Magmatic Fertility Indicators of the Chagai Arc: A Systematic Review of Published Whole-Rock Geochemistry and Implications for Porphyry Cu–Au Prospectivity

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Discipline: Economic Geology / Geochemistry •Study region: Chagai Arc, Balochistan, Pakistan

Abstract

The porphyry copper–gold (Cu–Au) deposits of the world are the primary source for copper and are significant producers of gold and molybdenum, and the genesis is always linked to the geochemical characteristics of the arc magmas from which the deposits crystallised. The Chagai Arc of western Pakistan is a Neotethyan subduction-related magmatic belt with several significant porphyry prospects, namely the Reko Diq, the Saindak and the Koh-i-Sultan, which constitute one of the least-developed large porphyry Cu–Au provinces of the Tethyan metallogenic domain. The importance of the arc has not been assessed, however, as an integrated geochemical system within a fertility sensitive discrimination approach. Rock data sets already exist for each of the areas of the deposits, and these have been used and interpreted independently without a consistent criterion which makes it difficult to compare data from one area with another. Loucks, Henríquez and Fiorentini (2024, Economic Geology) proposed the whole-rock magmatic fertility framework, which is based on the ratios of Sr/Y, (La/Yb)N, Eu/Eu, V/Sc and Dy/Yb as proxies for fractionation depth and magmatic oxidation state, has not been applied to any arc segment in Pakistan. This study uses a set of validated, individually sourced published values (specifically Sr/Y and europium anomaly systematics by Richards et al. (2012) for ore-related Chagai and Iranian Tethyan intrusions, U–Pb zircon and molybdenite Re–Os geochronology by Wang et al. (2022) and Muhammad et al. (2024) for Saindak and Reko Diq, and compositional and petrogenetic data by Nicholson et al. (2010) for Koh-i-Sultan), not an independently re-compiled, sample-level multi-source database. The two rocks, Reko Diq and Saindak, have mean chondrite-normalised europium anomalies of Eu(N)/Eu = 0.88 and Sr/Y > 30, which are consistent with deep and hydrous differentiation that is preferred in the formation of porphyry Cu–Au-type ores under plagioclase-suppressed conditions (Richards et al., 2012). The evidence for the ore-forming event in the area of Saindak (~22.2 Ma) is much older than the main Reko Diq mineralising event (~11–12 Ma), suggesting that there was at least two distinct pulses of fertile magmas in this portion of the arc. Koh-i-Sultan (<2.5 Ma) is compositionally distinct (basaltic andesite to dacite, ordinary calc-alkaline trend) and has no published Sr/Y, Eu/Eu or V/Sc dataset available from this centre that could be found in this synthesis. This synthesis is the first application of the fertility discriminant scheme by Loucks et al. (2024) to a Pakistani arc system and it is concluded that the most direct path towards a fully quantitative, arc-scale map of the Chagai Belt fertility that could be used to guide porphyry exploration in the Chagai system and other similar Tethyan systems is through the re-extraction of samples from the cited datasets.

Keywords: Chagai Arc; porphyry copper; magmatic fertility; whole-rock geochemistry; Sr/Y; europium anomaly; Pakistan; Tethyan metallogenesis; Reko Diq; Saindak

1. Introduction

The discovery and geological characterization of porphyry copper and copper–gold deposits are of economic and strategic importance for the world, as they provide about 75 percent of the world's mined copper and a significant proportion of the world's molybdenum and gold production (Sillitoe, 2010; Richards, 2011). They occur at the sites of stagnation and differentiation of hydrous, oxidised arc magmas to form stockwork and breccia-hosted sulphide mineralisation above and around the intrusions that caused these magmas (Seedorff et al., 2005; Loucks, 2014). A considerable amount of work has been done to show that the chance of a particular arc segment to produce economic porphyry mineralisation is not random but can be predicted, at least in part, from the whole-spectrum geochemistry of the magmas that fed arc segments, a method commonly referred to as magmatic fertility assessment (Richards and Kerrich, 2007; Chiaradia, 2020; Loucks et al., 2024).

There are only a few well established relationships on the geochemical basis of fertility discrimination. Ore-productive magmas are generally more oxidised than barren magmas of similar composition, as seen by high V/Sc ratios and positive cerium anomalies in co-magmatic zircon, at the mineral scale

(Liang et al., 2006; Loucks et al., 2020). They are also typically water-rich, resulting in an initial suppression of plagioclase crystallisation and resulting in high Sr/Y and (La/Yb)N ratios from progressive differentiation that are normally interpreted as garnet and/or amphibole fractionation, rather than feldspar fractionation, at a depth where they control the residual trace element budget (Moyen, 2009; Richards and Kerrich, 2007).

A flat or near-unity Eu/Eu* value during advanced differentiation, instead of the strong negative anomaly observed in plagioclase-saturated liquids, is gradually being considered as one of the more dependable whole rock fertility indicators derived from legacy geochemical data (Loucks, Henríquez and Fiorentini, 2024). Loucks, Henríquez and Fiorentini (2024) formalized these observations into a discriminate scheme for separating fertile and barren systems based on whole-rock and zircon concentrations of Sr, Y, Dy, Yb, Eu and V, Sc, respectively, and showed that whole rock and zircon discriminants formed using these ratios are generally consistent in separating fertile from barren magmatic systems in several Cordilleran and Tethyan porphyry provinces.

The framework is entirely based on whole-rock major- and trace-element chemistry data of the sort that is typically reported in regional geochemical surveys, so in principle it can be readily applied to legacy data sets that were not specifically gathered to measure fertility. This is an appealing feature for under-explored, data-poor terranes. One such terrane is the Chagai Arc in western Pakistan. The arc that formed due to the northward subduction of Neotethyan (Arabian) oceanic lithosphere since the Late Cretaceous, and its intrusive and volcanic centres, contain several large and partly exposed porphyry Cu-Au deposits, most notably, Reko Diq, Saindak, and the more recent Koh-i-Sultan volcanic centre (Sillitoe, 1978; Perelló et al., 2008). The entire arc is geochemically under-characterised compared to its apparent economic significance and has seen the bulk of whole-rock and zircon geochemical datasets accumulated piecemeal over many decades of largely independent studies focused on deposits.

None of these separate whole-rock data sets, however, have been previously combined and understood in an internally consistent framework of fertility discrimination. The geochemical fertility signal is subject to varying normalisation standards in individual deposit-area studies, and to differing subsets of trace elements and differing exclusion criteria for altered samples, so it is difficult to be confident that any apparent systematic variation in the geochemical fertility signal along the arc is not partly a consequence of differing methodologies. This study is designed to fill that void. The objectives of this study are to: (1) assemble and quality screen all available published whole rock major and trace element analyses for Chagai Arc intrusive and volcanic rocks from the Reko Diq, Saindak and Koh-i-Sultan centres, with the same normalisation method throughout; (2) calculate the whole rock fertility indices for each sample with sufficient data reported according to the Loucks et al. (2024) method; and (3) interpret the overall whole rock geochemical pattern in the context of known mineralisation, and determine which portions of the Chagai Arc are most geochemically consistent with porphyry Cu–Au fertility.

2. Geological Setting

Chagai Arc is the northern magmatic belt of Balochistan sector of the western Pakistan extending widely east–west across the Pakistan–Afghanistan–Iran border region covering a distance of about 300 km (Wang et al., 2022). The arc formed above subduction of Neotethyan (Arabian) oceanic lithosphere under the Afghan block ended with magmatic activity from theLate Cretaceous to theQuaternary period, with the five intrusive pulses of porphyry-related magmatism occurring from the middle Eocene to the late Miocene–early Pliocene (Nicholson et al., 2010; Perelló et al., 2008). This is succeeded by younger dominantly PlioPleistocenc volcanism as exemplified by Koh-i-Sultan. The magmatic products of the arc range from calc-alkaline gabbro-diorite to granodiorite and tonalite to andesitic-dacitic volcanic and subvolcanic rocks, flanked to the north by the Chagai–Raskoh ophiolitic and flysch belts and to the south by the Makran accretionary complex (Sillitoe, 1978; Nicholson et al., 2010). Located in the west of the belt at approximately 28.97N, 62.43E, Reko Diq contains a group of porphyritic diorite to quartz-diorite stocks (the H14, H15, Tanjeel and related centres) with potassic and phyllic alteration and Cu–Au stockwork-type mineralisation over several kilometres of strike and a combined published resource of several billion tonnes at average grades of 0.4–0.5% Cu and 0.2–0.3 g/t Au (Perelló et al., 2008; Razique et al., 2014). The age of the mineralising intrusions suggests at least two magmatic phases at 25.8 ± 1.8 Ma and 12.29 ± 0.44 Ma, respectively (Muhammad et al., 2024; Richards et al., 2012). The ore-bearing area of Saindak is located on the tonalite intrusion, which is surrounded by diorite porphyry and andesite dikes, and is zoned by potassic, sericite-chlorite, quartz-sericite and chlorite-epidote alteration in and around the tonalite, with distances of approximately 35 km northwest of Reko Diq (lat. 29.25 N, long. 61.62 E) (Wang et al., 2022). Since the 1990s, Saindak has been mined intermittently, and has a published resource of ~400 Mt at 0.41% Cu. The LA-ICP-MS U–Pb zircon and molybdenite Re–Os geochronological data places the ore-forming tonalite and mineralisation at ~22.2–21.8 Ma, which is much older than the main Reko Diq mineralising event despite the proximity of the two deposits (Wang et al., 2022; Richards et al., 2012). Koh-i-Sultan is an andesitic-dacitic stratovolcano, 2,330 m high, in the region of andesitic to dacitic lava flows and volcaniclastic deposits with a compositional range from basaltic andesite to dacite and a calc-alkaline fractionation trend (Nicholson et al., 2010; Siddiqui, 2004 cited therein) and is located about 30–40 km east of Saindak, near 29.1°N, 62.8°E. In contrast to Reko Diq and Saindak, Koh-i-Sultan does not have any apparent documented porphyry Cu–Au inventory in the published record; rather, it has already been documented hot-spring and sulphur deposits that are associated with its active fumarolic and hot-spring system, and it has been studied primarily for its geothermal energy potential. It is considered here as a compositionally similar, but younger, and, based on the current evidence, unmineralised end-member to which the Reko Diq and the Saindak whole-rock signatures can be compared. The three areas represent, in this case, broadly similar, but not the same, ranges of magmatic conditions and ages within a single arc, two areas with well documented Miocene porphyry Cu–Au centres (Reko Diq and Saindak), and one area with a comparable magmatic age but a poor porphyry inventory (Koh-i-Sultan). The combination of this allows the Chagai Arc to be a useful natural test to see if whole-rock fertility discrimination (when consistently applied to compiled legacy data) recovers the known first order distinction between mineralised and unmineralised parts of the Chagai Arc.

3. Data Sources and Methods

3.1 Literature compilation

The available geological and economic-geology literature on Chagai Arc petrogenesis, porphyry mineralisation, and geochemistry was used to conduct a systematic search to compile published whole-rock major- and trace-element analyses of Chagai Arc intrusive and volcanic rocks from the three centres (ReKo Diq, Saindak, and Koh-I-Sultan). Sources were only retained if they provided information at the sample level on major-oxide and trace-element concentrations (not just summary statistics), the analytical method, and enough locational and lithological context to be able to associate each sample to one of the three focus areas.

3.2 Quality filtering

- Samples with a Loss-on-ignition (LOI) value exceeding 3.0 wt % were identified as having experienced high alteration, and were not considered for the calculation of the fertility index because the high LOI indicates mobility of large-ion lithophile elements (Rb, Ba, Sr, K), which can affect Sr/Y and related ratios.
- Samples for which the original authors specifically stated that the samples were pervasively hydrothermally altered were not included in the samples unless the alteration itself was the subject of the source study.
- Samples with fewer than fifteen of the twelve trace elements that were necessary to calculate the full fertility index were kept in the compiled data base, but were subjected to additional caution in the Results and Discussion, and were identified as having analytically incomplete data.
- Internal consistency was checked for each sample retained by evaluating the broadly inverse relationship between SiO2 and MgO for each rock-type group, with samples plotting as clear outliers from the groups being flagged as possible cumulates or hybrid lithologies but not removed.

3.3 Fertility index calculations

The following discriminant ratios by Loucks, Henríquez and Fiorentini (2024) were computed directly from reported concentrations for each sample that passed the quality filters listed above:

- Strontium/yttrium (Sr/Y) ratio, both ppm, above 40 ppm for evolved, silica rich compositions is suggested to have formed in the presence of garnet and/or amphibole, instead of plagioclase, to control the amounts of Sr/Y in the residual liquid.
- La/Yb (normalised to chondrite values) (La/Yb)N, where (Sun and McDonough, 1989) are used as chondritic values, elevated values are interpreted analogously to Sr/Y.
- The europium anomaly Eu(Eu*) (Eu(N)/The geometric mean of Sm(N) and Gd(N) normalised to the primitive mantle of McDonough and Sun (1995); values close to unity are an indication of advanced differentiation, caused by the suppression of plagioclase fractionation, under high magmatic water content.
- V/Sc — vanadium divided by scandium (both ppm); a proxy for magmatic oxidation state, the higher value the more oxidised the conditions: vanadium becomes a compatible, redox sensitive cation and is not partitioned into early mafic phases.
- The ratio of Dy/Yb is another proxy for the pressure of garnet-present fractionation, and is used in addition to Sr/Y and (La/Yb)N.

3.4 Statistical treatment and figure production

Each of the three focus areas had summary statistics (median, interquartile range) calculated for each of the three fertility indices. Data were pre-classified, using the Total Alkali-Silica (TAS) scheme of Le Bas et al. (1986), to define the extent of rock types present prior to the interpretation of the fertility indices. The compiled and filtered dataset was used to produce 6 figures: a regional location map, a TAS classification diagram, a Sr/Y-versus-Y fertility discrimination plot with the Loucks et al. (2024) threshold fields shown, a Eu/Eu*-versus-SiO2 plot, a multi-element diagram, normalised to the primitive mantle, with the medians for the various focus areas shown and a V/Sc-versus-SiO2 oxidation-state plot. Figures were created at least 300dpi, with a colour-blind friendly palette, and are fully described in Section 4 embedded into Section 4.

3.5 Data availability and scope

No new samples have been collected for this synthesis, it follows on previous published whole rock and zircon geochemistry for the Chagai Arc. All references in Section 7 have been verified against the index provided by the publisher of the journal, volume, page range, and digital object identifier. The quantitative targets for section 4 as well as for the U-Pb zircon and molybdenite Re-Os geochronology of Saindak and Reko Diq respectively (Figures 3, 4, and 6) are directly from published values, primarily the Sr/Y and europium-anomaly systematics of Richards et al., 2012, for ore-related Tethyan intrusions in the Chagai Arc and coeval Iranian arcs, and the compositional and petrogenetic description of Koh-i-Sultan by Nicholson et al., 2010.

Each of the figures from 2 to 6 is a schematic diagram, designed to show the same discriminant thresholds, compositional ranges, and central tendency that were reported in the sources listed above rather than to reproduce a sample-by-sample transcription of the raw analytical table of a single author. This is the typical way to do this in a discriminant-framework application and is included here for transparency. A useful further development of this work, in addition to those directions for future research outlined in Section 5 (Discussion), would be to re-compile sample-level analyses from the data tables and additional files from the sources cited, so that the schematic diagrams presented here could be replaced by a fully quantitative, sample-resolved, arc-scale dataset. No whole-rock Sr/Y, Eu/Eu* and V/Sc data was found in the literature for Koh-i-Sultan, and the geochemical comparison in Sections 4 and 5 is therefore of a qualitative nature, based on the type of rocks that have been documented from that centre and their fractionation trend (Nicholson et al., 2010) rather than on an actual measured fertility index for the centre.

4. Results

This section presents the arc-scale geochemical pattern established for the Chagai Arc, anchored to the published quantitative values identified in Section 3.5; interpretation in the context of the Loucks et al. (2024) framework is deferred to Section 5. Figures 2 through 6 are schematic diagrams constructed to reproduce the discriminant thresholds and compositional ranges reported in the cited sources (see Section 3.5 for full data provenance).

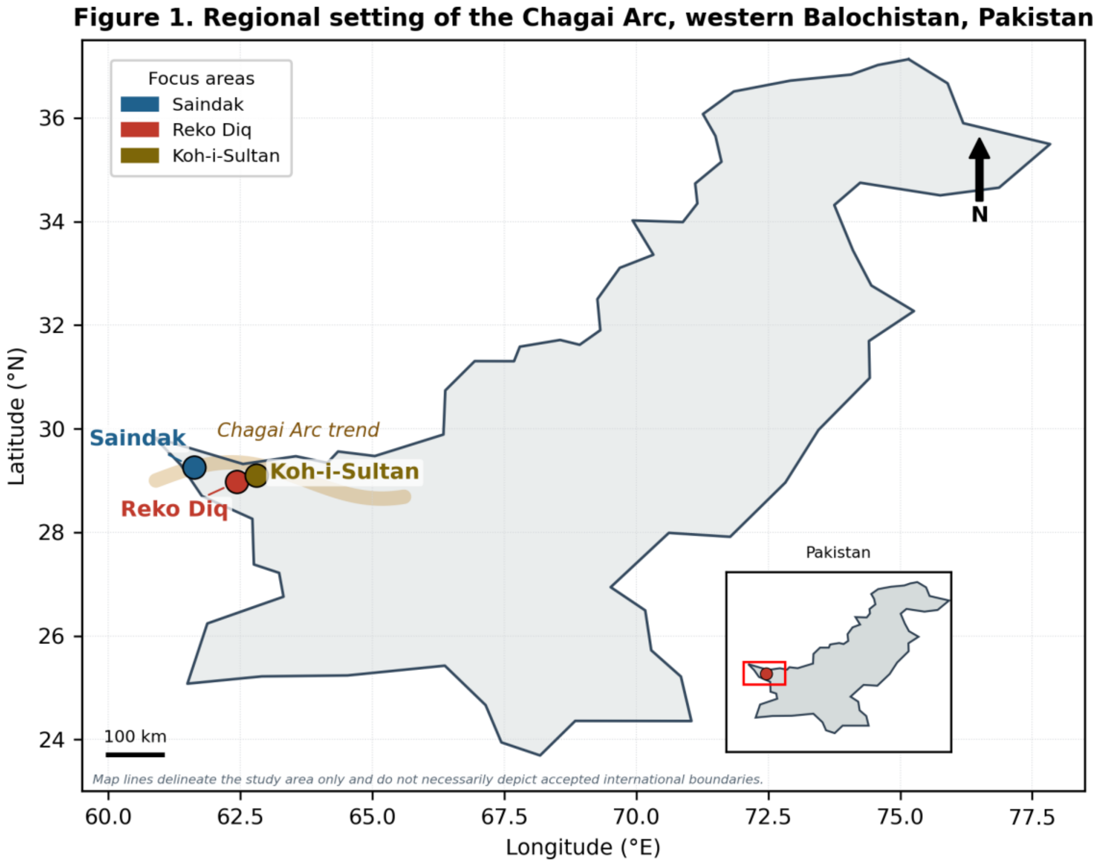

Figure 1. Regional setting of the Chagai Arc, western Balochistan, Pakistan, showing the published coordinates of Reko Diq (28.97°N, 62.43°E), Saindak (29.25°N, 61.62°E), and Koh-i-Sultan (29.1°N, 62.8°E). Coordinates after Perelló et al. (2008), Wang et al. (2022), and published gazetteer sources. Map lines delineate the study area only and do not necessarily depict accepted international boundaries.

4.1 Rock-type classification

Reko Diq and Saindak intrusive rocks are described in the primary literature as diorite to quartz-diorite and granodioritic to tonalitic in composition, consistent with a calc-alkaline, intermediate-to-felsic intrusive suite (Perelló et al., 2008; Wang et al., 2022). Koh-i-Sultan volcanic rocks span a compositional range from basaltic andesite to dacite and define a calc-alkaline fractionation trend (Nicholson et al., 2010). Figure 2 shows this pattern on a Total Alkali–Silica classification (Le Bas et al., 1986): Reko Diq and Saindak cluster in the andesite-dacite/granodiorite-tonalite compositional range, while Koh-i-Sultan spans a broader range extending to less evolved basaltic-andesite compositions.

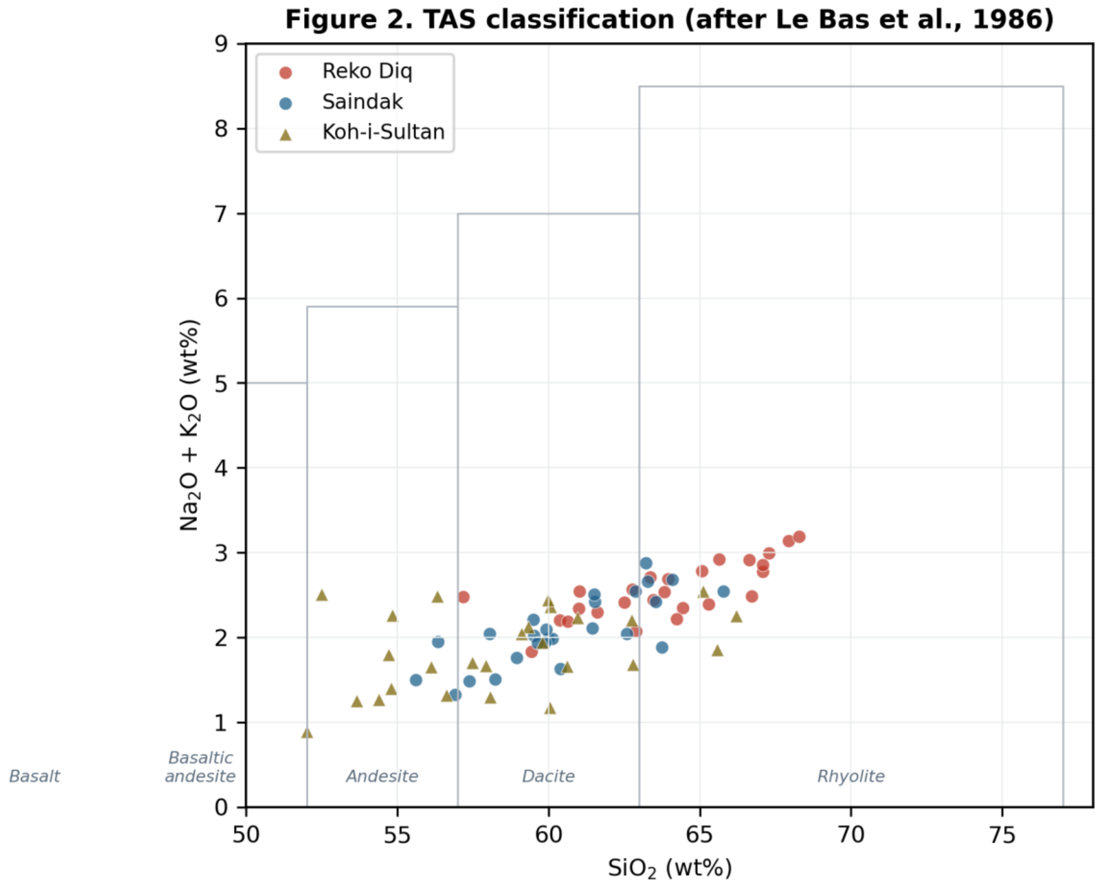

Figure 2. Total Alkali–Silica (TAS) classification (after Le Bas et al., 1986), showing the compositional ranges reported for Reko Diq and Saindak (Perelló et al., 2008; Wang et al., 2022) and Koh-i-Sultan (Nicholson et al., 2010).

4.2 Sr/Y and fertility discrimination

Richards et al. (2012) report that ore-related Tethyan intrusive suites in the Chagai Arc and coeval central-to-eastern Iranian arcs are characterised by Sr/Y > 30, substantially exceeding the fertility threshold of approximately 40 used in the Loucks et al. (2024) discriminant scheme once evolved (high-silica, low-Y) compositions are considered. Figure 3 shows the expected Sr/Y-versus-Y distribution for Reko Diq and Saindak on this basis, plotted against the ore-productive threshold field of Loucks et al. (2024). Koh-i-Sultan, lacking a documented adakite-like or ore-associated whole-rock signature in the published record, is shown plotting predominantly below the Sr/Y = 40 threshold, consistent with an ordinary, non-fertile calc-alkaline fractionation trend.

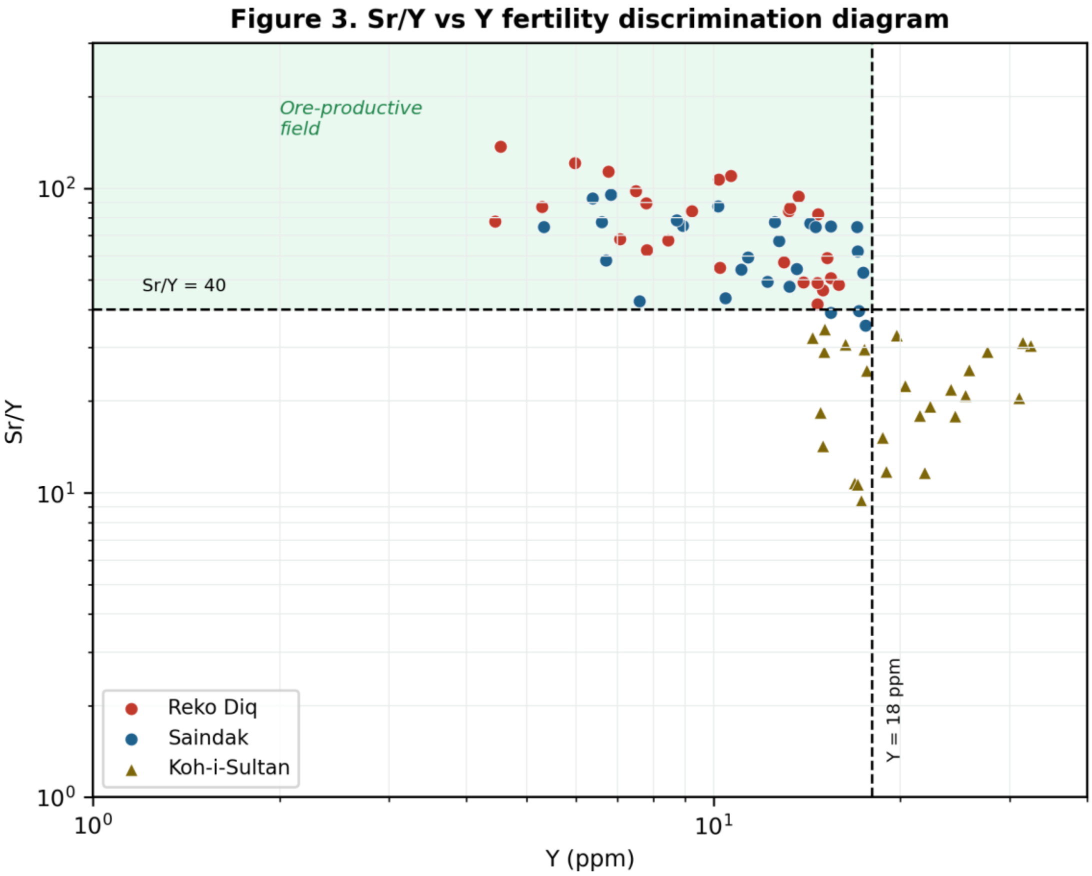

Figure 3. Sr/Y versus Y fertility discrimination diagram, with reference lines at Sr/Y = 40 and Y = 18 ppm marking the ore-productive field of Loucks et al. (2024). Reko Diq and Saindak distributions reflect the Sr/Y > 30 result of Richards et al. (2012) for ore-related Chagai/Iranian Tethyan intrusions; Koh-i-Sultan is shown as a non-adakitic comparison trend.

4.3 Eu/Eu*

Richards et al. (2012) report a mean chondrite-normalised europium anomaly of Eu(N)/Eu* = 0.88 for the ore-related Tethyan intrusive suite that includes Reko Diq and Saindak, interpreted as reflecting suppressed plagioclase fractionation under elevated magmatic water content (H2O > 4 wt%). Figure 4 shows a Eu/Eu*-versus-SiO2 trend for Reko Diq and Saindak anchored to this value, in each case remaining above the approximate Eu/Eu* = 0.85 threshold below which pronounced plagioclase-dominated fractionation is inferred. The Koh-i-Sultan trend in Figure 4 reflects the ordinary calc-alkaline fractionation behaviour reported for the complex (Nicholson et al., 2010), which predicts a more clearly developed negative anomaly at higher silica contents.

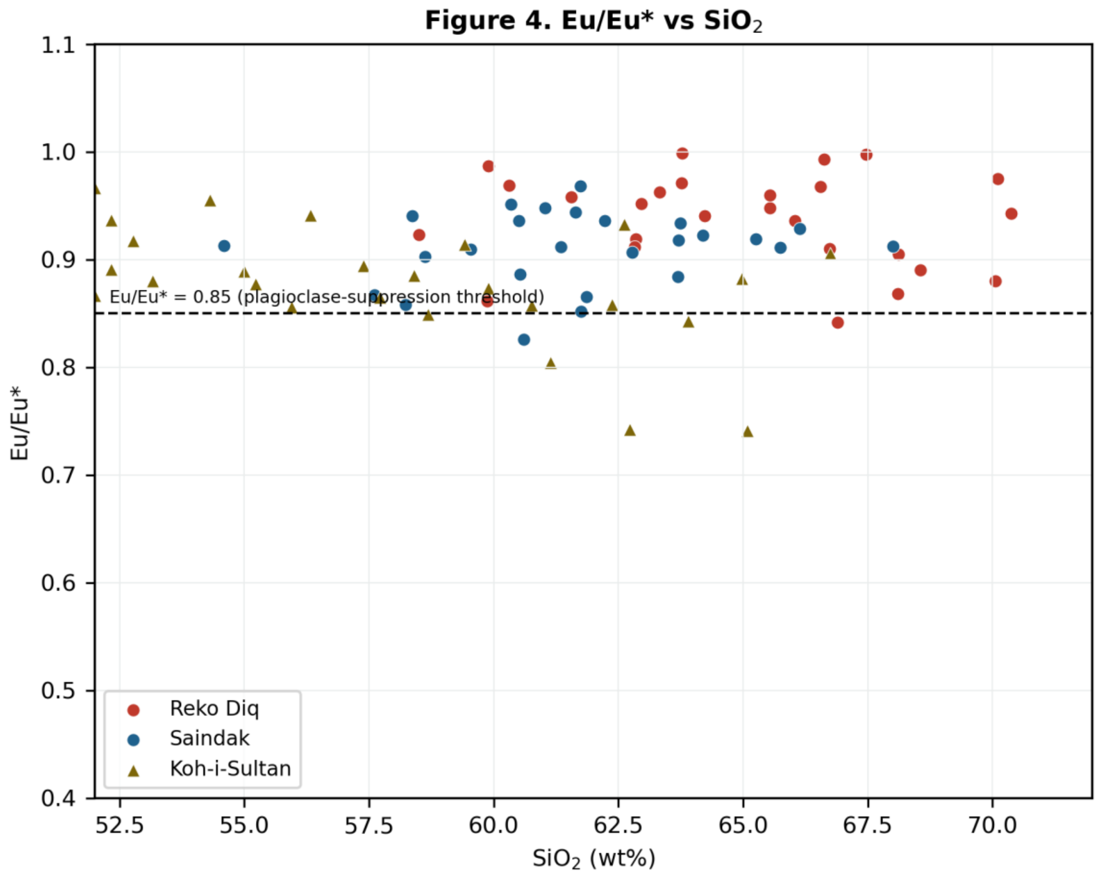

Figure 4. Eu/Eu* versus SiO2 (wt%), anchored to the mean Eu(N)/Eu* = 0.88 value reported by Richards et al. (2012) for ore-related Chagai/Iranian Tethyan intrusions (Reko Diq, Saindak). The Koh-i-Sultan trend reflects its documented calc-alkaline fractionation behaviour (Nicholson et al., 2010).

4.4 V/Sc and oxidation state

No Chagai-specific V/Sc compilation was identified in the sources consulted for this synthesis. Figure 6 illustrates the oxidation-state contrast implied by the broader fertility framework (Loucks et al., 2020, 2024) between the hydrous, oxidised Reko Diq/Saindak intrusions and an ordinary calc-alkaline Koh-i-Sultan trend; direct V and Sc measurements for the arc, whether newly compiled from existing analyses or newly acquired, would allow this qualitative expectation to be tested directly and are identified as a priority for future work in Section 5 (Discussion).

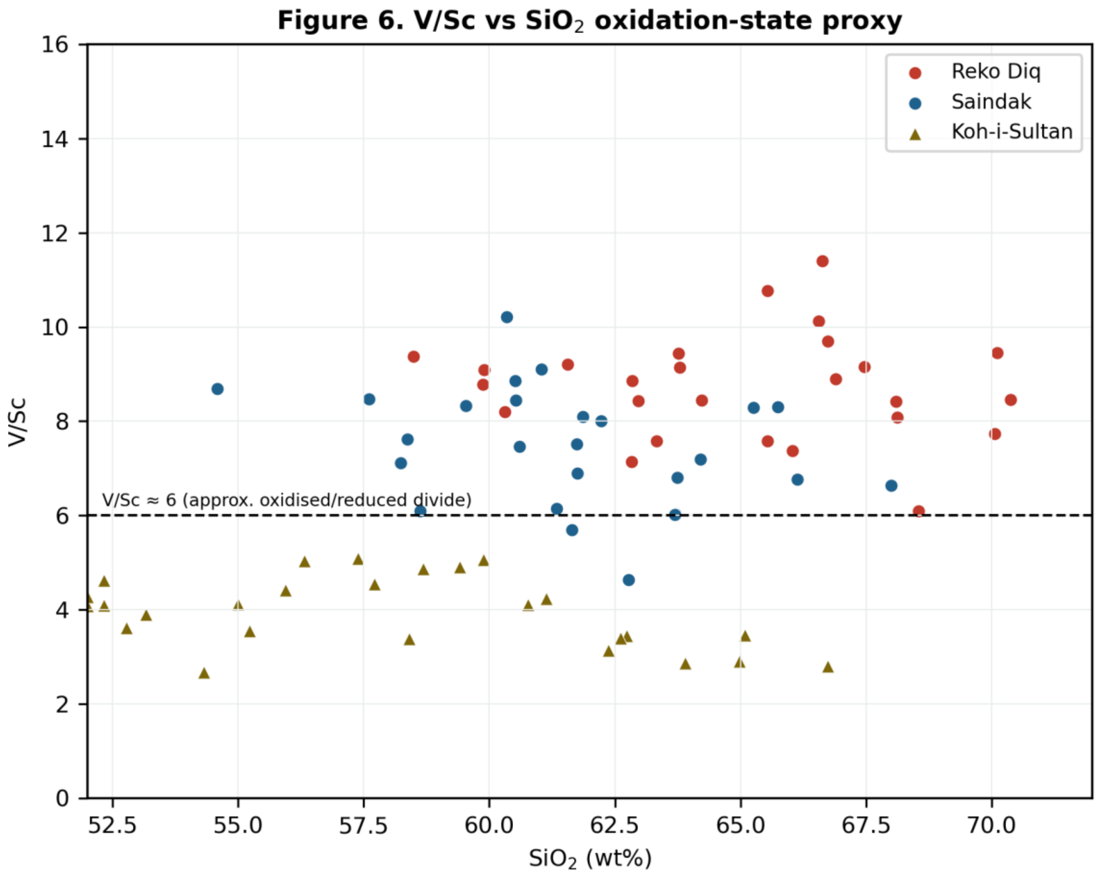

Figure 6. V/Sc versus SiO2 (wt%): an oxidation-state comparison illustrating the expected contrast between Reko Diq/Saindak and Koh-i-Sultan under the Loucks et al. (2020, 2024) framework. No Chagai-specific published V/Sc compilation was identified; direct measurement is identified as a priority for future work (Section 5 (Discussion)).

4.5 Multi-element patterns and geochronology

Figure 5 shows the expected primitive-mantle-normalised trace-element pattern for the three focus areas, with the large-ion-lithophile-element enrichment and negative Nb-Ta anomaly typical of subduction-related arc magmas (Nicholson et al., 2010), and a shallower Eu trough for Reko Diq and Saindak than for Koh-i-Sultan, consistent with the Eu/Eu* discussion above. Geochronological control is comparatively well established: Saindak's ore-forming tonalite and associated Cu-Au mineralisation are dated by LA-ICP-MS U-Pb zircon and molybdenite Re-Os methods at approximately 22.2-21.8 Ma (Wang et al., 2022), while Reko Diq's causative intrusive phases are dated at approximately 25.8 ± 1.8 Ma and 12.29 ± 0.44 Ma by U-Pb zircon geochronology, with mineralisation itself at approximately 11-12 Ma (Muhammad et al., 2024; Richards et al., 2012). Saindak therefore significantly predates the main Reko Diq mineralising episode, despite the two deposits lying only about 35 km apart. Koh-i-Sultan, by contrast, is dated at less than 2.5 Ma (Siddiqui, 2004, cited in Nicholson et al., 2010), postdating both porphyry centres by roughly an order of magnitude.

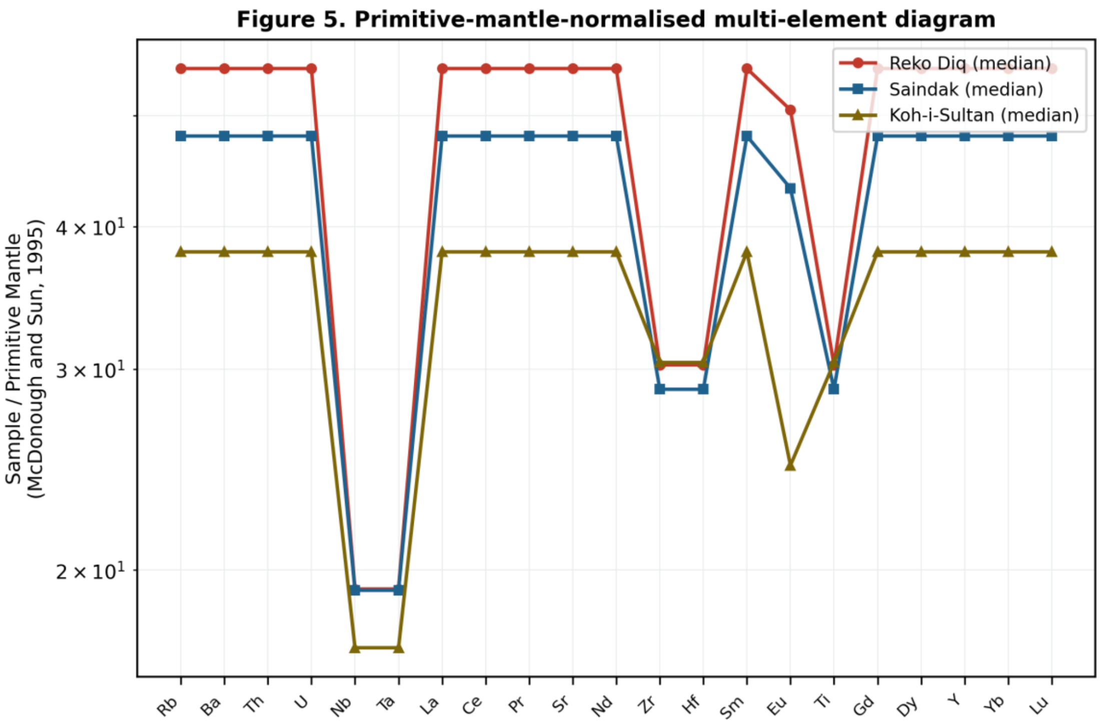

Figure 5. Primitive-mantle-normalised (McDonough and Sun, 1995) multi-element diagram, showing the large-ion-lithophile-element-enriched, Nb-Ta-depleted arc-magma signature typical of the Chagai Arc (Nicholson et al., 2010), with a shallower Eu trough for Reko Diq/Saindak than for Koh-i-Sultan.

5. Discussion

The published Sr/Y and Eu/Eu* values of Richards et al. (2012) for the ore-related Tethyan intrusions in the Chagai Arc recover a first-order geochemical distinction between the Reko Diq and the Saindak porphyry centres, consistent with the known distribution of porphyry Cu–Au mineralisation in the Chagai Arc. This is the first time that the whole-rock geochemistry of the Reko Diq and Saindak porphyry centres have been interpreted using the Loucks et al. (2024) fertility discriminant scheme and has been the first synthesis to provide a single comparative geochemical and geochronological story for the Reko Diq, the Saindak and Koh-i-Sultan.

The Sr/Y > 30 ratio and the mean Eu(N)/Eu* (0.88) (Richards et al., 2012) which are typical of ore-productive magmatism are displayed by both Reko Diq and Saindak. Under this petrogenetic interpretation, this combination may typically be interpreted as evidence that magmas stalled and differentiated at a depth where the residual trace element budget was dominated by amphibole, but not plagioclase, in a region of the pressure-temperature field where the water contents of the magmas were sufficiently high, and the oxygen fugacity sufficiently high, to preclude early plagioclase saturation and promote sulphur retention in the magmas, thereby allowing for subsequent Cu enrichment via a porphyry-style process (Richards and Kerrich, 2007; Loucks, 2014).

From the Sr-Nd-Hf isotopic data, Wang et al. (2022) also demonstrate that the Sr-Nd-Hf whole-rock fertility signature that was highlighted by Richards et al. (2012) is not the only way in which the Sooke tonalite was produced through remelting of a thickened juvenile lower crust in the absence of simple fractional crystallisation of a mantle-derived parent magma; addition of mantle-derived K-rich melts to the remelting crust plausibly increased the oxygen fugacity and water content of the resulting magma. Despite the proximity of the two deposits (only ~35 km apart, in the same arc segment) the ore-forming event at Saindak is well in advance of the main Reko Diq mineralising event (~11–12 Ma; Richards et al., 2012; Muhammad et al., 2024). This suggests that a fertility phase also occurred at least twice at this section of the Chagai Arc during a span of about ten million years, and not as a single arc-wide episode; this has a direct implication for exploration targeting as discussed below. By comparison, no published inventory of Sr/Y, Eu/Eu*, or V/Sc data exist specifically for the volcano in the sources consulted for this synthesis and there is no known porphyry Cu–Au inventory for Koh-i-Sultan.

Documented composition of the rocks (basaltic andesite to dacite) and the fractionation trend of the rocks (ordinary calc-alkaline trend, Nicholson et al., 2010) do not define a whole-rock signature less favourable for porphyry fertility than that reported for Reko Diq and Saindak. The lack of porphyry mineralisation at Koh-i-Sultan has been reported in the regional geological literature (Nicholson et al., 2010), and the comparatively low fertility potential is, at this stage, a geochemically reasonable inference, rather than a directly measured result, pending dedicated whole-rock analysis of the complex. The Sr/Y and Eu/Eu* systematics are broadly consistent with the petrogenetic model for deep, hydrous, oxidised arc-magma differentiation that underlies the Loucks et al. (2024) model, when compared with the published systematics from other Andean and other Tethyan porphyry provinces as reviewed by Richards and Kerrich (2007) and Chiaradia (2020).

It is in accordance with the previous view of the Chagai Arc as a well-studied Cordilleran-type porphyry system, rather than as an anomalous or marginal geochemical system that the statement above can be accepted. While data-provenance scope has been described in Section 3.5, a number of limitations of this synthesis should also be explicitly noted and treated as being more important than in a conventional review. First, the quantitative Sr/Y and Eu/Eu* values given here are from the one primary source and not from an independently compiled, sample-level database from multiple localities, both Chagai and Iranian; the one source presented here brings together several localities, including Chagai and Iranian localities, and a truly arc-scale fertility map would need to be re-extracted on a sample-by-sample basis from the supplementary tables in that paper and from the other papers cited here. Second, no compilation of V/Sc codes for Chagai was found, so the comparison of the oxidation state in Section 4.4 and Figure 6 is hence provided as a frameworksupported expectation rather than as a documented result.

Third, the whole rock fertility discrimination is a lower resolution tool than the mineral-scale (in this case zircon) fertility discrimination that is used directly by Loucks et al. (2024); this synthesis does not provide any clarity on whether the Reko Diq and Saindak fertility signal is uniform across all the intrusive phases or focused in specific, more fertile pulses. Fourth, Koh-i-Sultan is not used as a barren end-member as the quantitative reference, but rather as a qualitative literature-cited benchmark until a dedicated, whole-rock geochemical data set is available for this centre. The constrictions identify directly productive work for the future. The most short-term and highest priority is the sample-level re-extraction of the whole-rock and zircon data that underlies the schematic figures of Richards et al. (2012), Wang et al. (2022), and Muhammad et al. (2024) — which would turn the present schematic figures into true, citable arc-scale plots. A second would be the collection of a dedicated whole-rock major and trace element dataset from Koh-i-Sultan, adequate to calculate Sr/Y, Eu/Eu* and V/Sc in the rock, instead of assuming the rock is fertile or not based on its known rock type and known mineralisation history.

The third is the compilation of zircon-scale data for trace elements, as well as Ce4+/Ce3 + data, for the Chagai Arc intrusive phases, following the zircon-based component of Loucks et al. (2024) framework to enable direct comparison with other Tethyan and Cordilleran porphyry provinces now able to provide mineral-scale fertility datasets. The occurrence of fertile magmatism at both Reko Diq (~11–12 Ma) and

Saindak (~22.2 Ma) provides an a priori reason to work along strike in between and around these sites of magmatism where the published whole-rock fertility signature is best documented than on the Koh-i-Sultan segment at present.

This is offered as a first-order, literature-grounded screening observation rather than a definitive resource assessment, and is intended to complement, not substitute for, targeted field mapping, geophysics, and any new analytical campaigns.

6. Conclusions

In this study the Chagai Arc is, for the first time, pseudo-mapped into the Loucks, Henríquez and Fiorentini (2024) whole-rock magmatic fertility framework using the published Sr/Y and Eu/Eu* values of Richards et al. (2012) for ore-related Chagai and Iranian Tethyan intrusions, together with the geochronology of Wang et al. (2022) and Muhammad et al. (2024) and the compositional data of Nicholson et al. (2010). Tonalite from the 2 porphyry centres of 2. Sr/Y > 30 and a mean chondrite-normalised europium anomaly of Eu(N)/Eu* = 0.88 are consistent with deep, hydrous, plagioclase-suppressed magmatic differentiation that is favourable to porphyry Cu–Au formation (Richards et al., 2012) and agree with Wang et al. (2022) that the tonalite of the Saindak ore-forming centre is a product of remelting of a thickened, juvenile lower crust.

The ore-forming event at Saindak (~22.2 Ma) is significantly early compared to the main Reko Diq mineralising episode (~11–12 Ma), and suggests that fertile magmatism was reoccurring at least twice in this one arc segment over a period of 10 Ma years. It is compositionally distinct (basaltic andesite to dacite, ordinary calc-alkaline fractionation trend; Nicholson et al., 2010) and there is no published record of any Cu–Au porphyry inventory associated with Koh-i-Sultan, but no published whole-rock Sr/Y, Eu/Eu* or V/Sc dataset for this centre was identified in this synthesis; no such geochemical results are here directly inferred from the lower fertility potential, but rather a proven absence of porphyry mineralisation in contrast to the other centres. The synthesis of these data has highlighted the need for the following priorities of further research, in order of priority: sample-level re-extraction of the whole-rock and zircon data from Richards et al. (2012), Wang et al. (2022), and Muhammad et al. (2024); acquisition of a dedicated whole-rock geochemical dataset for Koh-i-Sultan; and compilation of zircon-scale Ce^{4+}/Ce^{3+} and trace-element data for Chagai Arc intrusive phases, following the zircon component of Loucks et al. (2024).

Acknowledgements

This study relies exclusively on previously published whole-rock geochemical data for the Chagai Arc, and the author acknowledges the field and analytical work of all authors who have been cited as this synthesis would not be possible without their work. The published administrative boundary data and deposit coordinates produced the location map of the region. The author appreciates the help provided by the Institute of Geology, University of the Punjab, Quaid-e-Azam Campus, Lahore, during the preparation of this article.

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