

Magma Fertility In Magmatic–Hydrothermal Systems: Mineral Chemistry Indicators, Tectonic Controls, And Implications For Mineral Exploration

Adeyinka Olasehinde, Miranda N. Mboringong, Auwalu Dalha, Edafetano C, Ashano And Abubakar Yusuf

Department Of Geology, Faculty Of Science Gombe State University
Department Of Geology, Faculty Of Science, University Of Jos

Abstract

The concept of magma fertility has become central to modern mineral exploration because it provides a framework for understanding why only a small proportion of magmatic systems generate economically viable ore deposits. Fertile magmas are characterized by favorable combinations of metal enrichment, volatile budgets, oxidation state, and thermodynamic conditions that enable efficient transport and deposition of metals in hydrothermal systems. This review synthesizes recent advances in mineral geochemistry and economic geology to evaluate how rock-forming minerals and accessory phases record the physicochemical conditions of fertile magmatic systems. Particular emphasis is placed on amphibole, biotite, and plagioclase as recorders of magma differentiation, and zircon and apatite as robust indicators of oxidation state and volatile content. The review integrates global case studies from major porphyry provinces including the Andes, Tibet, and Indonesia, and summarizes quantitative geochemical proxies widely used in exploration. Recent analytical developments such as Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry (LA-ICP-MS) mineral mapping and machine-learning classification of geochemical datasets are also discussed. The synthesis demonstrates that fertile magmatic systems typically form in thick continental crust within subduction-related arcs where hydrous and oxidized magmas undergo prolonged differentiation before fluid exsolution. Integration of mineral chemistry with regional geodynamic models provides a powerful predictive framework for identifying prospective mineralized systems during early-stage exploration.

Keywords: magma fertility, mineral chemistry, porphyry deposits, zircon geochemistry, mineral exploration, magmatic-hydrothermal systems

Date of Submission: 13-04-2026

Date of Acceptance: 23-04-2026

I. Introduction

The formation of large magmatic–hydrothermal ore deposits is closely linked to the fertility of their parent magmas. Magma fertility refers to the capacity of a magmatic system to generate metal-bearing hydrothermal fluids capable of forming economic mineral deposits (Richards, 2011). In recent decades, economic geology research has shifted from descriptive models of ore formation to quantitative frameworks that evaluate the physicochemical parameters controlling metal transport and deposition.

Porphyry copper deposits represent the most important source of copper globally and provide an ideal context for studying magma fertility. These deposits form in subduction-related continental arcs where mantle-derived magmas interact with thick continental crust and undergo extensive differentiation before releasing metal-bearing fluids (Sillitoe, 2010). Despite the widespread occurrence of arc magmatism, only a small proportion of intrusions produce significant mineralization, indicating that additional factors beyond magma generation are required for ore formation.

Several studies have shown that fertile magmatic systems are characterized by elevated oxidation states, high water contents, and significant volatile budgets (Loucks, 2014; Wilkinson, 2013). Oxidized magmas maintain sulfur in the form of sulfate rather than sulfide, preventing early sequestration of copper and gold into sulfide phases during magma differentiation (Lee et al., 2012). Hydrous conditions also suppress early plagioclase crystallization and promote amphibole and garnet fractionation at depth, resulting in high Sr/Y ratios that are commonly associated with porphyry-forming magmas (Chiaradia, 2014).

Mineral chemistry has emerged as a powerful tool for evaluating magma fertility because minerals crystallizing from magma preserve geochemical signatures that record the thermodynamic conditions of the melt. Rock-forming minerals such as amphibole, biotite, and plagioclase provide insights into magma differentiation

processes, while accessory minerals such as zircon and apatite retain information about oxidation state and volatile budgets (Trail et al., 2011).

Recent analytical advances, including Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry (LA-ICP-MS), have significantly improved the resolution at which mineral chemistry can be analyzed. Combined with machine learning approaches that analyze large geochemical datasets, these techniques allow exploration geologists to identify fertile magmatic systems with increasing accuracy. This paper presents a comprehensive review of magma fertility and its geochemical indicators, focusing on the role of mineral chemistry in identifying ore-forming magmatic systems.

II. Conceptual Framework Of Magma Fertility

The conceptual model of magma fertility illustrates the geological processes linking mantle melting, crustal differentiation, and hydrothermal mineralization. In subduction environments, dehydration of the descending slab releases fluids into the mantle wedge, lowering the melting temperature and generating hydrous basaltic magmas. These magmas ascend into the crust, where they undergo differentiation within lower crustal magma reservoirs.

Prolonged storage within thick continental crust allows magmas to evolve under hydrous and oxidized conditions. Amphibole and garnet fractionation during this stage produces characteristic geochemical signatures such as elevated Sr/Y ratios and rare earth element fractionation patterns. Eventually, volatile saturation triggers the exsolution of metal-rich fluids that ascend into the upper crust and form porphyry-type mineral deposits.

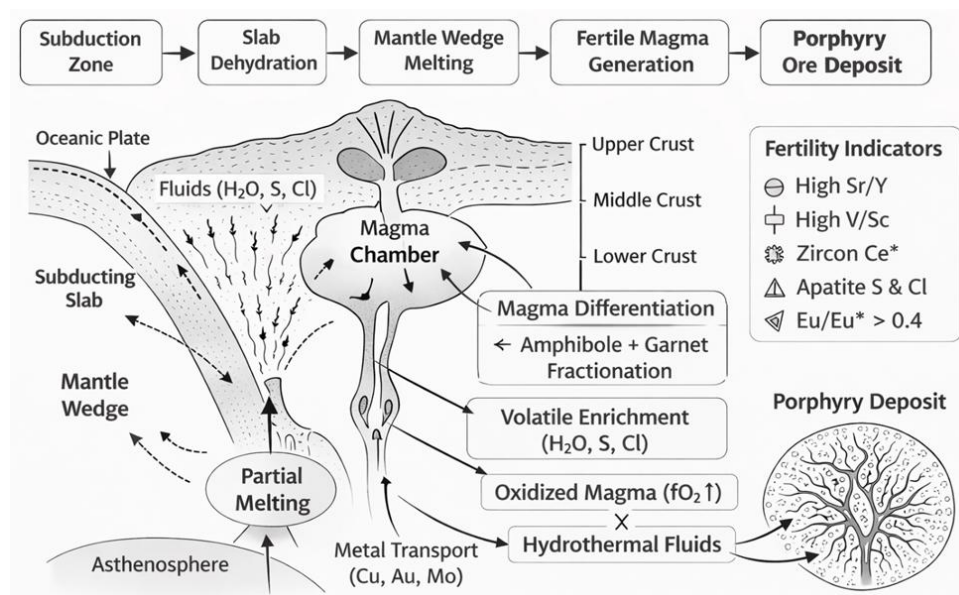


Figure 1. Conceptual Model of Magma Fertility

III. Methodology

The methodology focuses on the systematic synthesis of published geological and geochemical datasets. Priority was given to studies that provided quantitative geochemical datasets or mineral chemistry analyses. Geochemical proxies reported in the literature were compiled and standardized to allow comparison between fertile and barren magmatic systems. Whole-rock and mineral chemistry parameters such as Sr/Y, V/Sc, zircon Ce anomalies, and apatite volatile contents were extracted and evaluated. The compiled data were analyzed to identify consistent geochemical trends associated with fertile magmatic systems. These trends were compared across different tectonic settings, including continental arcs, island arcs, and post-collisional environments. Existing genetic models of porphyry formation were synthesized to construct a conceptual exploration framework linking tectonic setting, magma differentiation, and mineralization processes.

IV. Geochemical Proxies Of Magma Fertility

Whole-rock geochemical proxies provide some of the most widely used indicators for evaluating magma fertility at regional and district scales. These proxies reflect the pressure–temperature conditions, mineral fractionation processes, and volatile budgets that characterize the evolution of magmatic systems capable of generating hydrothermal ore deposits. Among the most widely applied proxies are Sr/Y ratios, V/Sc ratios, rare earth element (REE) fractionation patterns, and Eu anomalies (Table 1), all of which provide insights into the crystallization history and oxidation state of magmatic systems.

High Sr/Y ratios are particularly diagnostic of hydrous magmatic differentiation occurring at relatively high pressures within thick continental crust. Under such conditions, amphibole and garnet tend to dominate the fractionation assemblage, while plagioclase crystallization is suppressed due to elevated water content in the melt. This suppression of plagioclase results in the retention of strontium in the melt while yttrium becomes preferentially incorporated into amphibole and garnet, leading to elevated Sr/Y values. Numerous studies have demonstrated that porphyry copper–gold deposits are commonly associated with magmas exhibiting Sr/Y ratios greater than approximately 65, reflecting differentiation within deep crustal magma reservoirs (Richards, 2011; Chiaradia, 2014).

Another important indicator of magma fertility is the V/Sc ratio, which reflects the oxidation state of the magma. Vanadium behaves as a multivalent element whose partitioning behavior is strongly influenced by oxygen fugacity. In oxidized magmas, vanadium tends to remain in the melt rather than being incorporated into early crystallizing minerals, leading to elevated V/Sc ratios. Fertile magmatic systems commonly exhibit V/Sc values greater than 5, indicating oxidized conditions favorable for the transport of chalcophile elements such as copper and gold (Wilkinson, 2013).

Reduced magmatic systems, by contrast, tend to have lower V/Sc ratios and are less favorable for large-scale hydrothermal mineralization. Rare earth element fractionation patterns also provide valuable information about magma evolution and fertility. Elevated La/Yb ratios indicate high-pressure crystallization conditions and are commonly associated with amphibole- or garnet-dominated fractionation assemblages. Such conditions are typical of hydrous arc magmas that evolve within thick continental crust prior to emplacement at shallower crustal levels (Loucks, 2014). Similarly, Eu anomalies provide insights into plagioclase crystallization behavior. Positive or weakly negative Eu anomalies often indicate suppressed plagioclase fractionation, which is consistent with high water contents in fertile magmatic systems.

Table 1. Whole-Rock Geochemical Fertility Indicators

Proxy	Threshold (Fertile System)	Geological Interpretation	Exploration Significance	References
Sr/Y	> 65	High-pressure crystallization dominated by amphibole ± garnet fractionation	Indicates hydrous magmas typical of porphyry Cu systems	Richards (2011)
La/Yb	> 20	Fractionation under high-pressure conditions with suppressed plagioclase crystallization	Suggests deep crustal magma evolution	Loucks (2014)
V/Sc	> 5	Indicator of oxidized magmas	Discriminates fertile oxidized suites from reduced barren suites	Wilkinson (2013)
Eu/Eu*	> 0.8	Limited plagioclase fractionation due to high water content	Reflects hydrous magma evolution	Chiaradia (2014)
10,000 × (Eu/Eu*) / Y	> 850	Hydrous magmatic signature linked to arc magma fertility	Regional exploration proxy	Richards (2011)
Cu/Zr	> 1	Elevated copper relative to zirconium	Indicates metal-enriched magmatic source	Lee et al. (2012)

Whole-rock geochemical ratios provide regional-scale indicators of magma evolution and have been widely used in mineral exploration. High Sr/Y ratios are particularly characteristic of porphyry-forming magmas and reflect amphibole-dominated fractionation at high pressure (Richards, 2011). These geochemical proxies provide a quantitative framework for evaluating magma fertility in exploration settings. When integrated with geological and tectonic data, whole-rock geochemical indicators can help identify prospective magmatic systems even in regions where direct evidence of mineralization has not yet been discovered.

Conceptual magma fertility proxy (Figure 2) based on whole-rock geochemical ratios (Loucks, 2014) illustrates the relationship between Sr/Y and V/Sc ratios as indicators of magma fertility. Magmatic systems with Sr/Y > 65 and V/Sc > 5 fall within the fertile field, reflecting hydrous, oxidized magmas that evolved under high-pressure conditions favorable for porphyry-style mineralization. Lower ratios characterize barren magmatic systems, typically associated with early plagioclase crystallization, reduced oxidation states, and limited volatile enrichment. These geochemical thresholds provide useful screening criteria for identifying prospective magmatic systems during regional mineral exploration.

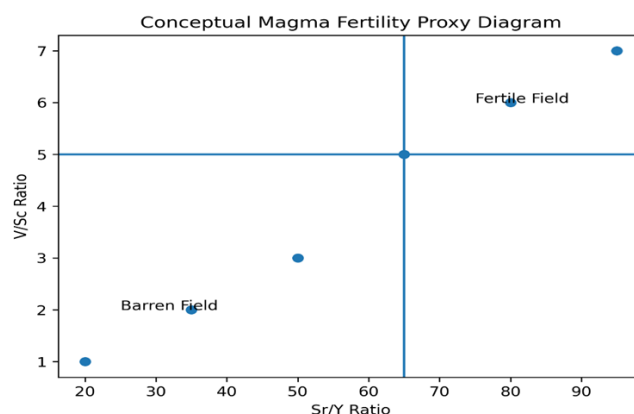


Figure 2. Conceptual magma fertility discrimination diagram using whole-rock geochemical proxies (Sr/Y and V/Sc). Fertile magmatic systems associated with porphyry mineralization typically show Sr/Y > 65 and V/Sc > 5, reflecting hydrous high-pressure crystallization conditions (Richards, 2011; Loucks, 2014).

V. Mineral Chemistry Indicators

While whole-rock geochemical data provide important insights into magma evolution, mineral chemistry offers a more direct record of the physicochemical conditions prevailing during crystallization. Minerals crystallizing from magma incorporate trace elements in proportions that reflect temperature, pressure, oxygen fugacity, and volatile content. As a result, the compositions of rock-forming and accessory minerals can serve as robust indicators of magma fertility.

Zircon has emerged as one of the most valuable minerals for assessing magma fertility because of its exceptional chemical durability and resistance to hydrothermal alteration (Table 2). Zircon crystals commonly preserve trace element signatures that record the oxidation state and crystallization conditions of the magma from which they formed. One of the most widely used indicators is the cerium anomaly (Ce/Ce*), which reflects the oxidation state of the magma. Under oxidizing conditions, cerium is preferentially oxidized to Ce⁴⁺, which is more compatible in the zircon lattice. Consequently, fertile magmatic systems often exhibit pronounced positive Ce anomalies in zircon crystals (Trail et al., 2012).

The europium anomaly (Eu/Eu*) in zircon also provides important insights into magma evolution. Europium can exist in both divalent and trivalent states, and its partitioning behavior is influenced by plagioclase crystallization. When plagioclase crystallizes early in the magma evolution, europium is preferentially incorporated into the plagioclase lattice, producing negative Eu anomalies in the residual melt and subsequently in zircon crystals. In contrast, hydrous magmatic systems where plagioclase crystallization is suppressed tend to exhibit weaker Eu anomalies, resulting in zircon Eu/Eu* values greater than approximately 0.4. Such signatures are commonly associated with fertile magmatic systems capable of generating porphyry deposits (Loucks, 2014).

Apatite provides another important mineralogical indicator of magma fertility because it records the volatile content of the magma. Apatite can incorporate significant concentrations of sulfur, chlorine, and fluorine, which are critical components of ore-forming hydrothermal fluids (Table 3). Elevated sulfur concentrations in apatite (commonly expressed as SO₃ content exceeding 0.2 wt%) indicate sulfur-rich magmas capable of producing sulfide mineralization. Similarly, high chlorine concentrations in apatite reflect volatile-rich magmas that enhance the transport of metals in hydrothermal fluids (Wilkinson, 2013).

The integration of zircon and apatite geochemistry therefore provides powerful insights into the oxidation state, volatile budget, and differentiation history of magmatic systems. These mineralogical indicators are increasingly used in mineral exploration to distinguish fertile magmatic systems from barren intrusions.

Table 2. Zircon Trace-Element Indicators of Magma Fertility

Parameter	Fertile Threshold	Petrogenetic Meaning	Exploration Application	References
Ce/Ce*	> 750	High oxygen fugacity	Oxidized magma capable of transporting Cu and Au	Trail et al. (2012)
Eu/Eu*	> 0.4	Suppressed plagioclase crystallization	Indicates hydrous magma evolution	Loucks (2014)
Ti-in-Zircon Temperature	700–850°C	Magmatic crystallization temperature	Identifies fertile intrusive phases	Watson et al. (2006)
Zr/Hf Ratio	> 35	Fractionation of zircon during magma evolution	Indicates evolved fertile melts	Belousova et al. (2002)
U/Yb vs Hf Plot	Elevated U/Yb	Oxidized arc magma source	Distinguishes arc magmas from MORB sources	Grimes et al. (2007)

Zircon is particularly valuable because it is resistant to hydrothermal alteration and preserves primary magmatic signatures. High Ce anomalies in zircon indicate oxidized magmatic conditions that favor copper transport (Trail et al., 2012).

Table 3 Apatite Volatile and Trace Element Fertility Indicators

Parameter	Fertile Threshold	Interpretation	Exploration Significance	References
SO ₃	> 0.2 wt.%	High magmatic sulfur content	Indicates potential for sulfide mineralization	Wilkinson (2013) Wilkinson et al., (2009)
Cl	> 0.3 wt.%	Chlorine-rich magma	Promotes metal transport in hydrothermal fluids	Loucks (2014)
F/Cl Ratio	Low values	Chlorine-dominant volatile system	Favorable for Cu-Au porphyry deposits	Richards (2011)
Sr in Apatite	Elevated	Hydrous magmatic differentiation	Associated with fertile arc magmas	Chiaradia (2014)

VI. Global Examples Of Fertile Magmatic Systems

The global distribution of porphyry deposits provides compelling evidence that magma fertility is strongly controlled by tectonic setting (Table 4). Most major porphyry copper provinces occur within convergent plate margins, particularly in subduction-related continental arcs where mantle-derived magmas interact with thick continental crust.

The Andes of South America represent the largest and most productive porphyry copper province in the world. Deposits such as Chuquicamata, El Teniente, and Escondida are associated with calc-alkaline magmatic systems that evolved within the thickened crust of the Andean continental margin. These systems exhibit geochemical characteristics consistent with hydrous, oxidized magmas that underwent prolonged differentiation within lower crustal magma reservoirs (Sillitoe, 2010). Elevated Sr/Y ratios, strong zircon Ce anomalies, and high volatile contents recorded in apatite are common features of these fertile magmatic systems.

Table 4. Major Global Porphyry Systems

Region	Major Deposit / District	Tectonic Setting	Magma Fertility Indicators	Dominant Mineralization	Key References
Chile (Central Andes)	Chuquicamata	Continental arc above subduction zone	High Sr/Y (>70), oxidized magmas ($\Delta FMQ +2$), hydrous arc magmas	Cu–Mo porphyry	Richards (2011); Sillitoe (2010)
Chile (Central Andes)	El Teniente	Thickened continental arc crust	High Ce anomaly in zircon, high Cl and S in apatite	Cu–Mo porphyry	Loucks (2014); Wilkinson (2013)
Peru–Chile Andes	Escondida	Andean continental margin	Elevated La/Yb, Sr/Y ratios, high water content	Giant Cu porphyry	Sillitoe (2010)
Tibet Plateau (Gangdese Belt)	Qulong	Post-collisional arc magmatism	High zircon Ce/Ce*, Eu/Eu* > 0.4, oxidized hydrous magmas	Cu–Mo porphyry	Chiaradia (2014)
Tibet (Gangdese Arc)	Jiama	Subduction-related arc magmatism	Amphibole fractionation, high Sr/Y magmas	Cu–Mo–Au porphyry	Hou et al., (2015); Yang & Cao, (2024)
Indonesia (Sunda Arc)	Grasberg	Oceanic arc with thickened crust	High magmatic sulfur and chlorine, oxidized magma	Cu–Au porphyry	Sillitoe (2010)
Indonesia (Sumbawa Island)	Batu Hijau	Island arc setting	High volatile contents, hydrous calc-alkaline magmas	Cu–Au porphyry	Richards (2011)
Philippines Arc System	Tampakan	Subduction arc environment	High Sr/Y adakitic magmas	Cu–Au porphyry	Cooke et al. (2005)
USA (Arizona)	Resolution	Continental arc magmatism	High oxidation state and hydrous magma evolution	Cu porphyry	Seedorff et al. (2005)

Similarly, the Gangdese porphyry belt of southern Tibet represents one of the most significant porphyry copper provinces in Asia (Figure 3). Deposits such as Qulong and Jiama formed within a post-collisional magmatic arc environment associated with the convergence of the Indian and Eurasian plates. Magmatic systems in this region display strong geochemical signatures of magma fertility, including high oxidation states, elevated Sr/Y ratios, and hydrous mineral assemblages indicative of deep crustal magma storage (Hou et al., 2015; Yang & Cao, 2024).

Island arc systems also host major porphyry deposits, as demonstrated by the Grasberg deposit in Indonesia, one of the largest copper–gold deposits in the world. The magmatic systems associated with Grasberg are characterized by high sulfur and chlorine concentrations in apatite, reflecting volatile-rich magmas capable of transporting large quantities of metals in hydrothermal fluids (Richards, 2011; Richards & Kerrich, 2007).

These global examples highlight the importance of tectonic environment in controlling magma fertility. Thick crust, hydrous mantle-derived magmas, and oxidizing conditions appear to be critical factors in the formation of large porphyry deposits. These regions share common characteristics including thick continental crust, hydrous magmatism, and oxidized magmatic conditions (Richards & Kerrich, 2007; Sillitoe, 2010).

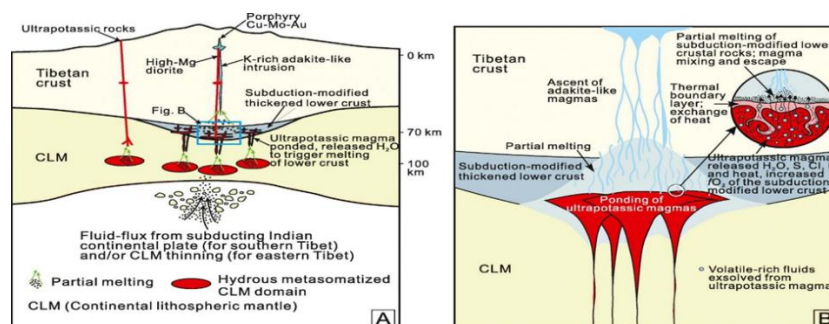


Figure 3. Conceptual tectono–magmatic model for the generation of adakite-like magmas and associated porphyry Cu–Mo–Au mineralization in thickened continental crust in Tibet. (After Yang & Cao, 2024) (A) Ultrapotassic magmas derived from a metasomatized continental lithospheric mantle (CLM) ascend through thickened crust and release volatile-rich fluids (H₂O, S, Cl), which trigger partial melting of subduction-modified lower crustal rocks. This process generates K-rich adakite-like magmas that ascend to form porphyry Cu–Mo–Au systems. (B) Schematic illustration of magma ponding at the base of the crust, where heat and fluid transfer from ultrapotassic magmas induce partial melting of the lower crust. The resulting adakitic magmas rise through the crust, carrying metals and volatiles that eventually contribute to hydrothermal mineralization.

VII. Physicochemical Controls On Magma Fertility: Distinguishing Fertile And Barren Magmatic Systems

A fundamental question in economic geology is why only a small proportion of magmatic systems produce economically significant mineral deposits. Comparative studies (Table 5) of fertile and barren intrusions provide valuable insights into the factors that control ore formation.

One of the most important differences between fertile and barren magmatic systems is their oxidation state (Audétat et al., 2008). Fertile magmas are typically highly oxidized, with oxygen fugacities above the fayalite–magnetite–quartz (FMQ) buffer. Under such conditions, sulfur remains dissolved in the magma as sulfate rather than sulfide. This prevents early precipitation of sulfide minerals that would otherwise sequester copper and gold at depth (Lee et al., 2011; 2012; Wilkinson et al., 2009). Reduced magmas, by contrast, tend to form sulfide phases early during magma evolution, removing metals from the melt before hydrothermal fluids can transport them to higher crustal levels.

Water content is another critical factor controlling magma fertility. Hydrous magmas promote the crystallization of amphibole rather than plagioclase during differentiation, resulting in geochemical signatures such as elevated Sr/Y ratios. High water contents also facilitate the exsolution of hydrothermal fluids during magma ascent, which is essential for the formation of porphyry deposits (Loucks, 2014).

The volatile budget of the magma also plays a key role in determining whether mineralization occurs. Fertile magmas typically contain significant concentrations of sulfur, chlorine, and fluorine, which enhance the solubility and transport of metals in hydrothermal fluids (Wilkinson et al., 2009). Barren magmatic systems often lack sufficient volatile concentrations to generate metal-rich fluids capable of forming economic mineral deposits (Wilkinson, 2013).

Finally, crustal thickness and tectonic environment influence magma fertility by controlling the depth and duration of magma storage. Thick continental crust promotes prolonged magma differentiation within lower crustal reservoirs, allowing metals and volatiles to accumulate in the residual melt. In contrast, magmas emplaced within thin crust tend to ascend rapidly to shallow levels, limiting the degree of differentiation and reducing the potential for ore formation (Heinrich, & Candela, 2014; Chiaradia, 2014).

Together, these factors explain why fertile magmatic systems represent a relatively rare combination of favorable geological conditions. Understanding these differences is essential for mineral exploration because it allows geologists to focus on magmatic systems that exhibit the key characteristics associated with ore formation. These differences explain why many intrusions fail to generate mineralization.

Table 5. Comparison of Fertile and Barren Magmas

Parameter	Fertile Magmatic Systems	Barren Magmatic Systems	Exploration Significance	References
Oxidation State (fO₂)	High oxidation state (ΔFMQ +1 to +3)	Reduced magmas (ΔFMQ 0 to -2)	Oxidized magmas allow sulfur to remain dissolved and transport Cu, Au, and Mo	Richards (2011); Loucks (2014)
Water Content (H₂O)	High (>4 wt.% H ₂ O)	Low (<2 wt.% H ₂ O)	Hydrous magmas promote volatile exsolution and hydrothermal fluid formation	Wilkinson (2013)
Sulfur Content	High sulfur budget	Low sulfur content	Required for sulfide ore formation	Lee et al. (2011)
Crustal Thickness	Thick crust (>45 km)	Thin crust (<30 km)	Thick crust promotes magma differentiation	Chiaradia (2014)
Magma Differentiation	Extensive fractionation (amphibole ± garnet)	Limited differentiation	Leads to metal enrichment in residual melt	Richards (2011)
Plagioclase Fractionation	Suppressed early plagioclase crystallization	Early plagioclase crystallization	Maintains high Sr/Y ratios	Loucks (2014)
Sr/Y Ratio	>65	<40	Indicates high-pressure crystallization	Richards (2011)
V/Sc Ratio	>5	<3	Indicator of oxidized magmatic conditions	Wilkinson (2013)
Zircon Ce/Ce*	>750	<200	Indicates high oxygen fugacity	Trail et al. (2012)
Zircon Eu/Eu*	>0.4	<0.2	Indicates hydrous magma evolution	Loucks (2014)
Apatite Sulfur (SO₃)	>0.2 wt.%	<0.05 wt.%	Indicates sulfur-rich magma	Wilkinson (2013)
Apatite Chlorine (Cl)	High Cl content	Low Cl content	Chlorine enhances metal transport	Richards (2011)
Magmatic Volatile Budget	High Cl, S, F	Low volatile content	Essential for hydrothermal ore formation	Cooke et al. (2005)
Hydrothermal System Development	Strong fluid exsolution and alteration halos	Weak or absent hydrothermal system	Determines ore formation potential	Sillitoe (2010)

VIII. Exploration Targeting Using Mineral Chemistry

Modern mineral exploration increasingly relies on the integration of mineral chemistry with geophysical and geochemical datasets to identify fertile magmatic systems. Minerals crystallizing from magma preserve geochemical signatures that reflect the physicochemical conditions of magma evolution, including oxidation state, volatile content, and crystallization depth. Because many accessory minerals remain stable during hydrothermal alteration, they serve as reliable indicators of magma fertility even when whole-rock compositions have been modified (Sillitoe, 1997; Trail et al., 2012).

Zircon geochemistry is particularly useful for exploration targeting. Parameters such as the cerium anomaly (Ce/Ce*) and europium anomaly (Eu/Eu*) provide information about magma oxidation state and plagioclase crystallization. Fertile magmatic systems commonly show strong positive Ce anomalies and relatively weak Eu anomalies, reflecting oxidized and hydrous magma conditions favorable for metal transport (Richards, 2011; Loucks, 2014).

Apatite chemistry complements zircon data by recording the volatile budget of magmatic systems. Elevated sulfur and chlorine concentrations in apatite indicate volatile-rich magmas capable of generating hydrothermal fluids that transport copper and other chalcophile elements (Simmons et al., 2005; Wilkinson, 2013). In addition, the compositions of rock-forming minerals such as amphibole and biotite can provide constraints on magma storage depth and volatile evolution.

Advances in analytical techniques such as electron microprobe analysis and as LA-ICP-MS have significantly improved the ability to analyze mineral compositions at high resolution. When combined with machine learning methods (Wen et al., 2024) that evaluate large geochemical datasets, these approaches allow exploration geologists to distinguish fertile magmatic systems from barren intrusions with greater accuracy (Grimes et al., 2008). The integration of mineral chemistry with regional geological, geophysical, and geochemical data provides a powerful framework for identifying prospective exploration targets and improving the efficiency of mineral discovery. Table 6 summarizes key rock-forming and accessory minerals that record physicochemical conditions of magmatic systems. Geochemical indicators such as Al-in-amphibole, halogen enrichment in biotite, zoning patterns in plagioclase, and trace-element anomalies in zircon and apatite provide insights into magma storage depth, oxidation state, volatile budgets, and magma recharge processes. These mineralogical signatures are widely used as exploration tools to identify fertile magmatic systems capable of generating porphyry-style mineralization.

Table 6. Mineral chemistry indicators of magma fertility and their significance in mineral exploration.

Mineral	Geochemical Indicator	Interpretation	Exploration Relevance
Amphibole	High Al-in-amphibole	High pressure crystallization depth	Indicates deep crustal magma storage
Biotite	Elevated Cl and F	High halogen content	Reflects volatile-rich magmas
Plagioclase	Reverse An zoning	Magma recharge events	Linked to fluid exsolution and mineralization
Zircon	High Ce anomaly	Oxidized magma	Promotes Cu-Au transport
Apatite	High sulfur and chlorine	Volatile-rich magma	Indicator of ore-forming fluids

Figure 4 illustrates an integrated exploration strategy that combines regional geological mapping, whole-rock geochemical analysis, and in-situ mineral chemistry to evaluate magma fertility. Key geochemical indicators such as Sr/Y and V/Sc ratios, zircon Ce anomalies, apatite sulfur and chlorine contents, and Eu anomalies are used to assess magma differentiation, volatile enrichment, and oxidation state. These parameters help distinguish fertile magmatic systems from barren intrusions. The workflow culminates in machine learning assisted classification and drill testing to confirm exploration targets associated with porphyry-style mineralization.

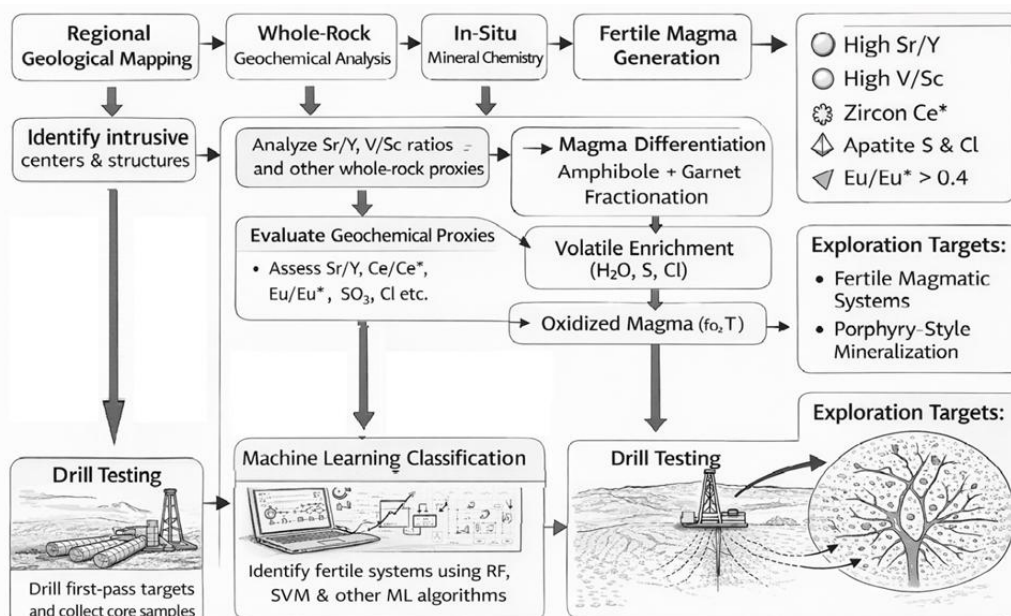


Figure 4. Exploration workflow for identifying fertile magmatic systems using mineral chemistry and geochemical proxies.

IX. Integrated Synthesis: Linking Tectonics, Magma Evolution, And Mineralization

The formation of magmatic–hydrothermal ore deposits results from the interaction of tectonic processes, magma evolution, and hydrothermal fluid generation (Candela, 1997; Richards, 2003). At the regional scale, tectonic setting provides the primary control on magma fertility. Most large porphyry deposits occur in subduction-related continental arcs where dehydration of the subducting slab releases fluids into the mantle wedge, generating hydrous basaltic magmas enriched in volatile components such as H₂O, S, and Cl (Mungall, 2002; Richards, 2011).

As these mantle-derived magmas ascend into the crust, thick continental lithosphere promotes prolonged magma storage and differentiation in lower crustal reservoirs (Cox and Singer, 1986; Mungall, 2002). Fractionation of amphibole and garnet during this stage produces characteristic geochemical signatures such as elevated Sr/Y and La/Yb ratios, which are widely associated with fertile magmatic systems (Chiaradia, 2014). Oxidized conditions further enhance magma fertility by preventing early sulfide saturation and allowing copper, gold, and molybdenum to remain dissolved in the melt (Lee et al., 2012).

Mineral chemistry provides a key record of these processes. Zircon and apatite preserve geochemical indicators of oxidation state, volatile content, and magma evolution, while rock-forming minerals record crystallization conditions and magma differentiation history. Eventually, volatile saturation leads to the exsolution of hydrothermal fluids that transport metals through fractures and permeable zones in the upper crust, forming porphyry-style mineralization (Sillitoe, 2010). Thus, magma fertility reflects the integration of tectonic environment, magmatic differentiation, and volatile enrichment. Understanding these relationships provides a predictive framework for identifying prospective magmatic systems during mineral exploration. The integration (Table 7) of mineral chemistry, whole-rock geochemistry, and tectonic analysis provides a powerful framework for identifying fertile magmatic systems. Exploration strategies increasingly rely on quantitative geochemical

thresholds derived from global datasets. Machine learning algorithms are also becoming important tools for analyzing large geochemical databases and identifying subtle patterns associated with ore formation.

Table 7 Integrated Exploration Decision Criteria for Magma Fertility

Indicator Type	Key Proxy	Fertility Threshold	Exploration Decision
Whole-rock geochemistry	Sr/Y	> 65	Potential fertile magma
Whole-rock geochemistry	V/Sc	> 5	Oxidized magmatic system
Zircon geochemistry	Ce/Ce*	> 750	Strong porphyry potential
Zircon geochemistry	Eu/Eu*	> 0.4	Hydrous magma
Apatite volatile content	SO ₃	> 0.2 wt.%	Sulfur-rich magma
Mineral chemistry	Amphibole stability	Hydrous conditions	Favorable magma storage depth

X. Future Research Directions

Although significant progress has been made in understanding magma fertility, several research directions remain important for advancing exploration strategies. One emerging area is the application of high-resolution mineral chemistry techniques, such as LA-ICP-MS trace element mapping, which allows detailed reconstruction of magma evolution and crystallization histories at the scale of individual mineral grains.

Another important development is the use of machine learning and artificial intelligence to analyze large geochemical datasets. These computational approaches can identify subtle geochemical patterns associated with fertile magmatic systems and improve the ability to distinguish fertile intrusions from barren ones. Future research should also focus on expanding global geochemical databases of mineral chemistry indicators and integrating these datasets with tectonic and geophysical models. Such multidisciplinary approaches will enhance the predictive capability of exploration models and support the discovery of new mineral resources. As global demand for critical metals continues to increase, improving the ability to identify fertile magmatic systems at an early exploration stage will remain a major priority in economic geology.

XI. Conclusion

This study provides a comprehensive synthesis of the concept of magma fertility and its significance in the formation of magmatic–hydrothermal ore deposits. The review demonstrates that magma fertility is controlled by a combination of tectonic, geochemical, and mineralogical factors that operate from mantle melting to hydrothermal mineralization in the upper crust. Subduction-related tectonic environments, particularly continental arcs with thickened crust, provide favorable conditions for the generation of hydrous and oxidized magmas capable of transporting and concentrating metals such as copper, gold, and molybdenum.

Whole-rock geochemical proxies, including Sr/Y and V/Sc ratios, provide important regional-scale indicators of magma evolution and oxidation state. Elevated Sr/Y ratios reflect high-pressure crystallization and suppression of plagioclase fractionation in hydrous magmas, whereas high V/Sc ratios indicate oxidized magmatic systems that favor the retention of chalcophile elements in the melt. These geochemical signatures therefore serve as useful tools for distinguishing fertile magmatic systems from barren intrusions during early exploration stages.

Mineral chemistry offers even more robust indicators of magma fertility because minerals preserve direct evidence of the physicochemical conditions under which magmas evolve. Accessory minerals such as zircon and apatite record key parameters including oxidation state and volatile budgets through trace element anomalies and volatile concentrations. In particular, zircon Ce anomalies and Eu anomalies provide insights into magma oxidation state and hydration, while sulfur and chlorine contents in apatite reflect the volatile enrichment necessary for hydrothermal ore formation. Rock-forming minerals such as amphibole, biotite, and plagioclase further record crystallization conditions and magma recharge processes that influence metal transport and fluid exsolution.

The integration of mineral chemistry with whole-rock geochemistry, tectonic models, and geophysical data forms the basis of modern exploration strategies for porphyry-style mineral systems. Advances in analytical techniques such as LA-ICP-MS and the application of machine learning to large geochemical datasets are further enhancing the ability to identify fertile magmatic systems and prioritize exploration targets. Magma fertility represents a critical link between mantle processes, crustal magma evolution, and hydrothermal mineralization. By integrating geochemical proxies, mineralogical indicators, and tectonic controls, geologists can develop predictive exploration models capable of identifying prospective magmatic systems before mineralization is directly discovered. Such integrated approaches will be essential for improving the efficiency of mineral exploration and meeting the growing global demand for critical metals.

References

- [1]. Audétat, A., Pettko, T., Heinrich, C. A., & Bodnar, R. J. (2008). Special Paper: The Composition Of Magmatic-Hydrothermal Fluids In Barren And Mineralized Intrusions. *Economic Geology*, 103(5), 877-908.
- [2]. Belousova, E. A., Griffin, W. L., O'Reilly, S. Y., & Fisher, N. I. (2002). Igneous Zircon: Trace Element Composition As An Indicator Of Source Rock Type. *Contributions To Mineralogy And Petrology*, 143(5), 602–622. <https://doi.org/10.1007/S00410-002-0364-7>
- [3]. Candela, P. A. (1997). A Review Of Shallow, Ore-Related Granites: Textures, Volatiles, And Ore Metals. *Journal Of Petrology*, 38(12), 1619-1633
- [4]. Chiaradia, M. (2014). Copper Enrichment In Arc Magmas Controlled By Overriding Plate Thickness. *Nature Geoscience*, 7(1), 43–46. <https://doi.org/10.1038/Ngeo2028>
- [5]. Cooke, D. R., Hollings, P., & Walshe, J. L. (2005). Giant Porphyry Deposits: Characteristics, Distribution, And Tectonic Controls. *Economic Geology*, 100(5), 801–818. <http://Econgeol.Geoscienceworld.Org/Content/100/5/801>
- [6]. Cox, D. P., & Singer, D. A. (1986). Mineral Deposit Models. U.S. Geological Survey Bulletin 1693.
- [7]. Grimes, C.B., John, B.E., Kelemen, P.B., Mazdab, F., Wooden, J.L., Cheadle, M.J., Hanghøj, K., Schwartz, J.J. (2007). Trace Element Chemistry Of Zircons From Oceanic Crust: A Method For Distinguishing Detrital Zircon Provenance. *Geology*, 35(7), 643–646. <https://doi.org/10.1130/G23603A.1>
- [8]. Grimes, C.B., John, B.E., Cheadle, M.J., Wooden, J.L. (2008). Protracted Construction Of Gabbroic Crust At A Slow-Spreading Ridge: Constraints From 206Pb/238U Zircon Ages From Atlantis Massif And IODP Hole U1309D (308N MAR). *Geochem Geophys Geosyst* 9:Q08012. [doi:10.1029/2008GC002063](https://doi.org/10.1029/2008GC002063)
- [9]. Heinrich, C. A., & Candela, P. A. (2014). Fluids And Ore Formation In The Earth's Crust. In H. D. Holland & K. K. Turekian (Eds.), *Treatise On Geochemistry* (2nd Ed., Pp. 1–28). Elsevier.
- [10]. Hou, Z.Q.; Yang, Z.M.; Lu, Y.; Kemp, A.; Zheng, Y.; Li, Q.; Duan, L. (2015). A Genetic Linkage Between Subduction- And Collision-Related Porphyry Cu Deposits In Continental Collision Zones. *Geology*, 43, 247–250.
- [11]. Lee, C. T. A., Luffi, P., & Chin, E. J. (2011). Building And Destroying Continental Mantle. *Annual Review Of Earth And Planetary Sciences*, 39(1), 59-90.
- [12]. Lee, C. T. A., Luffi, P., Chin, E. J., Bouchet, R., Dasgupta, R., Morton, D. M., Le Roux, V., Yin, Q. & Jin, D. (2012). Copper Systematics In Arc Magmas And Implications For Crust-Mantle Differentiation. *Science*, 336(6077), 64-68.
- [13]. Loucks, R. R. (2014). Distinctive Composition Of Copper-Ore-Forming Arc Magmas. *Australian Journal Of Earth Sciences*, 61(1), 5–16.
- [14]. Mungall, J. E. (2002). Roasting The Mantle: Slab Melting And The Genesis Of Major Au And Au-Rich Cu Deposits. *Geology*, 30(10), 915-918.
- [15]. Richards, J. P. (2011). Magmatic To Hydrothermal Metal Flux In Convergent And Collided Margins. *Ore Geology Reviews*, 40(1), 1–26. <https://doi.org/10.1016/J.Oregeorev.2011.05.006>
- [16]. Richards, J. P. (2003). Tectono-Magmatic Precursors For Porphyry Cu-(Mo-Au) Deposit Formation. *Economic Geology*, 98(8), 1515–1533. <https://doi.org/10.2113/98.8.1515>
- [17]. Richards, J.P & Kerrich, R. (2007). Adakite-Like Rocks: Their Diverse Origins And Questionable Role In Metallogenesis. *Econ. Geol.*, 102, 537–576.
- [18]. Seedorff, E., Dilles, J. H., Proffett, J. M., Einaudi, M. T., Zurcher, L., Stavast, W. J., Johnson, D. A., & Barton, M. D. (2005). Porphyry Deposits: Characteristics And Origin Of Hypogene Features. *Economic Geology*, 100th Anniversary Volume, 251–298.
- [19]. Sillitoe, R. H. (2010). Porphyry Copper Systems. *Economic Geology*, 105(1), 3–41. <https://doi.org/10.2113/Gsecongeo.105.1.3>
- [20]. Sillitoe, R. H. (1997). Characteristics And Controls Of The Largest Porphyry Copper–Gold Deposits In The Circum-Pacific Region. *Australian Journal Of Earth Sciences*, 44(3), 373–388.
- [21]. Simmons, S. F., White, N. C., & John, D. A. (2005). Geological Characteristics Of Epithermal Precious And Base Metal Deposits. In Hedenquist, J. W., Thompson, J. F. H., Goldfarb, R. J., And Richards, J. P. (Eds.), *Economic Geology 100th Anniversary Volume*. Littleton: Society Of Economic Geologists, Pp. 485–522.
- [22]. Trail, D., Watson, E. B., & Tailby, N. D. (2011). The Oxidation State Of Hadean Magmas And Implications For Early Earth's Atmosphere. *Nature*, 480(7375), 79-82.
- [23]. Trail, D., Watson, E. B., & Tailby, N. D. (2012). Ce And Eu Anomalies In Zircon As Proxies For The Oxidation State Of Magmas. *Geochimica Et Cosmochimica Acta*, 97, 70-87.
- [24]. Watson, E. B., Wark, D. A., & Thomas, J. B. (2006). Crystallization Thermometers For Zircon And Rutile. *Contributions To Mineralogy And Petrology*, 151(4), 413–433. <https://doi.org/10.1007/S00410-006-0068-5>
- [25]. Wen, Z. H., Li, L., Kirkland, C. L., Li, S. R., Sun, X. J., Lei, J. L., Xu, B. & Hou, Z. Q. (2024). A Machine Learning Approach To Discrimination Of Igneous Rocks And Ore Deposits By Zircon Trace Elements. *American Mineralogist*, 109(6), 1129-1142.
- [26]. Wilkinson, J. J. (2013). Triggers For The Formation Of Porphyry Ore Deposits In Magmatic Arcs. *Nature Geoscience*, 6(11), 917–925. <https://doi.org/10.1038/Ngeo1940>
- [27]. Wilkinson, J. J., Stoffell, B., Wilkinson, C. C., Jeffries, T. E. & Appold, M. S. (2009). Anomalously Metal-Rich Fluids Form Hydrothermal Ore Deposits. *Science* 323, 764–767
- [28]. Yang, Z., & Cao, K. (2024). Post-Collisional Porphyry Copper Deposits In Tibet: An Overview, *Earth-Science Reviews*, 258,104954, <https://doi.org/10.1016/J.Earscirev.2024.104954>.