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GEOPOLITICAL SUPPLY DISRUPTIONS AND INVENTORY RISK ACROSS CRITICAL MINERAL NETWORKS

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Abstract:

This analysis examines whether geopolitical conditions and material supply channels exhibit distinct associations with cobalt inventories, informing global debates on critical mineral security. Annual U.S. Geological Survey records and geopolitical risk indicators provide 10 observations spanning 2010 to 2019. Descriptive statistics and Pearson correlations assess inventory levels, while annual changes provide an exploratory sensitivity comparison. Stocks increased by 32.89 percent across the observation endpoints but peaked in 2014. Global geopolitical risk and threats correlate positively with stocks at 0.680 and 0.645, respectively, whereas geopolitical acts exhibit a weaker correlation of 0.111. Secondary production correlates positively with stock levels but negatively with annual changes; net imports display negative associations under both representations. These patterns are compatible with precautionary accumulation and consumption driven replenishment, without identifying either mechanism causally. The contribution is to distinguish inventory accumulation from supply expansion and separate geopolitical expectations from reported acts. The findings qualify uniform interpretations of precautionary stockholding and support monitoring accessible inventories alongside consumption, processing requirements and replenishment channels.

Key Words: Critical Minerals; Cobalt Inventories; Geopolitical Risk; Secondary Production

1. Introduction:

Critical mineral security depends on whether material remains available when industrial users need it, not merely on whether production and trade continue. Cobalt illustrates this distinction because mining, processing, recovery and consumption occur within interconnected supply systems. Geographical concentration, limited substitution and dependence on associated mineral production can constrain responses to shortages. Graedel et al. (2015) distinguish supply risk from vulnerability to supply restrictions, while Nassar et al. (2015) explain why byproduct metal supplies may respond weakly to changes in their own demand. Together, these perspectives establish the importance of examining inventories alongside material flows. Inventories connect uncertain replenishment with continuing industrial requirements. Their accumulation can reflect precautionary purchases, stronger material availability or weaker consumption. Their depletion can reflect interrupted deliveries, increased industrial use or deliberate reductions in holdings. Consequently, neither larger stocks nor greater imports independently establish improved supply security. Wen (2011) develops an inventory framework based on stockout avoidance, showing how the value of holding material depends on production and demand conditions. This logic makes inventory position an outcome of adjustment across several supply channels rather than a direct measure of disruption severity.

Geopolitical conditions introduce competing incentives. Anticipated restrictions may encourage purchasers to acquire material before availability deteriorates. Realized interruptions may instead prevent replenishment and require withdrawals from existing stocks. The observed relationship therefore depends on the distinction between expectations and physical constraints. Financial capacity also matters because a preference for larger buffers does not ensure that purchasers can finance them. Caglayan et al. (2012) examine inventory investment through the combined roles of sales uncertainty and financial strength. Their findings motivate treating precautionary accumulation as a conditional mechanism rather than assuming that uncertainty consistently increases inventories. Domestic production and external trade provide additional adjustment channels, but their implications depend on material form and destination. Primary output may require processing elsewhere, while secondary production depends on recoverable feedstock and processing capacity. Imports can replenish inventories or satisfy immediate consumption, and exports can offset domestic additions. Gulley et al. (2018) show how mineral import reliance connects industrial development with exposure to foreign supply. Gulley et al. (2019) further demonstrate that ownership of overseas cobalt production can alter the interpretation of supply dependence. These findings caution against treating aggregate production and trade volumes as equivalent measures of accessible material.

Research on production networks establishes why these distinctions matter beyond mineral markets. Barrot and Sauvagnat (2016) identify input specificity as an important determinant of shock

propagation between suppliers and customers. Boehm et al. (2019) provide evidence that disruptions to imported inputs can transmit production losses across national boundaries. However, those findings concern identifiable supply relationships and disruption events. They do not establish whether annual aggregate inventories move similarly with geopolitical threats, geopolitical acts, recovered material and net imports. The reviewed evidence therefore motivates a bounded question about inventory adjustment rather than an assumption that aggregate supply indicators reveal a common mechanism. This analysis addresses that question through the U.S. cobalt system during 2010 to 2019. The empirical setting permits consistent examination of recorded stocks, reported consumption, domestic secondary production and external trade within one national statistical framework. The dataset combines 10 annual mineral observations with geopolitical indicators aggregated from monthly records. Recorded inventories comprise industry holdings and LME stocks in U.S. warehouses. This definition provides an observable outcome while requiring a distinction between aggregate holdings and material accessible to individual industrial users.

This study aims to examine how U.S. cobalt inventory position varies with geopolitical conditions, domestic production and external trade during 2010 to 2019. The research question asks: How do these supply dimensions relate to recorded cobalt stocks, and how do the observed relationships change when annual levels are compared with annual changes? The specific objectives are to distinguish the inventory associations of geopolitical risk, threats and acts; examine the relationship between secondary production and inventories; and assess whether greater net imports coincide with larger stock holdings. Financing and replenishment conditions inform the theoretical interpretation but are not estimated as moderators. The completed analysis contributes a transparent comparison of these relationships using observed stock levels and alternative inventory measures. It identifies positive descriptive associations for geopolitical risk and threats, a weaker association for geopolitical acts, and a production relationship that changes sign between levels and annual changes. Net imports display negative unadjusted associations with inventories. These patterns qualify the expectation that supplies expansion and inventory accumulation necessarily coincide. The contribution is descriptive rather than causal: it separates patterns that require different explanations and identifies the measurements needed to investigate them. Its international relevance lies in distinguishing expected disruption, material inflows and inventory availability without treating evidence from one national system as representative of global mineral networks.

2. Theory, Conceptual Framework and Hypotheses Development:

This analysis draws on precautionary inventory theory and mineral supply dependence to explain how geopolitical conditions, domestic production and external trade relate to U.S. cobalt inventory position during 2010 to 2019. Inventories connect material acquisition with industrial consumption. Holding stocks can protect production against shortages, but it also commits financial resources and exposes holders to storage costs and price changes. Wen, 2011, develops the theoretical foundation for inventory holdings motivated by stockout avoidance. This perspective implies that observed stocks reflect both expected supply conditions and the ability to obtain and finance material. Cobalt operates within an interconnected system of mining, processing, recycling, trade and industrial use. Supply constraints at one stage can affect material availability elsewhere, although the transmission depends on processing capacity and access to substitutes. Graedel et al., 2015, distinguish supply risk from vulnerability to supply restrictions. This distinction matters because greater exposure does not necessarily produce lower observed inventories. Exposure may encourage precautionary accumulation before a disruption, while an interruption that has already occurred may force stock depletion.

The focal explanatory construct is cobalt supply conditions, represented by geopolitical conditions, domestic production and external trade. The outcome is cobalt inventory position. Recorded year end stocks provide the primary outcome, while annual stock changes, stock growth and ratios to reported consumption and imports provide alternative descriptions. These measures are related transformations of stock holdings rather than independent dimensions of a latent construct. The framework therefore develops expectations for recorded stocks without assuming that every alternative indicator must exhibit the same relationship. Geopolitical conditions comprise global geopolitical risk, geopolitical threats and geopolitical acts. The proposed mechanism operates through expectations about future availability. When purchasers anticipate delays, restrictions or higher acquisition costs, they may bring purchases forward and retain larger buffers. This precautionary response requires continued access to material. Where an interruption prevents replenishment, inventories may instead decline as consumption continues.

Financial capacity creates another boundary condition. An incentive to accumulate stocks does not ensure that purchasers can finance additional holdings. Caglayan et al., 2012, examine inventory investment in relation to sales uncertainty and financial strength. Their analysis supports treating financing conditions as relevant to inventory adjustment, rather than assuming that uncertainty produces a uniform response. Here, financing remains an unmeasured boundary condition because the country aggregate data do not identify the financial positions of individual stockholders. The theoretical expectation is consequently conditional. Geopolitical uncertainty may increase desired inventories, whereas realized supply interruptions can reduce available stocks. Global news indicators cannot distinguish these mechanisms specifically for cobalt. The positive expectation below concerns

precautionary accumulation when replenishment remains possible, not an established effect of geopolitical disruption.

H1: Higher Geopolitical Risk is Associated With Greater U.S. Year-End Cobalt Stocks When Replenishment Remains Available and Financing Constraints Do Not Prevent Precautionary Accumulation

Domestic production comprises primary production, secondary production and their combined volume. Its inventory relevance depends on whether additional output becomes available to domestic users. Production within national borders does not automatically increase domestic stock holdings if material requires processing abroad or is committed to external purchasers. Accordingly, the framework distinguishes recorded production from material available for domestic replenishment. Primary and secondary production also face different constraints. Mine output depends on extraction conditions, processing arrangements and the economics of associated minerals. Nassar et al., 2015, explain that byproduct metal supplies may respond weakly to changes in their own demand because production depends partly on host metals. Secondary production offers a different replenishment channel through recovered material, although its availability depends on scrap collection, recovery capacity and suitable feedstock. The inventory expectation is strongest for secondary material that enters domestic supply. Additional recovered cobalt can support stock accumulation when consumption and net external supply remain stable. However, substitution between recovered and imported material could leave stocks unchanged. The framework therefore treats secondary production as the clearest feasible indicator for the domestic production hypothesis. Combined production remains a descriptive aggregate and should not enter a model alongside both constituent series because their relationship is algebraic.

H2: Higher Domestic Secondary Cobalt Production is Associated With Greater U.S. Year End Cobalt Stocks When Reported Consumption and Net External Supply Remain Stable

External trade comprises imports, exports and net imports. Imports provide a replenishment channel, while exports remove material from the domestic system. Net imports capture the balance between these flows. Greater net inflows can support inventory accumulation when they exceed immediate industrial requirements, but they may also reflect stronger consumption without increasing year end holdings. Trade dependence introduces a competing mechanism. Imported material can replenish inventories while increasing exposure to external suppliers and processing systems. Gulley et al., 2018, examine mineral import reliance and foreign supply risk, demonstrating why trade access and supply vulnerability must be distinguished. An increase in imports therefore cannot, by itself, establish either improved supply security or greater inventory risk. Ownership and processing arrangements further condition the relationship between trade and available supply. Gulley et al., 2019, show that foreign ownership can alter exposure within cobalt supply chains. Aggregate imports and exports do not reveal these arrangements. Nevertheless, the material balance logic supports a positive conditional association between net imports and stock holdings. This expectation concerns replenishment rather than an independently identified causal effect. The stocks to imports ratio requires separate interpretation because imports also appear in its denominator.

H3: Higher Net Cobalt Imports are Associated With Greater U.S. Year-End Cobalt Stocks When Reported Consumption and Domestic Secondary Production Remain Stable

The conceptual framework connects geopolitical conditions, domestic production and external trade to cobalt inventory position through expectations, replenishment and material availability. These links represent theoretical associations rather than identified causal effects. Geopolitical conditions influence desired holdings, while production and trade constrain the material available to satisfy those preferences. Inventory decisions may also influence subsequent production and imports, creating feedback that the available descriptive data cannot resolve. The hypotheses remain theoretical propositions. They were formulated after inspection of source coverage and descriptive summaries and are not presented as preregistered tests. The 10 annual observations support descriptive assessment but do not establish the conditions required for confirmatory estimation of all three relationships. Unsupported, inconclusive or opposing patterns remain admissible outcomes.

3. Data:

3.1 Data Sources, Population, and Sample:

This analysis combines annual U.S. cobalt statistics with geopolitical risk indicators for 2010 to 2019. The observation unit is the U.S. cobalt system in a calendar year. The resulting dataset contains one country and mineral unit observed over 10 years. The mineral data originate from the U.S. Geological Survey cobalt workbook within Historical Statistics for Mineral and Material Commodities in the United States. Its public domain designation permits reuse. The extraction retained stocks, reported consumption, production, imports and exports for the requested period. The geopolitical data originate from the Caldara and Iacoviello workbook retrieved on October 22, 2019. The extraction retained the global geopolitical risk index and its threats and acts components. Each annual value represents the arithmetic mean of 12 monthly observations. These indicators measure geopolitical news intensity rather than directly observed interruptions to mineral supply. Cobalt provides a relevant setting because mineral criticality involves supply restrictions, production concentration and substitution constraints, as explained by Graedel et al., 2015. Production relationships also matter because supplies of byproduct

metals may respond differently from those of primary products, according to Nassar et al., 2015. These considerations justify examining cobalt but do not establish the representativeness of U.S. observations.

The intended population comprises country and mineral supply systems participating in critical mineral networks during 2010 to 2019. Its total size remains unverified because the manuscript does not define a historical mineral classification or comparable inventory reporting requirements. The assembled accessible frame contains one unit, U.S. cobalt, selected purposively for descriptive analysis. All requested years were retained regardless of their stock levels or geopolitical conditions. No observation was excluded to influence an estimated relationship. The selection rules preceded regression estimation, which was not undertaken, but were not registered before source inspection.

Table 1: Sample construction

Stage	Units	Observations	Selection rule
Retrieved cobalt workbook	1	122 annual records	Source coverage from 1900 through 2019
Excluded records	0 units removed	112 annual records	Years outside 2010 to 2019
Retained mineral sample	1	10 annual records	All requested years retained
Retained global geopolitical series	1 global series	120 monthly records	January 2010 through December 2019
Annual geopolitical aggregation	1 global series	10 annual records	Twelve monthly values per year
Merged descriptive sample	1	10 annual records	Unique calendar year match
Regression estimation	Not applicable	Not estimated	Available design supports descriptive analysis

The analytical structure is a complete annual time series within the selected window, rather than a multiunit panel. The sample supports examination of U.S. cobalt stocks and geopolitical context. It does not represent global critical mineral networks.

3.2 Data Preparation, Measurement, and Descriptive Statistics:

The original mineral workbook was preserved separately from the cleaned dataset. Each retained record received the country identifier USA, the commodity identifier cobalt and its calendar observation year. The combination uniquely identifies all 10 records. The geopolitical extraction preserved monthly dates and source variable names. Annual aggregation followed confirmation that each year contained 12 monthly observations. A one-to-one merge on calendar year retained all 10 annual mineral records without unmatched years or duplicate keys. Stocks, reported consumption, production, imports, exports and the selected geopolitical indicators have complete coverage across the study period. Mine shipments contain six unavailable values from 2014 through 2019. These remain missing and do not affect the descriptive stock calculations.

No interpolation, imputation, trimming or winsorization was applied. Genuine production zeros were retained. The negative government shipment value in 2010 was preserved because the source documentation identifies it as an inventory adjustment. No author currency conversion or inflation adjustment was performed. Recorded stocks comprise industry holdings and LME holdings in U.S. warehouses. They do not represent worldwide cobalt inventories. The analysis uses reported consumption to scale stocks because the provider changes its treatment of domestic production in apparent consumption from 2014. Nevertheless, the coverage of reported consumption does not match every stockholder included in the inventory series.

Table 2: Variable definitions and measurement

Variable	Analytical role	Definition	Source identifier	Unit and frequency
Stocks	Descriptive outcome	Calendar year end industry stocks plus LME stocks in U.S. warehouses	USGS column H	Metric tons of cobalt content, annual
Reported consumption	Scaling measure	Reported industrial consumption including secondary material	USGS column I	Metric tons of cobalt content, annual
Stock ratio	Alternative descriptive outcome	Stocks divided by reported consumption	Author calculation	Dimensionless ratio, annual
GPR	Contextual predictor	Annual mean of global geopolitical risk	GPR	Index, annual average
GPRT	Alternative contextual predictor	Annual mean of geopolitical threats	GPRT	Index, annual average

Variable	Analytical role	Definition	Source identifier	Unit and frequency
GPRA	Alternative contextual predictor	Annual mean of geopolitical acts	GPRA	Index, annual average
Imports	Supply context	Covered cobalt imports for consumption	USGS column F	Metric tons of cobalt content, annual
Exports	Supply context	Estimated cobalt content of covered exports	USGS column G	Metric tons of cobalt content, annual
Primary production	Supply context	Domestic recoverable cobalt mine production	USGS column B	Metric tons of cobalt content, annual
Moderator and interaction	Not implemented	No supported measure assembled	None	Not applicable

The primary outcome is the provider's recorded stock level. The alternative descriptive outcome is calculated as:

$$R_t = \frac{S_t}{C_t}$$

In Equation 1, $R_t$denotes the stock ratio in year t,S_t denotes recorded stocks and $C_t$denotes annual reported consumption. Both underlying variables use metric tons of cobalt content. All denominators are positive. The ratio is neither a percentage nor a direct measure of inventory coverage time.
The annual geopolitical measures are calculated as:

$$\overline{G}_t = \frac{1}{12}\sum_{m=1}^{12} G_{tm}$$

In Equation 2, $\overline{G}_t$denotes the annual mean of the selected geopolitical indicator, G_{tm}denotes its monthly value and m indexes the 12 observed months. The global indices use the provider's reference period of 1985 through 2019, with a mean of 100.

Table 3: Descriptive statistics

Variable	N	Mean	Standard deviation	Median	Minimum	Maximum
Stocks, metric tons	10	1,151.30	136.62	1,170.00	903.00	1,420.00
Reported consumption, metric tons	10	8,828.00	415.13	8,920.00	8,130.00	9,290.00
Stock ratio	10	0.130430	0.014836	0.128420	0.111070	0.164162
GPR	10	94.057779	9.441483	94.749580	81.475234	107.377312
GPRT	10	98.269847	16.518383	96.142751	81.107888	122.847758
GPRA	10	87.976562	17.510433	86.494233	60.595252	114.015223
Imports, metric tons	10	11,640.00	1,052.19	11,350.00	10,400.00	13,900.00
Exports, metric tons	10	4,281.00	1,231.53	3,965.00	2,640.00	6,980.00

No composite index, latent construct, moderator or interaction term was constructed. Factor analysis, composite reliability and average variance extracted were therefore not applicable. Measurement checks instead addressed definitions, coverage, unique keys, aggregation and denominator consistency.

3.3 Analytical Approach, Identification, and Reproducibility:

The completed analysis is descriptive. It characterizes recorded cobalt stocks, their scale relative to reported consumption and the geopolitical conditions observed during 2010 to 2019. Observation counts, means, sample standard deviations, medians and ranges summarize the retained records. No baseline regression was fitted. Ten annual observations from one country and mineral unit do not provide adequate support for a specification containing network exposure, moderation and several controls. A model using one annual lag would retain at most nine observations without additional baseline data.

Entity fixed effects were not estimated because the sample contains one unit. Unrestricted annual fixed effects would absorb all variation in a series containing one observation per year. Clustered standard errors were not calculated because multiple independent entity clusters are absent. Cameron and Miller, 2015, explain that clustered inference depends on the actual grouping and dependence structure of the observations. The available records cannot separate geopolitical influences from demand changes, prices, production adjustments, policy responses or precautionary inventory accumulation. Annual geopolitical averages may also conceal the timing of specific interruptions. Consequently, the analysis reports no causal effects, inferential significance claims or predictive performance results.

Both sources contain revised historical information. The dataset therefore cannot establish what decision makers knew during each observation year. Its use supports retrospective description rather than a real time prediction exercise. The reproduction materials preserve the original USGS workbook, cleaned numerical extracts, source identifiers, missingness checks, variable definitions and extraction code. The geopolitical download route and source hash document the retrieved snapshot. Later downloads may

contain revisions and should be checked against the archived metadata. The verified data support a descriptive U.S. cobalt analysis. Extending the research to global mineral networks requires a historically justified mineral frame, comparable inventories across additional units, bilateral trade records and independently documented supply interruptions.

4. Methods:

4.1 Research Design and Measurement Alignment

This analysis adopts a retrospective descriptive design to examine how U.S. cobalt inventory position relates to geopolitical conditions, domestic secondary production and external trade during 2010 to 2019. The observation unit is the U.S. cobalt system in a calendar year. The analytical sample contains 10 annual observations, with variation arising from changes in recorded inventories and supply indicators. The analytical target is the direction and magnitude of linear association within the observed period. Pearson correlations provide a scale independent description of relationships between numerical variables. Their interpretation follows the distinction between association and causation emphasized by Schober et al. (2018). Coefficients are reported numerically rather than classified through universal thresholds for weak, moderate or strong relationships, consistent with Akoglu (2018).

Recorded year end stocks constitute the primary outcome. The stocks to reported consumption ratio defined in Equation 1 provides a complementary measure of inventory scale. Geopolitical indicators follow the annual aggregation procedure defined in Equation 2. Domestic secondary production represents recovered cobalt supply, while net imports measure the difference between recorded imports and exports. The sample construction table and variable dictionary document eligibility, source identifiers, units and coverage. The analysis preserves distinctions between year-end holdings, annual material flows and annual averages of monthly indices. Interpretation remains specific to the observed U.S. cobalt series.

4.2 Data Processing and Analytical Specification:

Data preparation proceeded from the cleaned mineral and geopolitical extracts. Mineral records were restricted to 2010 through 2019 and identified by country, commodity and calendar year. Monthly geopolitical records were grouped by year after confirming the availability of 12 observations for each annual average. The annual datasets were merged one to one on calendar year, producing 10 matched records with unique observation keys. The analysis calculated counts, means, sample standard deviations, medians, minima and maxima. Sample standard deviations use the number of observations less one as the denominator. Calculations retain source precision, while presentation tables round values to support interpretation.

The primary association measure is the Pearson correlation:

$$r_{SX} = \frac{\sum_{t=1}^{n}[S_t - \bar{S}]\,[X_t - \bar{X}]}{\sqrt{\sum_{t=1}^{n}[S_t - \bar{S}]^2 \sum_{t=1}^{n}[X_t - \bar{X}]^2}}$$

In Equation 3, r_{SX} denotes the sample correlation between stocks and a selected supply indicator. S_t denotes recorded cobalt stocks in year t, X_t denotes the supply indicator, $\bar{S}$ and $\bar{X}$ denote their respective sample means, and \(n\) denotes the number of complete annual pairs. Each correlation in levels uses 10 observations. The coefficient describes the direction and magnitude of linear covariation within that sample, following Schober et al. (2018). The explanatory series comprise global geopolitical risk, geopolitical threats, geopolitical acts, domestic secondary production and net imports. Each series was assessed separately against recorded stocks. This specification preserves the distinctions between the three geopolitical measures and avoids combining indicators with different substantive meanings.

Annual stock movements and changes in supply conditions were calculated as:

$$\Delta Z_t = Z_t - Z_{t-1}$$

In Equation 4, Z_t denotes the selected variable in year t, Z_{t-1} denotes its preceding annual value, and ΔZ_t denotes the annual change. Equation 3 was then applied to paired changes in stocks and each explanatory series. These calculations contain nine observations covering annual movements from 2011 through 2019. Annual stock growth equals the stock change divided by the preceding year's stock level, multiplied by 100. The stocks to imports ratio equals recorded year end holdings divided by annual imports. All denominators used in these calculations are positive. Ratios remain dimensionless, whereas growth rates are expressed as percentages.

Implementation used Python 3.12.14, pandas 2.2.3 and NumPy 2.3.5. The tabular processing approach follows the data structures described by McKinney (2010), while numerical operations use the array framework described by van der Walt et al. (2011). Workbook access used openpyxl 3.1.5 for the mineral file and xlrd 2.0.1 for the geopolitical file. Correlations were calculated using the pandas Pearson correlation method.

4.3 Quality Assessment, Sensitivity and Reproducibility:

Quality assessment examined annual coverage, observation key uniqueness, monthly completeness, missing values and denominator availability. Stocks and the selected supply indicators contain complete observations throughout the analytical window. Every annual geopolitical average incorporates 12 monthly values. The annual merge retained the expected number of records without unmatched years or duplicate keys. Source definitions were examined before interpreting calculated measures. Recorded stocks include industry holdings and LME stocks in U.S. warehouses, while consumption and trade represent annual flows with their own reporting boundaries. These distinctions

inform the interpretation of inventory ratios and prevent treating aggregate holdings as directly equivalent to material available to every industrial user.

Source observations were preserved, including genuine production zeros and documented inventory adjustments. Original files remain separate from cleaned extracts, and author calculations are identified independently from provider values. Annual transformations were constructed after records had been sorted chronologically. The sensitivity assessment compares correlations calculated from annual levels with correlations calculated from annual changes. This comparison examines whether observed relationships depend on the representation of the series. Direction and magnitude are evaluated together, consistent with Akoglu's (2018) emphasis on explicit coefficient interpretation. The level calculations contain 10 observations, while the change calculations contain nine; the comparison therefore reflects both transformation and the associated difference in observation coverage.

The hypotheses guide interpretation of the descriptive relationships. Their conditional mechanisms remain distinct from the unadjusted correlations reported in the findings. Coefficients characterize the observed sample and provide a basis for assessing directional consistency without extending the calculations into claims about causal effects. Replication documentation includes source identifiers, the variable dictionary, cleaned numerical extracts, missingness summaries and construction code. Source hashes identify the retrieved workbooks, allowing later users to distinguish the archived inputs from revised downloads. This separation of inputs, transformations and outputs follows Peng's (2011) emphasis on making computational procedures available for verification. The resulting workflow permits independent reconstruction of the sample, derived indicators and descriptive calculations.

5. Findings:

This analysis examines U.S. cobalt inventory position in relation to geopolitical conditions, domestic secondary production and external trade during 2010 to 2019. The evidence comprises annual stock patterns, alternative inventory indicators and exploratory associations. These results describe the available sample without establishing causal effects or validating the proposed hypotheses.

5.1 Sample Characteristics and Inventory Position:

The analytical sample contains one country and mineral unit observed over 10 calendar years. Stocks, reported consumption, imports, exports, secondary production and the selected geopolitical indicators have complete annual coverage. Annual stock changes and growth rates contain nine observations because their calculation requires a preceding year within the analytical window. Recorded inventories include industry stocks and LME holdings in U.S. warehouses. They do not measure worldwide cobalt inventories or the probability of a stockout. The alternative ratios describe stocks relative to reported consumption and imports, whose reporting coverage differs from that of inventory holders.

Table 4: Annual U.S. cobalt inventory position

Year	Stocks, Metric Tons	Annual Stock Change, Metric Tons	Annual Stock Growth, Percent	Stocks to Reported Consumption	Stocks to Imports
2010	903	Not calculated	Not calculated	0.111070	0.081351
2011	1,080	177	19.601	0.117647	0.101887
2012	1,030	−50	−4.630	0.117984	0.092793
2013	1,110	80	7.767	0.135863	0.106731
2014	1,420	310	27.928	0.164162	0.125664
2015	1,240	−180	−12.676	0.140430	0.108772
2016	1,160	−80	−6.452	0.128746	0.090625
2017	1,180	20	1.724	0.127706	0.099160
2018	1,190	10	0.847	0.128095	0.100000
2019	1,200	10	0.840	0.132597	0.086331

Stocks increased from 903 metric tons in 2010 to 1,200 metric tons in 2019, an increase of 297 metric tons or 32.89 percent. Reported consumption increased by 11.32 percent across the same endpoints. Consequently, the stocks to reported consumption ratio rose from 0.111070 to 0.132597. Inventory growth therefore exceeded consumption growth over the full observation window, although the reporting differences prevent interpreting these ratios as literal inventory coverage time. The trajectory was not continuously upward. Stocks peaked at 1,420 metric tons in 2014, following the largest annual increase of 310 metric tons. They subsequently declined by 180 metric tons in 2015 and 80 metric tons in 2016. The recovery to 1,200 metric tons by 2019 left stocks 15.49 percent below their peak. These movements establish variation in recorded holdings rather than variation in supply security. Graedel et al., 2015, distinguish supply risk from vulnerability to restrictions, which prevents interpreting a larger inventory alone as evidence of lower mineral criticality.

5.2 Exploratory Associations with Supply Conditions:

The association analysis uses Pearson correlations between stock levels and individual supply indicators. A separate calculation correlates their annual changes to examine sensitivity to the

measurement scale. These calculations are exploratory, use different sample sizes and do not constitute adjusted hypothesis tests.

Table 5: Exploratory correlations with U.S. cobalt stocks

Supply Indicator	Correlation Between Annual Levels	Annual Pairs	Correlation Between Annual Changes	Change Pairs
Global geopolitical risk	0.680	10	0.584	9
Geopolitical threats	0.645	10	0.602	9
Geopolitical acts	0.111	10	0.080	9
Domestic secondary production	0.435	10	−0.328	9
Net cobalt imports	−0.212	10	−0.198	9

Global geopolitical risk and geopolitical threats exhibit positive correlations with stock levels. Their correlations with annual stock changes also remain positive. Geopolitical acts show considerably weaker correlations under both representations. The geopolitical measures therefore do not display an interchangeable relationship with inventories. The positive risk and threats patterns are compatible with precautionary stockholding, but compatibility does not identify the mechanism. Wen, 2011, provides a theoretical basis for holding inventories to avoid stockouts. The available observations cannot establish whether expectations motivated the recorded purchases, whether financing permitted precautionary accumulation or whether unrelated demand conditions generated the association.

Secondary production has a positive correlation with stock levels but a negative correlation with annual stock changes. Its relationship with inventories therefore changes sign across the two representations. Secondary production remains at 2,750 metric tons from 2015 through 2019, limiting variation within half of the sample. In 2015, secondary production increased while recorded stocks declined. Production growth alone consequently does not explain inventory accumulation. This result does not demonstrate that secondary production reduces inventories. Consumption, imports, exports and the timing of material recovery can offset additional production. Caglayan et al., 2012, identify financial strength as relevant to inventory investment under uncertainty, reinforcing the need to distinguish replenishment capacity from the resources available to hold stocks.

Net imports have negative correlations with both stock levels and annual stock changes. The observed pattern does not support a simple unconditional expectation that greater net inflows coincide with larger inventories. However, imports may meet current industrial requirements rather than accumulate as stocks, and the aggregate records do not separate these uses. Trade volumes also omit ownership and processing arrangements that influence access to cobalt. Gulley et al., 2019, demonstrate the relevance of foreign ownership within cobalt supply chains. The negative descriptive correlations therefore cannot establish that external supply reduces inventory holdings or improves inventory efficiency.

5.3 Hypothesis Assessment and Evidential Limits:

The hypotheses specify conditional relationships, while the completed calculations describe unadjusted associations. Their assessment must therefore distinguish directional consistency from empirical support.

Table 6: Assessment of the proposed hypotheses

Hypothesis	Observed evidence
H1: Higher geopolitical risk accompanies greater stocks when replenishment and financing permit precautionary accumulation	Risk and threats correlate positively with stocks; acts show a weaker relationship
H2: Higher secondary production accompanies greater stocks when consumption and net external supply remain stable	Positive correlation in levels becomes negative in annual changes; conditioning variables are not held constant
H3: Higher net imports accompany greater stocks when consumption and secondary production remain stable	Both descriptive correlations are negative, but the stated conditions are not imposed

The comparison between levels and annual changes provides a limited sensitivity check. Geopolitical risk and threats retain positive directions, geopolitical acts remain weakly associated, and net imports retain negative directions. The secondary production relationship changes sign. These results identify measurement sensitivity but do not establish robustness to confounding, serial dependence or alternative specifications. The supported conclusion is that U.S. cobalt stocks increased across the observation endpoints, peaked in 2014 and subsequently adjusted without returning to that peak. Their descriptive associations differ across geopolitical, production and trade indicators.

6. Discussion:

Larger cobalt inventories do not necessarily indicate a more secure supply system. Table 4 shows that stocks increased across the observation endpoints but peaked before the period ended, while Table 5 reveals different associations across geopolitical indicators. Global geopolitical risk correlates positively

with stocks at 0.680, whereas geopolitical acts show a weaker correlation of 0.111. The contribution of this analysis is this differentiation within the U.S. cobalt sample: anticipated geopolitical exposure and reported geopolitical acts do not display equivalent inventory patterns. Equation 2 aligns their observation periods but does not make their meanings interchangeable. Barrot and Sauvagnat (2016) identify input specificity as an important condition for shock transmission through production networks. The cobalt evidence complements that perspective by showing why an aggregate geopolitical measure should not automatically represent material disruption. These correlations describe associations, rather than regression effects or statistically established causal relationships.

The findings distinguish two plausible inventory responses: accumulation in anticipation of shortages and depletion when replenishment becomes constrained. Positive associations for geopolitical risk and threats in Table 5 are compatible with precautionary accumulation, but the weaker association for geopolitical acts prevents treating that interpretation as a general response to all geopolitical conditions. Equation 1 also separates recorded holdings from their scale relative to consumption, helping distinguish inventory expansion from changes in industrial use. However, neither equation identifies an intervening behavioral pathway. No mediator was measured and no mediation model was estimated, so coefficient attenuation, partial mediation and full mediation cannot be reported. Imai et al. (2010) show that causal mediation requires explicit identification assumptions and sensitivity assessment. The conceptual advance here is therefore a sharper distinction between mechanisms that fit the observations and mechanisms demonstrated by the research design.

The strongest descriptive associations concern geopolitical risk and threats, but their relative correlations cannot be interpreted as shares of a total effect. Table 5 contains separate associations, not an additive decomposition. More revealing is the production relationship: its positive correlation in levels becomes negative when annual changes are examined. This sign reversal shows that relatively high production levels and contemporaneous inventory accumulation are different empirical propositions. The negative net import associations likewise indicate that additional external inflows do not consistently coincide with larger recorded stocks. Acemoglu et al. (2012) explain how the structure of production linkages shapes aggregate responses to individual shocks. The cobalt results motivate examining where material enters the system, how quickly it is consumed and which holders retain it, rather than treating aggregate supply volumes as sufficient explanations of inventory adjustment. They do not establish which pathway dominates.

The distinction between material flows and usable inventory exposes a practical measurement problem with theoretical consequences. Stocks combine industry holdings with LME holdings in U.S. warehouses, while consumption and imports cover different material movements and reporting populations. Consequently, the ratios in Table 4 cannot serve as direct measures of operational resilience or literal coverage time. Equation 1 changes when either stocks or consumption changes, and the stocks to imports ratio introduces a similar denominator dependence. This means that apparent inventory improvement can arise without additional material being available to a particular processor. Brandon-Jones et al. (2014) identify information sharing and connectivity as resources supporting visibility and resilience among UK manufacturing plants. The cobalt analysis adds a measurement implication: visibility requires identifying inventory location, material form and accessibility, rather than relying on an aggregate stock total.

The international relevance lies in distinguishing replenishment from resilience across interconnected production systems. Boehm et al. (2019) provide evidence that disrupted Japanese input supplies transmitted production losses to firms in the United States. The negative descriptive relationship between net cobalt imports and stocks in Table 5 is not evidence against that transmission mechanism: imported inputs can sustain current output without accumulating as inventories. The comparison redirects attention from import volume alone to the purpose, substitutability and timing of incoming material. Decision makers should therefore interpret geopolitical threats separately from realized interruptions, distinguish accessible industrial stocks from other holdings and assess secondary production alongside consumption requirements. Table 6 supports retaining these distinctions rather than claiming hypothesis validation. Future research should investigate whether supplier exposure predicts precautionary purchases, whether actual interruptions trigger withdrawals and whether recovered cobalt replaces imports or expands buffers. The contribution extends beyond the selected setting through these testable distinctions, while the empirical conclusions remain specific to U.S. cobalt.

7. Conclusion and Implications:

Industrial continuity depends on accessible material, making aggregate supply growth an incomplete guide to preparedness. This analysis shows that expectations and replenishment channels display different relationships with recorded holdings. Anticipated exposure aligns more closely with larger buffers than reported acts, while the association involving recovered material changes direction between levels and annual changes. Greater external inflows do not consistently coincide with accumulation. The contribution is a distinction between obtaining material, holding material and being protected against interruption. This distinction qualifies precautionary inventory reasoning by showing that compatible aggregate patterns do not establish the purchasing behavior behind them. Managers should therefore assess buffer adequacy alongside consumption requirements, material form, processing needs and

ownership. Procurement teams should distinguish purchases serving immediate operations from additions intended to protect future continuity. Policymakers should improve reporting that separates industrial holdings from exchange stocks and identifies accessibility across processing stages. These actions would make preparedness assessments more informative without assuming that larger totals guarantee resilience. For internationally connected industries, the broader implication is to evaluate protection through the alignment of supply access and operational requirements. Better information could support targeted resource allocation and reduce avoidable interruptions, although the analysis does not estimate these wider economic or social benefits.

The evidence creates opportunities for designs that connect aggregate patterns with identifiable decisions. A longer observation window and comparable records across countries and minerals would permit assessment of institutional differences and changing supply structures. Firm records could distinguish precautionary purchases from routine replenishment and identify financing constraints. Documented interruption events could establish timing and support stronger identification strategies. Separating inventories by ownership, location and material form would improve the interpretation of available buffers. Future research should also examine whether recovered material substitutes for imports or expands holdings, using temporal ordering and sensitivity analysis to evaluate proposed mechanisms rather than infer them from correlations alone.

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