INC	**0.71**	***	**1.59**	***	**0.67**	***	2,919
	(0.06)		(0.11)		(0.16)		
FIRST MAJESTIC SILVER CORP	**0.41**		**2.01**	***	**0.65**		68
	(0.48)		(0.63)		(1.17)		
FORTUNA MINING CORP	**0.64**		**1.38**	**	**0.98**		68
	(0.46)		(0.60)		(1.11)		
PRETIUM RESOURCES INC	**0.22**	***	**1.46**	***	**0.73**	**	1,000
	(0.07)		(0.20)		(0.30)		
TAHOE RESOURCES INC	**0.23**		**1.61**	*	**1.21**		233
	(0.23)		(0.88)		(1.20)		
ALAMOS GOLD INC NEW	**0.29**	***	**1.81**	***	**0.55**	***	2,836
	(0.04)		(0.11)		(0.16)		
SIBANYE STILLWATER LTD	**0.55**	***	**2.21**	***	**0.34**		1,259
	(0.12)		(0.23)		(0.32)		
B2GOLD CORP	**0.77**	***	**1.87**	***	**1.13**	***	377
	(0.23)		(0.29)		(0.42)		
KIRKLAND LAKE GOLD LTD	**0.23**	***	**1.66**	***	**0.68**	***	1,106
	(0.05)		(0.15)		(0.23)		
EQUINOX GOLD CORP	**0.48**	***	**1.36**	***	**1.11**	***	1,262
	(0.06)		(0.15)		(0.22)		

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 6.

Real Option (Portfolio based) complete regressions

Adj-HUI	Period							
Estimate	1998 - 2025		1998 - 2007		2007 - 2016		2016 - 2025	
(Intercept)	**0.00**	***	**-0.01**	***	**0.00**	***	**0.00**	***
	(0.00)		(0.00)		(0.00)		(0.00)	
Market_return	**0.40**	***	**0.09**		**0.66**	***	**0.36**	***
	(0.04)		(0.07)		(0.05)		(0.05)	
Gold_return	**1.53**	***	**1.40**	***	**1.48**	***	**1.81**	***
	(0.07)		(0.14)		(0.11)		(0.13)	
D_Positive	**0.00**	***	**0.01**	***	**0.00**	*	**0.00**	
	(0.00)		(0.00)		(0.00)		(0.00)	
Gold_return * D_Positive	**0.40**	***	**0.50**	**	**0.35**	**	**0.47**	***
	(0.11)		(0.22)		(0.14)		(0.17)	
Multiple R-squared:	0.5437		0.4502		0.6312		0.5999	
Adjusted R-squared:	0.5434		0.4492		0.6306		0.5992	

HUI	Period							
Estimate	1998 - 2025		1998 - 2007		2007 - 2016		2016 - 2025	
(Intercept)	**0.00**	***	**-0.01**	***	**0.00**	***	**0.00**	***
	(0.00)		(0.00)		(0.00)		(0.00)	
Market_return	**0.40**	***	**0.09**		**0.66**	***	**0.35**	***
	(0.04)		(0.07)		(0.05)		(0.05)	
Gold_return	**1.52**	***	**1.40**	***	**1.48**	***	**1.76**	***
	(0.07)		(0.14)		(0.11)		(0.13)	
D_Positive	**0.00**	***	**0.01**	***	**0.00**	*	**0.00**	
	(0.00)		(0.00)		(0.00)		(0.00)	
Gold_return * D_Positive	**0.39**	***	**0.50**	**	**0.35**	**	**0.46**	***
	(0.11)		(0.22)		(0.14)		(0.17)	
Multiple R-squared:	0.5433		0.4504		0.6312		0.5979	
Adjusted R-squared:	0.543		0.4494		0.6306		0.5972	

GDM	Period							
Estimate	1998 - 2025		1998-2007		2007-2016		2016-2025	
(Intercept)	**0.00**	***	**0.00**	***	**0.00**	***	**0.00**	**
	(0.00)		(0.00)		(0.00)		(0.00)	
Log_market_return	**0.40**	***	**0.14**	***	**0.65**	***	**0.32**	***
	(0.04)		(0.05)		(0.05)		(0.04)	
Log_gold_return	**1.42**	***	**1.29**	***	**1.42**	***	**1.54**	***
	(0.06)		(0.12)		(0.10)		(0.11)	
D_Positive	**0.00**	***	**0.01**	***	**0.00**		**0.00**	
	(0.00)		(0.00)		(0.00)		(0.00)	
Log_gold_return:D_Positive	**0.32**	***	**0.38**	**	**0.34**	**	**0.34**	**
	(0.09)		(0.18)		(0.13)		(0.13)	
Multiple R-squared:	0.5839		0.4945		0.6701		0.6245	
Adjusted R-squared:	0.5836		0.4936		0.6695		0.6239	
Observations	**6,776**		**2,254**		**2,263**		**2,259**	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 7.

Quarterly panel regression

Quarterly **Independent variable:**	**Dependent variable: Beta gold miner** Gold Beta		**Market Beta**	
VARGold	**-2,116.16**	**	**1,635.29**	***
	1,023.54		513.52	
Int	**-0.02**		**-0.09**	**
	0.06		0.04	
HighGold	**-0.40**	**	**0.20**	**
	0.15		0.10	
Lev	**1.62**	***	**-1.08**	***
	0.42		0.28	
GPR	**2.17E-03**	**	**-6.92E-04**	
	(1.07E-03)		(7.17E-04)	
EPU	**7.39E-04**		**-2.72E-03**	**
	(9.97E-04)		(8.36E-04)	
Adj R	0.302962		0.258734	
Within R	0.185417		0.174672	
Firm Fixed effects	**YES**		**YES**	
Cluster by firm & Date	**YES**		**YES**	
Observations	**1.532**		**1,532**	
Firms	**37**		**37**	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table 8.

Quarterly time series beta regression (Portfolio Level)

Quarterly	Dependent variable: Beta Adj-HUI			
Independent variable:	**Gold Beta**		**Market Beta**	
Intercept	**1.16**	**	**1.51**	***
	(0.45)		(0.19)	
VARGold	**-1,471.00**		**1,043.60**	**
	(1,194.90)		(505.04)	
Int	**-0.08**		**-0.02**	
	(0.06)		(0.05)	
HighGold	**-0.06**		**-0.05**	
	(0.24)		(0.14)	
Lev	**4.86**	***	**-3.12**	***
	(1.38)		0.79	
GPR	**1.56E-03**		**-6.80E-04**	
	(1.30E-03)		(6.46E-04)	
EPU	**8.32E-04**		**-2.65E-03**	**
	(1.08E-03)		(1.05E-03)	
Observations	**109**		**109**	
R	0.4124		0.4616	
Adjusted R	0.3779		0.43	

Gold and market beta are estimated based on log portfolio returns, log gold returns, and log market returns, respectively. Standard errors are in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Statement on the usage of AI Tools

In accordance with the MSc Finance policy on AI usage in written assignments, I confirm that AI tools were used only in a supportive capacity during the preparation of this thesis. AI tools were **not** used to generate content. All analysis, conclusions, and interpretations presented in this thesis are entirely my own work. Specifically, I used AI tools for the following purposes:

- Coding support: To assist with debugging R code used in the empirical analysis and offering suggestions for solving coding problems.
- Proofreading: To improve the spelling, grammar, and coherence of the written text.

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