

## Mineral Exploration and Ore Genesis of the Central Tethyan Metallogenic Belt in Balochistan: A Geochemical and Geochronological Approach

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### Abstract

The Central Tethyan Metallogenic Belt in Balochistan, Pakistan, represents a frontier province for porphyry Cu-Au exploration within the Chagai-Raskoh double-arc system, formed through multi-stage Neotethys closure involving Late Cretaceous intra-oceanic subduction and Cenozoic continental arc magmatism. This study integrates geochemical (major/trace elements, Sr-Nd-Pb isotopes) and geochronological (U-Pb zircon, Re-Os molybdenite) data to elucidate ore genesis, emphasizing adakitic signatures, oxidized mantle sources, and crustal contamination as key fertility indicators for giant deposits like Reko Diq (2.4 Gt @ 0.41% Cu, 0.22 g/t Au) and Saindak. Magmatic evolution from juvenile tholeiitic basalts (Sinjrani Volcanic Group) to calc-alkaline andesites (Humai Formation) reflects slab melting and metasomatism, with mineralization linked to Miocene-Pliocene potassic intrusions. Hyperspectral remote sensing and geophysical surveys (aeromagnetism) enhance targeting under post-mineral cover, revealing untapped potential in the Makran forearc and Dalbandin Trough. Findings underscore the role of ridge subduction and slab tears in generating high-Sr/Y magmas, providing a predictive model for polymetallic exploration in analogous Tethyan segments.

**Keywords:** Tethyan Metallogenic Belt, Balochistan, porphyry Cu-Au, Ore Genesis, Geochemistry, Geochronology, Chagai-Raskoh Arcs, Adakitic Magmatism, Reko Diq, Saindak, Subduction Tectonics, Mineral Exploration

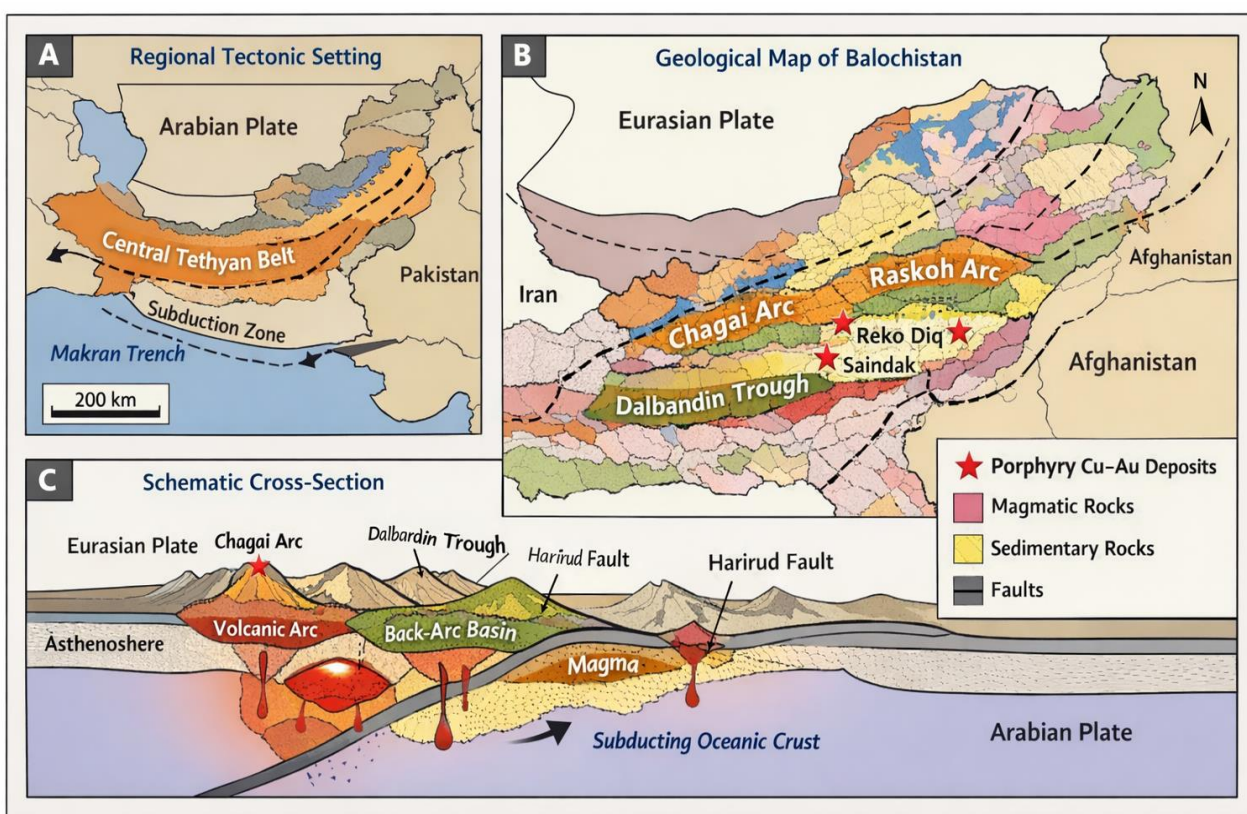
### 1. Introduction

The Tethyan mountain ranges represent a colossal geological edifice, stretching from the Atlantic margins of northwestern Africa and Western Europe to the remote reaches of the southwest Pacific Ocean, constituting the most extensive continuous orogenic belt on the planet (Moritz & Baker, 2019). Within this vast expanse, the Tethyan Metallogenic Belt (TMB) emerges as an exceptionally fertile corridor of mineralization, hosting a diverse array of ore deposit types including porphyry copper-gold (Cu-Au), epithermal systems, skarns, and volcanogenic massive sulfides (VHMS) (Perelló et al., 2008). The Central Tethyan segment, specifically the portion traversing the Balochistan province of Pakistan, serves as a critical nexus where the convergence, subduction, and accretion of various Gondwana-derived microplates against the Eurasian margin have orchestrated a complex metallogenic history (Mastoi et al., 2019). This region, primarily defined by the Chagai and Raskoh magmatic arcs, represents one of the world's premier frontier provinces for base and precious metal exploration, characterized by giant deposits such as Reko Diq and

Saindak (Razique et al., 2014). Figure 1 highlighting the map of Chagai and Raskoh arcs, Dalbandin Trough, major deposits (Reko Diq, Saindak), and fault zones (Chaman, Harirud). The geodynamic evolution of this segment is intrinsically linked to the multi-stage closure of the Neotethys. The transition from juvenile intra-oceanic subduction in the Late Cretaceous to mature continental arc magmatism in the Cenozoic has left a distinct geochemical and geochronological fingerprint on the intrusive and volcanic suites of Balochistan (Siddiqui, 2004). Modern exploration strategies increasingly rely on deciphering these signatures specifically the role of adakitic magmatism, the oxidation state of the sub-arc mantle, and the isotopic evolution of the crust to identify fertile porphyry systems buried beneath extensive alluvium and post-mineral volcanic cover (Sillitoe, 2010).

## 2. Geodynamic Framework and Tectonic Architecture of the Balochistan Segments

The tectonic assembly of Balochistan is the product of a protracted Wilson Cycle, culminating in the collision between the Indian and Arabian plates with Eurasia (Kazmi & Jan, 1997).



**Figure 1: Geological map of Balochistan showing the Central Tethyan Metallogenic Belt with major porphyry Cu-Au deposits and tectonic features**

Morphostructurally, the region is partitioned from south to north into five primary units: the Makran accretionary prism, the Hamun-i-Mashkhel forearc basin, the Chagai magmatic arc, the Dalbandin depression, and the Raskoh arc. This architectural arrangement reflects an Andean-type continental margin setting that has been active since the Mesozoic (Malkani, 2020).

### 2.1 The Chagai-Raskoh Double Arc System

The Chagai and Raskoh arcs form a distinctive double-arc system, separated by the Dalbandin Trough. The Chagai belt, extending over 500 kilometers with a general east-west trend, is convex

toward the south and terminates against the Chaman transform fault zone in the east and the Harirud fault zone in the west (Ullah et al., 2023). This belt is a primary component of the TMB, hosting at least 48 documented porphyry systems and prospects (Muhammad et al., 2024).

The evolution of these arcs began in the Late Cretaceous with the eruption of the Sinjrani Volcanic Group in the Chagai arc and the Kuchakki Volcanics in the Raskoh arc. These units, primarily basaltic to andesitic in composition, represent a juvenile "intra-oceanic" stage of arc development (Ghalamghash et al., 2019). Geochemical data from the Sinjrani group reveal a ~2-kilometer-thick succession of lavas and tuffs that lack significant crustal contamination, pointing to a derivation from partial melting of the sub-arc mantle in an oceanic environment (Hafeez et al., 2026).

## 2.2 Stratigraphic Succession and Sedimentary Evolution

The maturation of the arc system is recorded in the overlying sedimentary and volcanic sequences. The Sinjrani Volcanic Group is sequentially succeeded by the calcareous and clastic rocks of the Humai Formation (Late Cretaceous), followed by the Paleocene Juzzak, Eocene Saindak, and Oligocene Amalaf Formations (Ghorbani, 2021).

**Table 1: Stratigraphic Succession and Sedimentary Evolution of the Chagai Arc**

Age	Formation/Group	Lithological Characteristics	Tectonic Context
Late Cretaceous	Sinjrani Volcanic Group	Basaltic to andesitic lava flows, tuffs, agglomerates	Intra-oceanic island arc initiation (Malkani, 2020; Siddiqui, 2004)
Late Cretaceous	Humai Formation	Carbonate units, limestone, calcareous shale	Shallow marine sedimentation on volcanic basement (Siddiqui, 2004)
Paleocene	Juzzak Formation	Shale, sandstone, conglomerate, interbedded andesites	Transition to mature arc setting (Malkani, 2020; Siddiqui, 2004)
Eocene	Saindak Formation	Siltstone, sandstone, limestone, volcanic flows	Subsidence and continued arc volcanism (Malkani, 2020; Siddiqui, 2004)
Oligocene	Amalaf Formation	Siltstone, shale, mudstone, andesitic lava flows	Post-collisional sedimentation and volcanism (Malkani, 2020; Siddiqui, 2004)
Miocene	Reko Diq Formation	Andesitic lavas, pyroclastics, tuff, agglomerate	Peak porphyry Cu-Au mineralization (Perelló et al., 2008; Siddiqui, 2004)
Plio-Pleistocene	Koh-e-Sultan Group	Dacitic-andesitic lavas, pumice, ash	Terminal arc volcanism and epithermal activity (Siddiqui, 2004; Perelló et al., 2008)

This stratigraphic progression highlights a shift from submarine volcanism to shallow-marine and eventually terrestrial environments, coinciding with the thickening of the crust as the Afghan micro-continental block was amalgamated into the Eurasian margin (Shroder et al., 2022).

## 3. Magmatic Evolution and the Petrotopography of Ore Genesis

The genesis of world-class ore deposits in Balochistan is fundamentally a magmatic-hydrothermal phenomenon. The transition from primitive, mantle-derived melts to highly evolved, water-rich,

and oxidized magmas is a prerequisite for the formation of large porphyry Cu-Au systems (Park et al., 2021).

### 3.1 Transition from Tholeiitic to Calc-Alkaline Suites

The early Late Cretaceous magmatism in the Chagai arc was predominantly tholeiitic to calc-alkaline, reflecting high degrees of partial melting in the mantle wedge. However, by the Miocene, the magmatic character shifted decisively toward calc-alkaline and locally alkaline (shoshonitic) compositions (Yang et al., 2025). This evolution is characterized by an enrichment in large-ion lithophile elements (LILE) and a depletion in high-field-strength elements (HFSE), creating a classic "subduction-related" geochemical signature marked by negative Nb, Ta, and Ti anomalies (Ullah et al., 2023).

The Miocene volcanic rocks, often described as the Buze Mashi Koh Volcanic Group, form gently dipping calderas of collapsed stratovolcanoes. These rocks comprise basaltic-andesite, andesite, and trachyandesite, with sub-alkaline and alkaline series distinguished by their K<sub>2</sub>O content (Bergal-Kuvikas et al., 2019). The sub-alkaline rocks, with MgO values between 8.12 and 11.38 wt.% and high Cr and Ni concentrations, suggest direct derivation from partial melting of the mantle source. In contrast, the alkaline rocks show more evolved signatures, indicating significant fractionation and crustal assimilation (Cruz-Urbe et al., 2018).

### 3.2 Adakitic Signatures and Porphyry Fertility

A critical discovery in the study of Balochistan's metallogeny is the identification of adakitic magmas associated with mineralization. Adakites are characterized by high Sr content (>400 ppm), high Sr/Y ratios (>20-40), and depleted HREE (eY < 18 ppm, Yb < 1.9 ppm) (Mastoi et al., 2019).

At the Saindak deposit, the mineralizing granodiorites are identified as typical high-silica adakites (HSA). These rocks exhibit low K<sub>2</sub>O/Na<sub>2</sub>O ratios and decoupled Sr/Y-(La/Yb)<sub>N</sub> ratios, which are interpreted as signatures of slab-derived melts (Chen et al., 2023). The proposed mechanism involves the partial melting of the subducted Neotethys oceanic crust beneath the Eurasian continent, followed by interaction with the overlying mantle wedge (Qiao et al., 202).

**Table 2: Geochemical Signatures and Mineralization Status of Magmatic Rocks**

Rock Type	SiO <sub>2</sub> (wt.%)	Sr (ppm)	Y (ppm)	Sr/Y	Mineralization Status
Saindak Granodiorite	63-68	600-900	8-12	60-85	Fertile (Cu-Au) (Mastoi et al., 2019)
Saindak Monzodiorite	52-58	300-450	18-25	15-22	Barren (Mastoi et al., 2019)
Reko Diq Quartz Diorite	60-65	500-800	10-15	40-70	Fertile (Cu-Au) (Razique et al., 2014)
Koh-e-Sultan Andesite	55-60	400-550	15-20	25-35	Sub-economic/Epithermal (Siddiqui, 2004)

The lack of a negative Eu anomaly in the fertile suites further supports high magmatic water content (H<sub>2</sub>O melt > 3.5 wt.%), as high water pressure suppresses the crystallization of plagioclase, thereby preventing the depletion of Eu in the residual melt (Dygert et al., 2024).

## 4. Geochronological Framework of the Central Tethyan Belt

Precise geochronology has revealed that mineralization in the Chagai belt occurred in several discrete pulses rather than a single continuous event. Using LA-ICP-MS U-Pb zircon dating and Re-Os molybdenite dating, researchers have constrained the timing of magmatism and mineralization across the province (Razique et al., 2014).

#### 4.1 The Eocene and Oligocene Precursors

While the Miocene is the most productive period, mineralizing events began as early as the Eocene. The Ziarate prospect has been dated to  $43.1 \pm 1.1$  Ma, while the Ganshero prospect in the eastern Chagai belt formed around  $36.1 \pm 1.1$  Ma (Zighmi et al., 2023).

#### 4.2 The Miocene Climactic Event

The Miocene epoch saw a massive surge in porphyry formation. At the Saindak deposit, U-Pb zircon ages for the ore-fertile quartz diorite porphyry are  $22.15 \pm 0.22$  Ma, while the barren diorite porphyry crystallized at  $22.21 \pm 0.33$  Ma (Hong et al., 2025). Re-Os dating of molybdenite from the K-silicate alteration zone at Saindak yields an age of  $22.2 \pm 0.3$  Ma, showing a perfect temporal correlation between magmatic emplacement and hydrothermal mineralization (Khalil et al., 2025). The Reko Diq complex represents a slightly younger but even more intense period of mineralization. The hypogene Cu-Fe-sulfide mineralization is associated with intrusions of Miocene age, ranging from  $12.9 \pm 0.3$  to  $11.9 \pm 0.2$  Ma. At Reko Diq, the western porphyry centers (H13, H14, H15, and H79) were emplaced over a window of approximately 1 million years (Xu et al., 2023).

#### 4.3 Late Miocene to Pliocene Terminal Activity

As subduction slowed and the tectonic regime shifted, terminal arc activity produced epithermal systems and smaller porphyry prospects. The Koh-e-Sultan volcano, for instance, represents Late Miocene to Early Pliocene activity (6 to 4 Ma), characterized by quartz-alunite epithermal alteration (Rabayrol et al., 2021). The last explosive activity of this volcano is dated to just 0.09 million years ago, representing the final embers of the Tethyan subduction (Hovakimyan et al., 2019).

### 5. Geochemical and Isotopic Anatomy of Major Deposits

#### 5.1 The Saindak Case Study

The Saindak porphyry system is characterized by three tonalite porphyry stocks North, South, and East intruded into a NW-trending folded sequence of Eocene to Oligocene sediments. The alteration zoning is concentric, influenced by both lithology and structural fabric (Singer et al., 2008).

1. Potassic Core: Secondary biotite, K-feldspar, and magnetite. This zone hosts primary copper mineralization as disseminations and stockwork veins (Siddiqui, 2004).
2. Propylitic Halo: Outer periphery dominated by chlorite, epidote, and calcite (Singer et al., 2008).

Mineralogically, the ore assemblage includes pyrite, chalcopyrite, molybdenite, galena, sphalerite, and bornite. Sr and Nd isotopic data for Saindak ( $87\text{Sr}/86\text{Sr} = 0.7065$  to  $0.7069$ ;  $\epsilon_{\text{Nd}}(t) = -0.7$  to  $-2.4$ ) suggest a source reflecting crust-mantle interaction (Din et al., 2025).

#### 5.2 The Reko Diq Porphyry Cluster

Reko Diq is a giant volcano-magmatic complex containing 18 known porphyry centers within a 10 x 3 km corridor. The H14-H15 system is the most significant, with a global resource of 4,100 Mt @ 0.50% Cu and 0.29 g/t Au (Liu et al., 2024).

- Porphyry Phases: The system is composed of four intrusions (PFB1 to PFB4). Highest grades ( $>0.60\%$  Cu) are in early PFB1 and PFB2 phases (Schertz, 2019).
- Vein Evolution: Early "A-style" quartz-magnetite veins, followed by "B-style" quartz-sulfide veins, and late-stage "D-style" massive pyrite-chalcopyrite veins (Sillitoe, 2010).

## 6. Isotopic Tracing and Source Determination

### 6.1 Sulfur Isotopes and Magmatic Primacy

In the Kerman and Chagai belts, delta 34S values for sulfides typically cluster around 0 permil (ranging from -4 to +7), strongly suggesting a magmatic origin for the sulfur. In specific systems like the Huangshaping deposit, deeper sulfides show magmatic values (+4.4 to +6.6 permil), while shallower sulfides incorporate reduced sulfur from evaporite sediments (+8.3 to +16.3 permil) (Sholeh & Richards, 2023).

### 6.2 Lead Isotopes and Crustal Leaching

Lead isotope ratios ( $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$ ) in the Chagai belt display linear trends indicating binary mixing. At Saindak and Reko Diq, Pb isotopic signatures suggest a combination of lead from the subducting slab and lead leached from host volcanic rocks (Muhammad et al., 2024).

### 6.3 Hf Isotopes in Zircon: The Mantle Connection

Zircon Lu-Hf isotope data provide a window into deep processes. At Saindak, epsilon Hf(t) values range from +4.7 to +7.3. These positive values indicate that magmas originated from a juvenile source likely subduction-modified lithospheric mantle or juvenile lower crust (Sarjoughian et al., 2019).

## 7. Ore Genesis of Non-Porphyry Systems in Balochistan

### 7.1 Manganese Deposits of the Bela Ophiolite

The Bela Ophiolitic Complex contains hydrothermal manganese deposits. Geochemical analysis shows a strong correlation between MnO and FeO ( $r = 0.73$ ), with major minerals being braunite and psilomelane. These deposits formed on the seafloor during the Late Cretaceous (Rashid et al., 2022).

### 7.2 Iron Ore and Skarn Mineralization

Iron ore deposits, such as those in Mashki Chah and Spezand, occur as veins and massive bodies. The Mashki Chah deposits are primarily magnetite and hematite, affected by descending meteoric fluids that created thick oxidation zones (Ahmed et al., 2023).

### 7.3 Epithermal Gold and Silver

The Koh-e-Sultan volcanic center represents a high-sulfidation epithermal environment. Intense acid-sulfate alteration (quartz-alunite) suggests potential for epithermal gold-silver mineralization (Perelló et al., 2008).

## 8. Advanced Mineral Exploration Methodologies

**Table 3: Advanced Exploration Methodologies and Field Results in Balochistan**

Exploration Method	Target/Response	Key Success in Balochistan
Magnetics	Porphyry stocks, magnetic destruction zones	Mapping epithermal trends at Siah Diq (Khalil et al., 2022)
IP/Resistivity	Disseminated sulfides, pyrite shell	Discovery of Siah Diq under 46m alluvium (Khalil et al., 2022)
BLEG Geochemistry	Regional Au and Cu anomalies	Delineation of Reko Diq and Dasht-e-Kain (Perelló et al., 2008)

Remote Sensing (ASTER)	Alteration minerals (clay, sulfate, iron oxides)	Mineralogical mapping in western Chagai (Khalil et al., 2022)
Drilling and Logging	Subsurface verification and grade estimation	Evaluation of the Spezand iron ore deposit (Beyer, 2025)

## 9. Comparative Analysis: Balochistan vs. Neighboring Belts

The Balochistan segment of the Tethyan belt bears similarities to the Kerman belt in Iran and the Lhasa terrane in Tibet (Khan et al., 2025).

### 9.1 The Kerman Belt (Iran)

The Kerman belt is the direct western continuation of the Chagai arc. Giant deposits like Sar Cheshmeh share the Miocene mineralization window (~13-12 Ma) with Reko Diq. The Chagai segment is more Au-enriched due to thinner, more juvenile crust (Sholeh & Richards, 2023).

### 9.2 The Lhasa Terrane and Gangdese Belt (Tibet)

In the Lhasa terrane, Miocene adakite-like intrusions originated from partial melting of thickened mafic lower crust during post-collisional extension (Qiao et al., 202).

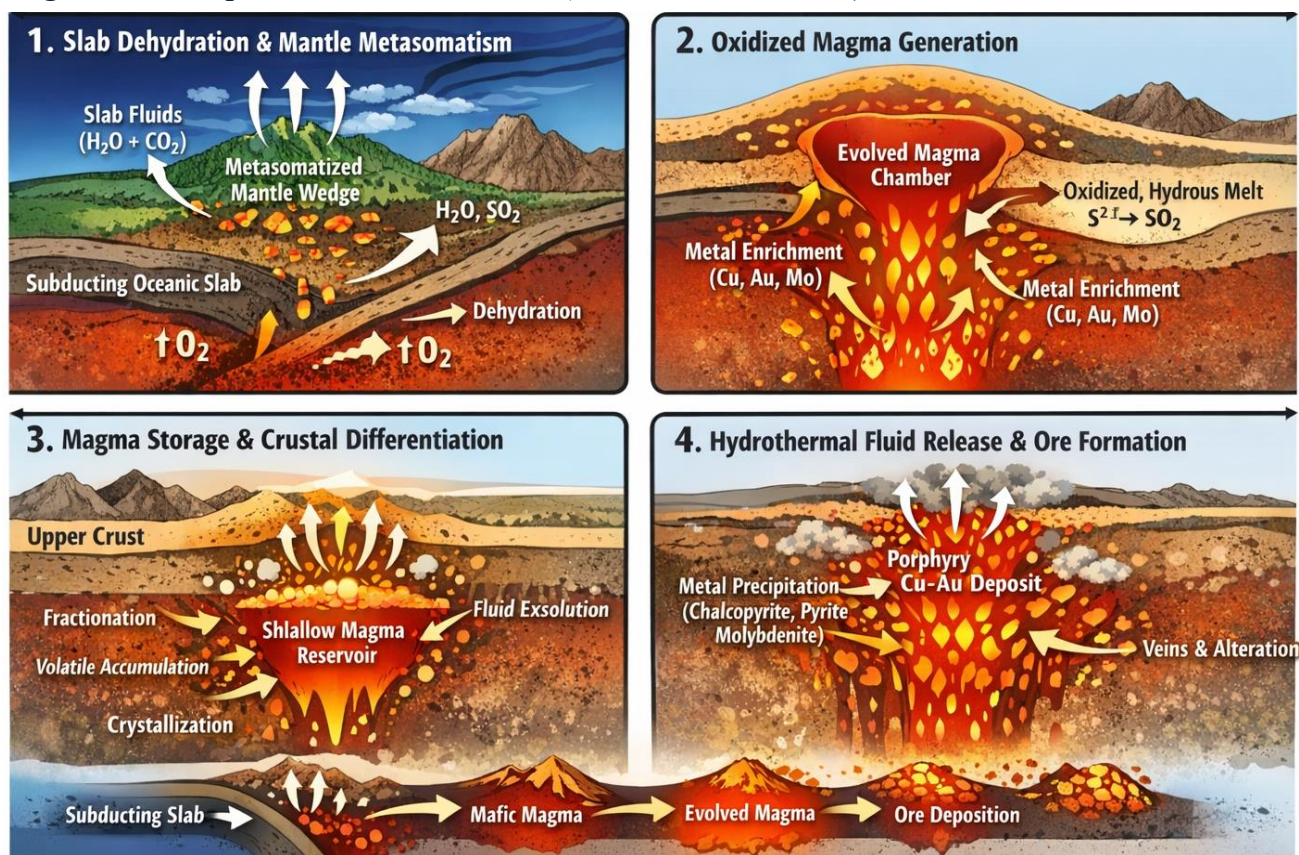
## 10. Synthesis of Ore Genesis Models

As showed in figure 2, Conceptual model of ore genesis in the Central Tethyan Belt of Balochistan. The "Balochistan Model" for ore genesis follows a four-stage process:

1. Slab-Fluid Injection: Rapid subduction increased LILE and LREE fluids in the sub-arc mantle (Chen et al., 2023).
2. Oxidized Magma Generation: Fluids triggered partial melting of mantle wedge and slab, generating high-silica adakitic magmas (Mastoi et al., 2019).
3. Crustal Maturation and Storage: Magmas stored in upper crustal reservoirs; fractional crystallization ensured retention of metals (Park et al., 2021).

4. Hydrothermal Release: Rapid depressurization led to hydrothermal fluid release and porphyry stock formation (Sillitoe, 2010).

**Figure 2. Conceptual Ore Genesis Model (“Balochistan Model”)**



## 11. Future Directions in Exploration and Research

Future exploration lies in understanding deep dynamic processes (Bergal-Kuvikas et al., 2019).

- Deep Crustal Imaging: Magnetotellurics and deep seismic reflection are needed to identify feeder structures (Hong et al., 2025).
- Critical Metals: Focus on lithium in pegmatites and minerals in the Zhob Ophiolite (Ullah et al., 2023).
- Big Data: Integration of geochemical and satellite data through machine learning (Khalil et al., 2022).

## 12. Nuanced Implications for Tethyan Metallogeny

The Chagai arc's transition from juvenile intra-oceanic to mature continental margin arc is a textbook example of magmatic maturation. The "sweet spot" occurs during this transition, where crust is thick enough for adakitic melting but juvenile enough for mantle-derived metal flux (Rabayrol et al., 2021).

## Conclusion

The Central Tethyan Metallogenic Belt in Balochistan exemplifies a dynamic interplay of geodynamic processes driving world-class porphyry Cu-Au mineralization, with geochemical and geochronological evidence confirming the pivotal role of oxidized, adakite-like magmas derived from metasomatized mantle during Neotethys subduction and collision. Deposits like Reko Diq and Saindak highlight the region's untapped economic potential, but challenges such as post-

mineral cover and structural complexity necessitate advanced exploration tools like hyperspectral imaging and isotopic fingerprinting. By integrating these approaches, predictive models can guide sustainable resource development, mitigate environmental impacts while bolstering Pakistan's mining sector. Future research should focus on underexplored segments, such as the Makran prism, to unravel additional polymetallic systems and inform global Tethyan metallogeny.

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