

New Insights into the Evolution and Age of the Neoproterozoic Jebel Ohier Porphyry Copper Deposit, Red Sea Hills, Northeastern Sudan

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Abstract

New SHRIMP U–Pb data from dioritic to granodioritic synmineral intrusions associated with the Jebel Ohier porphyry copper deposit (mineral inventory, including NI43-101-compliant total inferred and indicated resources, of 593 million tonnes [Mt] at 0.33% Cu and 0.05 ppm Au, for 1.953 Mt of contained Cu and 933,600 oz of Au at 0.15% Cu cutoff) in the Red Sea Hills of northeastern Sudan have bracketed the age of mineralization to ca. 816 to 812 Ma. This age range, as well as constraints from new and existing lithogeochemical data, is consistent with the deposit's formation from a productive parental magma source during the early stages in the evolution of an intra-Mozambique Ocean island arc. The Jebel Ohier porphyry copper deposit bears many similarities to well-documented Phanerozoic analogues elsewhere in terms of (1) the mapped style and zonation of hydrothermal alteration (i.e., proximal K-silicate-dominated, to sericitic, to distal propylitic alteration), (2) the occurrence of intense Cu-bearing A- and B-type vein stockwork, as well as sulfide-only C-type veins, anhydrite veins, and younger, peripheral D-type veins, and (3) the geochemical fingerprint of the associated porphyry, which is akin to those of ore-related Tertiary porphyries in the Escondida area in northern Chile. The multiphase intrusion hosting the Jebel Ohier porphyry copper deposit has been intruded by several generations of mafic to felsic postmineralization dikes and voluminous plutons, with a peak in magmatic activity coinciding with the suturing of the Gebeit terrane at ca. 724 Ma. In spite of, or perhaps because of, the occurrence of extensive postmineralization magmatism, and regardless of subsequent deformation, regional metamorphism, uplift, and erosion, the deposit has remained remarkably intact. The discovery of a relatively ancient, yet well-preserved porphyry copper deposit in the Neoproterozoic Arabian-Nubian Shield has major implications for the exploration potential of this resource-rich geologic terrain.

Introduction

The Neoproterozoic Arabian-Nubian Shield in northeast Africa is well-known for hosting numerous world-class volcanogenic massive sulfide (VMS) and orogenic gold deposits (e.g., Barrie et al., 2016). The ca. 850 to 550 Ma assemblage comprises a series of subduction-related lithotectonic blocks, accreted juvenile arc terranes, and syn- to post-tectonic intrusions. The Arabian-Nubian Shield formed as a result of Rodinia breakup, opening and closure of the Mozambique

Ocean, and final incorporation into end-Neoproterozoic Gondwana (Johnson et al., 2017). From a tectono-metallogenic viewpoint, the makeup and early evolution of the intra-oceanic, island-arc-dominated Arabian-Nubian Shield can be regarded as an ancient analogue to the present-day southwest Pacific, which hosts some of the world's largest porphyry copper deposits (e.g., Cooke et al., 2005; Garwin et al., 2005). However, due to its relatively old geologic age and the perceived low preservation potential of porphyry copper deposits in Precambrian terranes (e.g., Cooke et al., 2005; Groves et al., 2005; Kesler and Wilkinson, 2006), the accretionary belts of the Arabian-Nubian Shield were long disregarded as a potential target for porphyry copper (-gold) exploration. The recent discovery of the Jebel Ohier porphyry copper deposit, the first confirmed deposit of this type in the Arabian-Nubian

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Shield (Bierlein et al., 2016a, b), has underlined the peril of adhering to established exploration targeting paradigms. It also highlights the potential for further discoveries of this globally important deposit type in the Neoproterozoic basement successions of Sudan and neighboring countries. Other mineralization types associated with porphyry systems and orogenic settings (epithermal, skarn, iron oxide copper-gold, intrusion-related gold systems, etc.) may, by implication, also be present within the Arabian-Nubian Shield.

The Jebel Ohier porphyry copper deposit is currently held under license by QMSD Mining Co. Ltd., a wholly owned subsidiary of Qatar Mining. The deposit is situated some 220 km west of Port Sudan in the Red Sea Hills (Fig. 1), in an area that is dominated by sandy desert plains with laterally extensive areas of outwash and wadi alluvium, clusters of rocky hills, and rugged (up to 1,200 m above sea level [m a.s.l.]) high mountain ranges. Access to the project area from the sealed Khartoum-Port Sudan highway is via an unpaved road to the Ariab mine

and ~150 km of dirt tracks over open ground. An initial mineral resource estimate for Jebel Ohier reported in accordance with NI43-101 definitions and based on assays from 22 diamond and 85 reverse circulation (RC) drill holes was completed in early 2018. The inferred resources totaled 246.3 million tonnes (Mt) at 0.44% Cu and 0.08 ppm Au, for 1.087 Mt of contained Cu and 646,200 oz of Au at 0.2% Cu cutoff (J. Espitalier and R. Bosc, unpub. report to QMSD, 2018). An NI43-101-compliant upgrade to the mineral resource was completed in May 2019, incorporating data from an additional ~80 diamond and 30 RC drill holes. The updated mineral inventory includes NI43-101-compliant total indicated and inferred resources of 593 Mt at .33% Cu and 0.05 ppm Au, for 1.953 Mt of contained Cu and 933,600 oz of Au at 0.15% Cu cutoff (J. Espitalier and R. Bosc, unpub. report to QMSD, 2019). The mineralized zone remains open laterally and at depth. Infill drilling of the current resource and stepout drilling to test and grow the deposit's overall tonnage is ongoing.

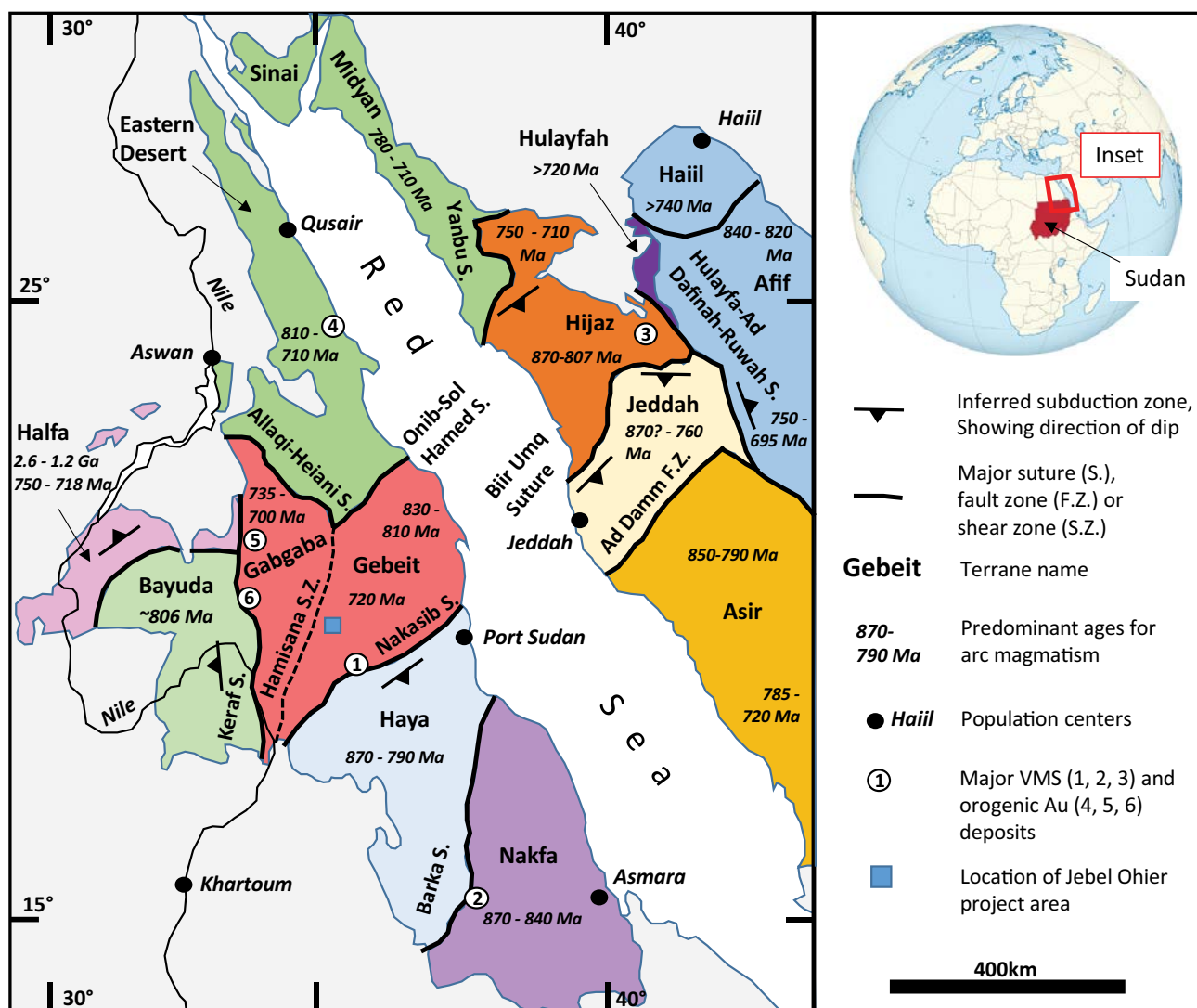


Fig. 1. Terranes and sutures of the Arabian-Nubian Shield showing major structural elements and predominant ages for arc magmatism in each terrane (adapted from Kröner and Stern, 2005), as well as principal localities, the location of the Jebel Ohier project, and significant volcanogenic massive sulfide (VMS) and gold deposits. 1 = Ariab/Hassai, 2 = Bisha, 3 = Bulghah, 4 = Sukurai, 5 = Galat Safur, 6 = Gabgaba. Modified from Bierlein et al. (2016b). Inset shows location of area in main figure.

Initial descriptions of the deposit geology, ore paragenesis, and hydrothermal alteration by Bierlein et al. (2016a, b) used information from surface exposures and limited RC chips. Based on preliminary inductively coupled plasma-mass spectrometry (ICP-MS) U-Pb data from a dioritic intrusion interpreted as synmineralization, the age of mineralization was given as ca. 730 Ma (Bierlein et al., 2016a). This paper integrates new data from diamond and RC drilling, detailed mapping, core logging, and whole-rock geochemical analyses, with more tightly constrained SHRIMP U-Pb data, to develop a refined model for the evolution and age of this new porphyry copper discovery. The understanding of the Jebel Ohier deposit has substantial implications for tectono-metallogenic modeling of the Arabian-Nubian Shield, as well as exploration targeting elsewhere in this relatively underexplored terrane.

Regional Geologic Setting

The Red Sea Hills in northeastern Sudan are underlain by the Arabian-Nubian Shield, which extends over an area of 1.9 million km² along both sides of the Red Sea from Egypt in the northwest, the Sinai Peninsula in the north, and Saudi Arabia in the northeast to Kenya and Yemen in the southwest and southeast, respectively (Fig. 1). The shield records a complete orogenic cycle that was initiated by the breakup of Rodinia (870–800 Ma), continued throughout the opening, inversion, and closure of the Mozambique Ocean (800–650 Ma), and terminated with the final collision between East and West Gondwana between 650 and 550 Ma (e.g., Johnson et al., 2011, and references therein). The opening of the ca. 30 Ma Red Sea rift and development of the East African rift in Ethiopia has significantly impacted on the outcrop extent of the present-day Arabian-Nubian Shield, with recent volcanoclastic rocks and lava flows covering large areas of it in Saudi Arabia, Yemen, and Ethiopia (Stern and Johnson, 2019). The Arabian-Nubian Shield represents an enormous tract of well-preserved Neoproterozoic predominantly juvenile intraoceanic island arcs, suprasubduction ophiolites, oceanic islands, volcano-sedimentary basins, and microcontinental terranes (Johnson and Woldehaimanot, 2003; Stern and Johnson, 2010). These were intruded and sutured by numerous subduction-related calc-alkaline I-type granitoids, granodiorites, and gabbrodiorite complexes (850–610 Ma) and again by younger, calc-alkaline A-type granites and rhyolites, syenites, monzogranites, and mafic to felsic dikes from 600 to 525 Ma during the Pan-African orogeny (Stern, 1994; Osman and El Kalioubi, 2014; El-Bialy and Omar, 2015; Barrie et al., 2016).

Bierlein et al. (2016a, b) described in detail the magmatic arc hosting the Jebel Ohier Porphyry Complex, which forms part of the Gebeit terrane, a segment of juvenile crust separated from geologically distinct blocks by ophiolite-bounded suture zones and comprising an assemblage of subalkaline, calc-alkaline, and tholeiitic, mostly subduction-related, intrusive and extrusive units. These arc assemblages are intercalated with incipient back-arc basins hosting accumulations of mafic-dominated bimodal volcano-sedimentary units (Kröner et al., 1987; Reischmann and Kröner, 1994; Abdelsalam, 2010; Shanks and Thurston, 2012). Several strongly deformed and metamorphosed (up to amphibolite facies) N- to NE-trending shear zones dissect and bound the terrane (e.g., Kröner et al., 1987; Miller and Dixon, 1992; Abdelsalam, 2010). Outboard

of these shear zones, the igneous-epiclastic successions have been variably deformed and metamorphosed to greenschist facies conditions and displaced by numerous reverse, normal, and strike-slip faults. Nonetheless, the succession surrounding Jebel Ohier has remained relatively intact and appears to have escaped significant structural dismemberment. Late-orogenic granites underlie extensive low-topography, sand-covered areas and, together with postcollisional alkaline syenite intrusions, also form prominent peaks of up to 1,200 m a.s.l. The Gebeit terrane, as well as the lithotectonic blocks and/or accretionary arcs surrounding it, has demonstrated potential for large to world-class orogenic gold and gold-rich polymetallic VMS deposits such as Galat Safur and Bulghah (Abanyin et al., 2015), Gabgaba (Managem, 2018), Sukari, Hassai, Bisha, and the Ariab mining district (Barrie et al., 2016; Fig. 1).

Jebel Ohier Geology

The discovery history of Jebel Ohier has been described previously in Bierlein et al. (2016a). At that time, access to subsurface material was limited to rock chips from some 5,600 m of widely spaced RC drilling (typically to 150–200 m depth). Since this publication, some 67,000 m of diamond drilling (to an average depth of 500 m) and nearly 22,000 m of RC drilling has been completed, along with detailed 1:2,500 geologic mapping. All mapping and drilling are routinely documented using the Anaconda method (Einaudi, 1997) prior to samples being processed and submitted for whole-rock multielement assaying at ALS Laboratories in Romania (48 elements by four-acid digest ICP-MS plus Au by fire assay). Detailed geologic, structural, and hyperspectral alteration mapping covers the entire Jebel Ohier project area, supported by ground-based gradient array induced polarization and magnetic surveys. From this work, it has been possible to constrain the geologic architecture, mineralization, and magmatic-hydrothermal history of Jebel Ohier to a significantly greater level of detail than that reported in the preliminary investigation by Bierlein et al. (2016a, b). In the following sections, we describe the deposit in terms of its principal lithological components, its structural architecture, vein styles, hydrothermal alteration, and geochemistry. The integration of this information permits the construction of a refined genetic model for Jebel Ohier and forms the basis for the interpretation of new geochronological data presented herein.

Jebel Ohier is a cluster of porphyry intrusive centers with associated mineralization zones, of which two (Quartz Knob and Malachite Mountain; Figs. 2, 3A) are the most well understood. The Old Mine Jebels area (the name makes reference to ancient hard-rock gold workings in this location; Figs. 2, 3A) of Jebel Ohier represents a higher-level, advanced argillic-altered zone with epithermal Au mineralization exploration potential, which may overlie a separate, blind porphyry copper deposit at depth. A somewhat deeper porphyry copper center is also interpreted at Jebel Ohier North, based on the presence of widespread development of D-type veins (as defined by Gustafson and Hunt, 1975) coincident with domains of quartz-sericite-pyrite (QSP) and clay alteration in this area. An extensive zone of weak to moderate A-type quartz vein stockwork (Gustafson and Hunt, 1975) crops out to the east of Malachite Mountain (informally known as the Eastern extension, or Alfrasco deposit; Figs. 2, 3A), and is

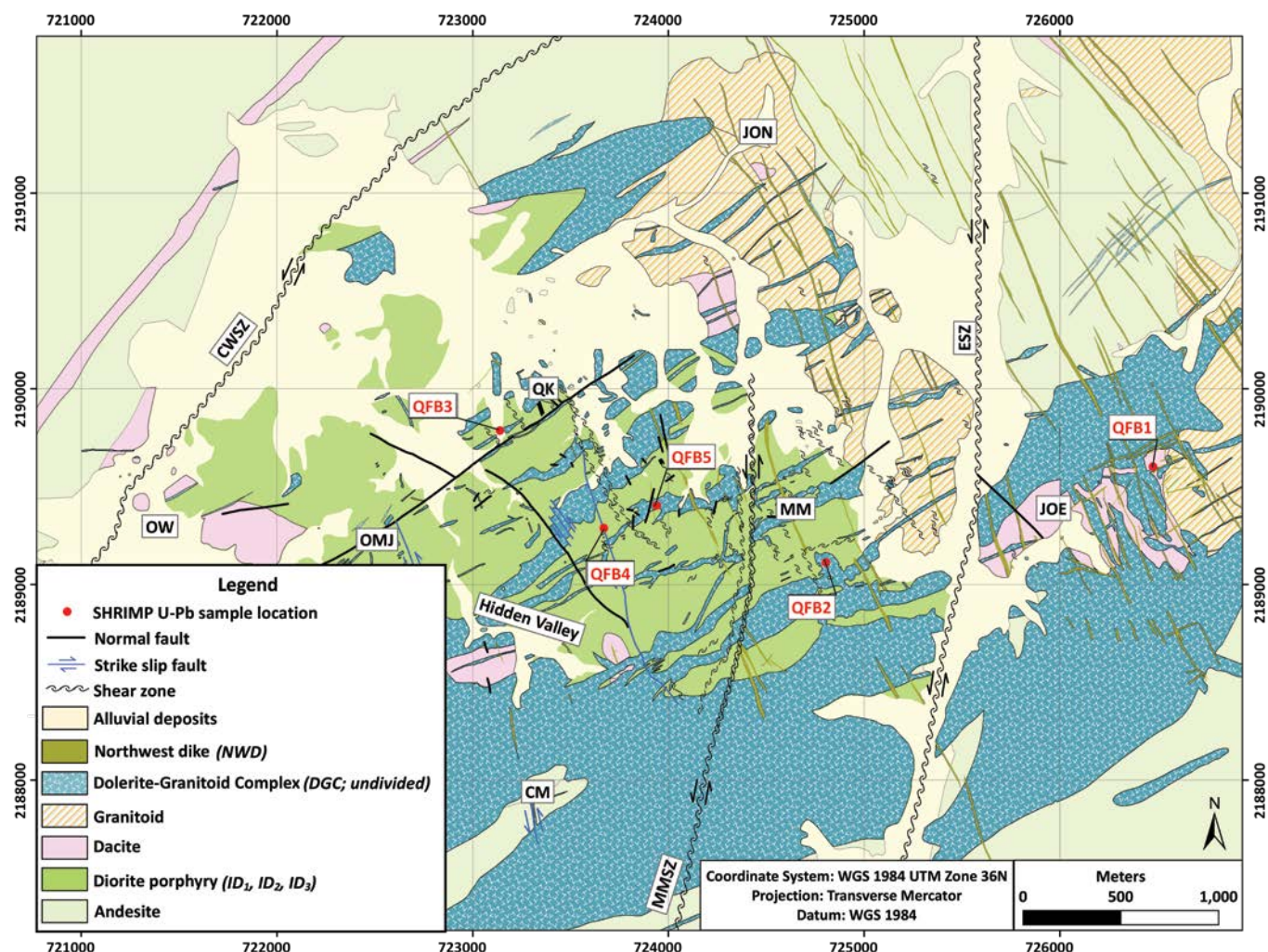


Fig. 2. Simplified geologic map of the Jebel Ohier project area showing the extent of principal intrusive phases and andesitic volcanoclastic rocks, location names, SHRIMP U-Pb sample locations, and main structures. Subordinate intermediate to felsic intrusive units (i.e., FQP and QFP) have been omitted for visual clarity. DGC (undivided) includes DGC_hb, DGC_bt, and DGC_MD. Abbreviations: CM = Chrysocolla Mountain, CWSZ = Central Wadi shear zone, ESZ = Eastern shear zone, JOE = Jebel Ohier East (Alfrasco deposit), JON = Jebel Ohier North, MM = Malachite Mountain, MMSZ = Malachite Mountain shear zone, OMJ = Old Mine Jebels, OW = Ohier West, QK = Quartz Knob.

associated with pervasive pyrophyllite, muscovite, and kaolin alteration of the dacitic host rock, which is considered to represent another mineralized porphyry center.

Host rock and postmineralization lithology

Table 1 summarizes the salient features of the lithological units encountered in the project area. The main precursor host rock to porphyry mineralization at Jebel Ohier is a fine- to medium-grained plagioclase-hornblende diorite (ID₁) with an age of >ca. 816 Ma. The ID₁ intruded voluminous andesitic volcanic and volcanoclastic units that crop out within 3 km on all sides of Jebel Ohier (Fig. 2; Table 1). However, these extrusive units and their proximal clastics are absent from the deposit itself. The ID₁ also occupies most of the area (at least 5 × 3 km) immediately surrounding the deposit that has not been intruded by younger rocks. Mineralogically, the ID₁ consists of ~20% large (up to 3 mm) euhedral to subhedral plagioclase crystals and ~15% 3- to 5-mm, euhedral hornblende in

a fine-grained plagioclase and hornblende groundmass (Fig. 3B). Its contacts with any surrounding older rocks are not defined. The principal stockwork-hosting unit in the Eastern extension zone is a dacitic intrusion (Figs. 2, 3C), which can be distinguished by its anhedral feldspar phenocrysts and contains up to 10% 1- to 2-mm rounded quartz-eye phenocrysts in a very fine grained to aphanitic groundmass of feldspar, hornblende, and quartz. Mineralogically and geochemically (more or less) identical late synmineralization intrusions (ID₂) have been recognized where dioritic intrusions host A-type vein stockworks and display K-silicate to sericitic alteration but have lower vein density than their adjacent premineral counterparts (Fig. 3D). At the contact between premineralization ID₁ and these weakly mineralized ID₂ intrusions, some of the stockwork veins in the precursor ID₁ intrusion are truncated by the contact, whereas younger stockwork veins cut the contact, demonstrating clear superposition timing relationships. A third generation of mineralogically and texturally

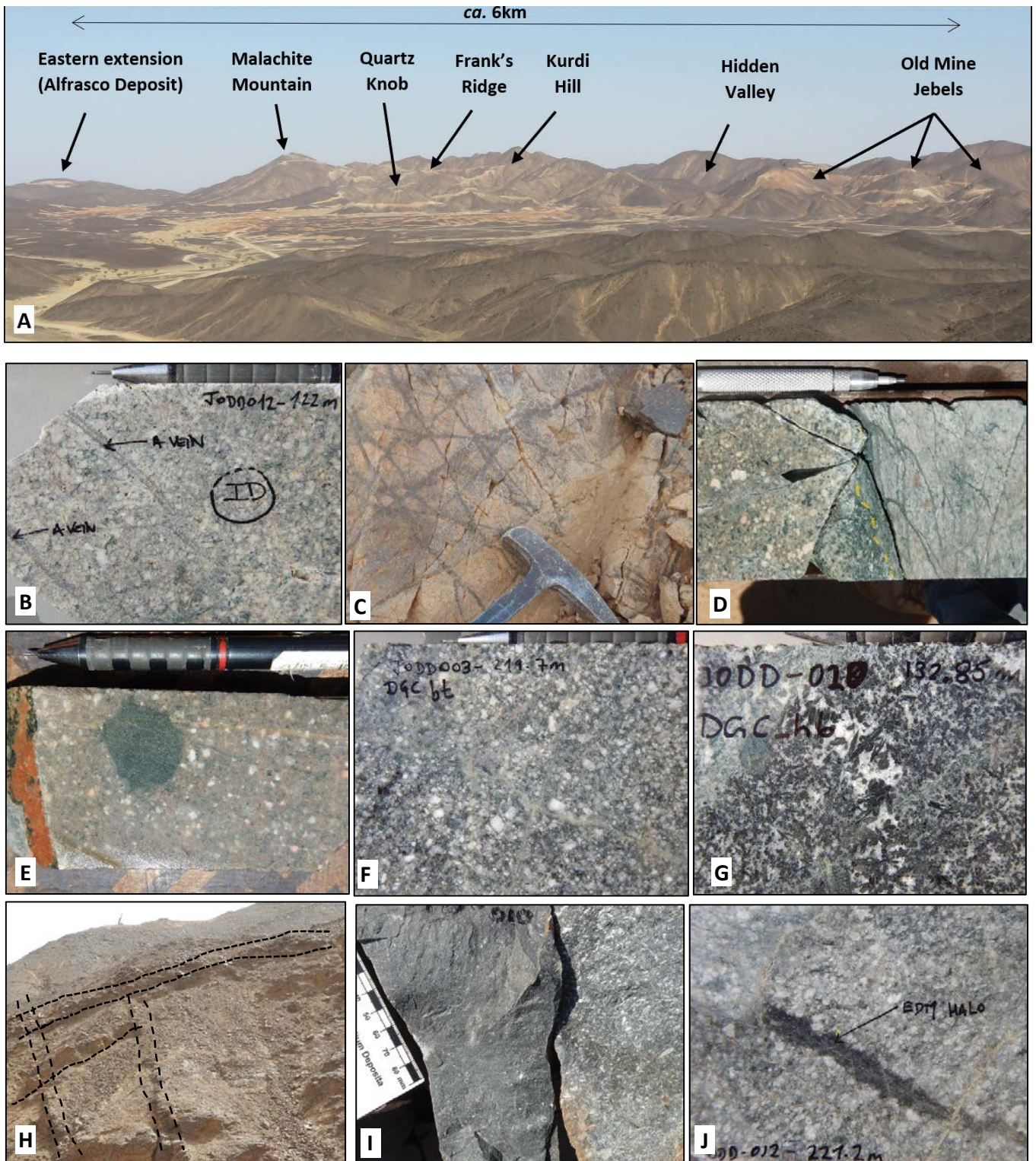


Fig. 3. (A) Overview of the Jebel Ohier deposit looking southeast. (B) Potassic-altered ID₁ diorite with sheeted A-type veins. (C) Altered dacite hosting A-vein stockwork in the Alfrasco deposit. (D) Intrusive contact separating weakly veined sericite-chlorite-altered ID₂ (left side of photograph) from potassic-altered, stockworked, and finer-grained ID₁ in drill core (right side). (E) Postmineralization QFP dike with doleritic xenolith. (F) Weakly altered equigranular DGC_{bt}. (G) DGC_{hb} intrusive phase with porphyritic plagioclase-hornblende segregation (field of view ~15 cm). (H) Example of NE-trending DGC_{MD} dikes on west side of Frank's Ridge (drill rig on far ridge for scale), being cut by a set of NW-trending NWD dolerites (left to right in photograph). (I) Example of variations in grain size and texture within the same DGC_{MD} shown in H. (J) Example of early dark micaceous (EDM) clot within potassic-altered ID₁ in drill core from Malachite Mountain. Field of view is approximately 5 cm.

Table 1. Summary of Jebel Ohier Lithologic Terminology, Rock Types, and Main Characteristics

Association	Terminology	Rock type	Main characteristics	Age
Preminalization	-	Andesite	Homogeneous, fine-grained andesitic unit; intruded by ID ₁	>816 Ma
	ID ₁	Diorite porphyry	Fine- to medium-grained, subalkaline hornblende-feldspar diorite; strong hydrothermal alteration; principal stockwork-hosting unit at Jebel Ohier	>816 Ma
	-	Dacite porphyry	Anhedral feldspar phenocrysts and quartz eyes in aphanitic feldspar-hornblende-quartz groundmass; A/B-vein stockwork-hosting unit at Jebel Ohier Eastern extension	>816 Ma
Synmineralization	ID ₂	Diorite porphyry	Truncates ID ₁ ; mineralogically and geochemically identical to ID ₁ , but less strongly altered with weakly developed A/B-vein stockwork	ca. 816–812 Ma
Postmineralization	ID ₃	Granodiorite porphyry	Mineralogically and texturally similar to ID ₁ and ID ₂ , but unmineralized; moderately phyllic/propylitic-altered	<812 Ma
	QFP	Quartz-feldspar porphyry	Rare, unaltered granitic dikes cutting across all ID units; uncrowded quartz ± feldspar phenocrysts in fine-grained quartz-feldspar-Fe oxide-biotite groundmass	<812 Ma
	FQP	Feldspar-quartz porphyry	As for QFP, but granodioritic and containing crowded albite and K-feldspar phenocrysts in aphanitic groundmass	<812 Ma
	-	Granitoid	Voluminous intrusive bodies identical in composition to QFP; peripheral and predominantly exposed to the northeast to the mineralized system at Jebel Ohier; contains rare mafic xenoliths	<812 Ma
	DGC_bt	Granodiorite	Voluminous medium-grained, equigranular dioritic to granodioritic phase comprising albite-hornblende-biotite ± quartz; unaltered; intrudes all earlier units at Jebel Ohier	ca. 724 Ma
	DGC_hb	Granodiorite	Forms rare irregular intrusive bodies and thick dikes; morphologically and texturally similar to DGC_bt but containing hornblende clusters in equigranular groundmass of hornblende-albite	Unconstrained, but presumed to be ca. 724 Ma
	DGC_MD	Andesitic basalt	Abundant NE-trending mafic-intermediate andesitic dikes with equigranular, medium- to fine-grained, doleritic to porphyritic texture within DGC	Unconstrained, but presumed to be ca. 724 Ma
	NWD	Andesitic basalt	Narrow, aphanitic to fine-grained equigranular basaltic-andesitic dikes trending northwest and crosscutting all other mapped units; mineralogically, texturally, and geochemically indistinguishable from DGC_MD	Unconstrained; 540 Ma? cf. Johnson et al., 2011

- = not applicable

similar granodioritic intrusions, devoid of any mineralization or stockwork veining and with only moderate phyllic or propylitic alteration, has been termed ID₃. The unmineralized, unaltered to weakly hydrothermally altered ID₃ consistently cuts across the ore-hosting ID₁ and ID₂ in drill core and as such is considered to provide a minimum age of the ore-forming event at Jebel Ohier.

Several felsic intrusions crosscut the porphyry copper deposit. These intrusive units are very weakly altered. In the study area, these intrusions are mostly narrow dikes. However, they may be coeval with some larger intrusions to the east and north of Jebel Ohier (Bierlein et al., 2016b). These include unmineralized late granodioritic dikes that are more or less mineralogically identical but markedly more porphyritic and substantially less altered than ID_{1–3} and a distinctive quartz-feldspar porphyry (QFP) unit that has been observed rarely in outcrop and drill core. The QFP forms rare, relatively narrow (0.5–10 m), dikes with sharp planar contacts that cut ID and porphyry mineralization and truncate all preexisting alteration assemblages. The QFP is characterized by an uncrowded quartz-feldspar porphyritic texture with subrounded quartz phenocrysts, ± rare feldspar phenocrysts, in a very fine grained

to aphanitic groundmass that comprises quartz, feldspar, and iron oxides and sporadic mafic phenocrysts (Fig. 3E). An equally rare but distinctive feldspar-quartz porphyry (FQP) unit, with a crowded feldspar porphyritic texture and granodioritic composition, has also been observed locally. The FQP forms narrow (<2 m wide) dikes composed of subrounded plagioclase, K-silicate, and rounded quartz phenocrysts in an aphanitic matrix with mafic xenoliths.

Within the mapped area, the most voluminous postmineral intrusions have been grouped together as the dolerite-granitoid complex (DGC). This DGC with a ²⁰⁶Pb/²³⁸U age of ca. 724 Ma (Table 2) comprises rocks ranging from diorite to granodiorite. They commonly exhibit magma-mingling textures at their contacts, implying that all of the complex was emplaced at the same time. Earlier postmineralization intrusions described in the previous paragraph are invariably truncated by the DGC. The most voluminous component of the complex (~40% estimated from mapping) is represented by a medium-grained, equigranular granodioritic phase termed DGC_bt (Fig. 3F), consisting of plagioclase (~60%, 3–5 mm), hornblende (~20%, 2 mm), and biotite (~20%, 3 mm), with rare rounded quartz phenocrysts (<3 mm). The DGC_bt forms

Table 2. Summary of SHRIMP U-Pb Sample Details and New Age Determinations for the Jebel Ohier Deposit

Sample ID	Sample type	Rock type	Latitude ¹	Longitude ¹	Elevation (m a.s.l.)	Description	Age	Mean square of weighted deviates
QFB1	B62-26721 (S)	Dacite	726477	2189601	641.8	Sericite-altered; intense A/B-vein stockwork; Eastern Extension zone	816.2 ± 3.4 Ma (concordia)	3.0 (of concordance; probability = 0.084)
QFB2	JODD_070 (C) 344.6–346.4 m	DGC_bt	724806	2189111	389.8	Unaltered; intruded into ID ₃ ; abundant biotite books and quartz phenocrysts	723.7 ± 6.7 Ma (weighted mean ²⁰⁶ Pb/ ²³⁸ U age)	1.08 (of equivalence)
QFB3	JODD_054 (C) 363.4–365.0 m	ID ₂	723141	2189785	243.8	A/B-vein stockwork; anhydrite veins; contact truncates deformed A-type vein in ID ₁	812.6 ± 4.0 Ma (concordia)	2.2 (of concordance; probability = 0.14)
QFB4	JODD_062 (C) 300.2m–302.0 m	ID ₂	723671	2189288	412.8	Contains D-type veins and disseminated pyrite; contact truncates weakly deformed A-type vein in ID ₁	813.1 ± 8.5 Ma (weighted mean ²⁰⁶ Pb/ ²³⁸ U age)	1.1 (of equivalence)
QFB5	JODD_065 (C) 254.3–256.2 m	ID ₂	723941	2189402	382.7	Contains A-vein stockwork and disseminated chalcopyrite; contact truncates deformed A-type veins in ID ₁	814.1 ± 8.5 Ma (weighted mean ²⁰⁶ Pb/ ²³⁸ U age)	1.15 (of equivalence)

(C) = core sample with interval, (S) = surface sample
¹UTM zone 36N

large irregular intrusive bodies and thick dikes that have irregular undulating contacts with other phases of the DGC intrusive suite. A second dioritic intrusive phase, termed DGC_hb, consists of large, unaltered, anhedral to locally euhedral hornblende phenocrysts (2–5 mm) or phenocryst clusters in equigranular, fine- to medium-grained (1–2 mm; 60% plagioclase, 40% hornblende) groundmass that otherwise closely resembles DGC_bt (without the magmatic biotite; Fig. 3G). The DGC_hb forms rare irregular intrusive bodies and thick dikes that have irregular undulating contacts and localized magma-mingling textures with other phases of the DGC. It is estimated that DGC_hb constitutes less than 1% by volume of the DGC series intrusions within the mapped area. Variably medium- to fine-grained, equigranular to porphyritic, mafic-intermediate intrusions of basaltic-andesite composition, termed DGC_MD, have also been included in this suite (Fig. 3H, I). These consist of (locally exceptionally) large plagioclase (10–35%, 1–50 mm) and smaller hornblende phenocrysts (5–20%, 1–5 mm) in a groundmass of plagioclase and hornblende (50–85%, <1 mm) in approximately equal proportions. DGC_MD intrusions predominantly form narrow to moderately thick (0.5–20 m) NE- to ENE-trending dikes. They have variably planar to irregular/undulating margins and rare magma-mingling textures with other DGC-series magma phases, particularly DGC_bt, indicating that most, if not all, DGC series magmatism was coeval. DGC dikes commonly exhibit finer-grained chilled margins, with grain size generally increasing with increasing dike thickness.

Lastly, a late (post-DGC) swarm of aphanitic to fine-grained (<<1–2 mm) equigranular basaltic-andesitic intrusions cross-cuts all mapped units including the DGC. This unit, logged as NWD, predominantly forms narrow dikes (0.3–15 m) with generally planar margins that strike northwest to north-northwest and dip steeply toward the east-northeast to northeast (Fig. 3H). The NWD rock types are mineralogically, texturally, and geochemically indistinguishable from the DGC_MD rock types. They tend to be more planar and thinner than DGC dikes, strike northwest, and do not have magma-mingling textures. However, they can only reliably be identified by their crosscutting relationship with DGC intrusions. The age of the NWD remains unconstrained.

Alteration

Mapped hydrothermal alteration at Jebel Ohier is strongly zoned around the Malachite Mountain and Quartz Knob porphyry copper A-vein stockwork zones (Fig. 4), and it is described here in terms of spatially proximal (chlorite-sericite, overprinting potassic biotite/K-feldspar), intermediate (QSP, overprinting chlorite-epidote), and distal (epidote-chlorite) assemblages relative to these centers. Sericitic alteration is slightly younger and both crosscuts and outboards the K-silicate alteration. Mineralization intensity and relict K-feldspar (± magnetite-biotite) alteration is spatially related to abundant sugary quartz A-type veins with bornite-chalcopyrite-pyrite and sulfide-only veins (chalcopyrite and/or pyrite). Within the proximal, K-silicate-altered domain there are rare dark alteration halos ranging in width from 1 to 4 cm with copper sulfides. These comprise a mixture of dark-green to brown and gray-green flaky minerals (biotite ± chlorite and magnetite) replacing both mafic and felsic magmatic mineral sites and

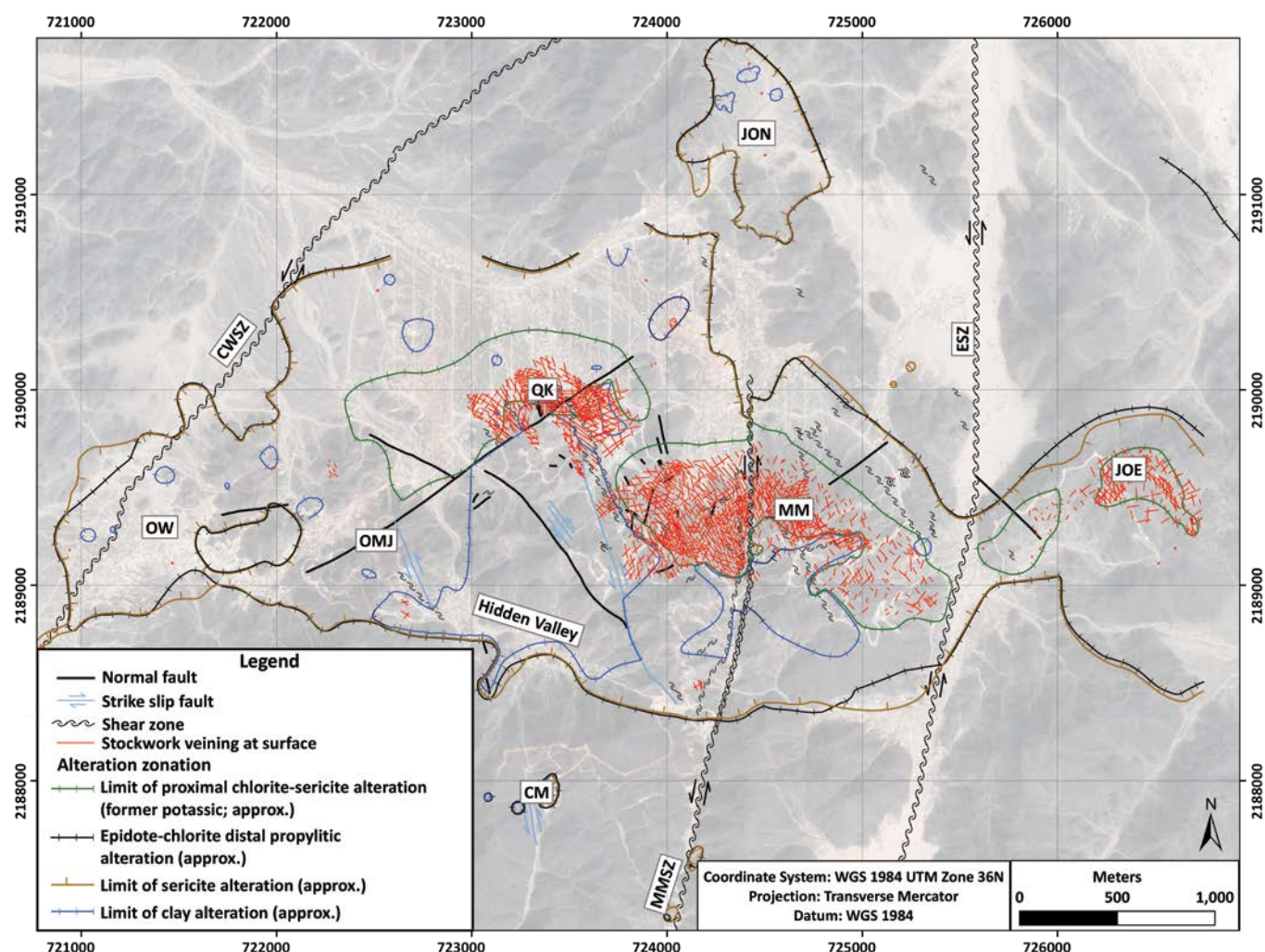


Fig. 4. Same area as in Figure 2, showing the approximate mapped extent of the exposed stockwork zone, as well as major hydrothermal alteration zones, draped over a satellite image of the Jebel Ohier project area (for abbreviated location names, see caption of Fig. 2).

resemble early dark micaceous halos described in porphyry copper deposits elsewhere (e.g., Shraake et al., 1996; Profett, 2003; Cernuschi, 2015; Sepp and Dilles, 2018; Fig. 3J). Proximal K-silicate alteration assemblages at Jebel Ohier are also partly obscured by a moderate to strong chlorite-sericite alteration overprint. Potassium-silicate-altered rocks affected by later chlorite-sericite alteration within the proximal stockwork zones have textures that suggest primary magmatic amphiboles were replaced by hydrothermal (shreddy) biotite, but this hydrothermal biotite was subsequently replaced by chlorite and sericite. Sericite also replaces feldspar mineral sites to varying degrees. In fact, sericite is prominent in most rocks in the mapped area. The outer limit of sericite alteration in the northeast and southwest of the mapped area is coincident with the inner limit of propylitic alteration (chlorite-epidote $\pm$ albite).

The spatially intermediate hydrothermally altered zone is dominated by coincident zones of QSP (phyllitic) alteration and D-type veins (as defined by Gustafson and Hunt, 1975). The transition from proximal to intermediate altered zones is commonly marked by a change (over 1–2 m) from green

chlorite-sericite-altered host rock with preserved igneous textures and mineralized A-type veins (with relict precursor K-silicate alteration), to bleached, intensely QSP altered rock with D-type veins, where lithological textures are destroyed and A-type veins are absent. The outer limit of the intermediate altered zone is coincident with the inner margin of distal epidote-chlorite (propylitic) alteration. This peripheral zone of alteration is extensively developed in all directions beyond the limits of sericite alteration at Jebel Ohier, though there is no clear zonation in propylitic alteration intensity with respect to distance from porphyry copper mineralization. Chlorite within the distal alteration zone is mostly finely disseminated in the groundmass and as a replacement of mafic minerals, whereas epidote may replace feldspar and mafic minerals, form discrete veins, or completely flood the rock mass. The absolute outer limit of this peripheral zone of hydrothermal alteration at Jebel Ohier is difficult to ascertain due to distal host rocks having undergone greenschist facies metamorphism. Thus, fine-grained metamorphic chlorite replacing primary mafic minerals is hard to distinguish in outcrop from distal, porphyry copper-related hydrothermal chlorite.

Quartz-sericite-pyrite alteration, with characteristic cubic boxwork voids after disseminated pyrite above the base of oxidation, is widespread in the sericite zone south of Malachite Mountain and Quartz Knob. Unlike the pervasive phyllic alterations in the intermediate and more distal alteration zones, proximal chlorite-sericite alteration is less intense, generally preserves textures, and appears not to have been grade destructive. Within the A-vein stockwork zone, texturally destructive phyllic alteration is restricted to D-type veins and their sericitic alteration halos. The combination of soft bleached rock with Fe staining after pyrite gives rise to a distinctive white and red “cookies and cream” appearance to weathered QSP-altered outcrops. Sericite is commonly very coarse and flaky within the QSP domain.

Linear to pod-like ledges of quartz-pyrite within a broad area of advanced argillic alteration (pyrophyllite-kaolinite) delineate a distal hydrothermal domain that is most prominent to the south of Malachite Mountain and Quartz Knob. At surface these are easily identified as very strongly quartz altered rock with fine-grained disseminated expyrite boxworks. In some areas, fresh pyrite is preserved at surface. Kaolinite is also widespread throughout the altered zone, but its origin is unclear. Some may be related to advanced argillic alteration, as evidenced by abundant pyrophyllite to the south of Malachite Mountain and Quartz Knob, or it may have predominantly formed during more recent supergene processes.

The outer alteration halo is generally marked by strong epidote alteration. Textures are mostly well preserved, and identifying lithology is not problematic in this alteration zone. Chlorite-epidote alteration is also developed in parts of some postmineralization intrusions, where it must postdate the porphyry copper deposit and represent a later event. Late epidote veins have been documented both regionally and within many parts of the deposit and are interpreted to be related either to postmineralization intrusions or to a later metamorphic event.

The stockwork domains at Jebel Ohier are weathered to 40 to 80 m (locally deeper at Malachite Mountain). The oxide profile within the proximal stockwork domain has zones of Cu depletion (particularly in the very near surface) and secondary Cu oxide enrichment (generally either lower down in the weathering profile where it approaches the transitional zone or on the relatively alkaline margins of barren, late mafic dikes). Copper is notably rich in formerly barren postmineral mafic dikes where chrysocolla and pseudomalachite, as well as minor azurite, black copper, neotocite, tenorite, and pitch limonite, was extensively (and in places spectacularly) precipitated (Fig. 5A). Within the oxide zone, formerly chalcopryite rich A-type veins are weathered to a rich-brown goethite within the former sulfide sites. Glassy limonite, jarosite, hematite, and goethite are also variably developed in the oxidized portion of Jebel Ohier (Fig. 5B).

Vein styles and mineralization

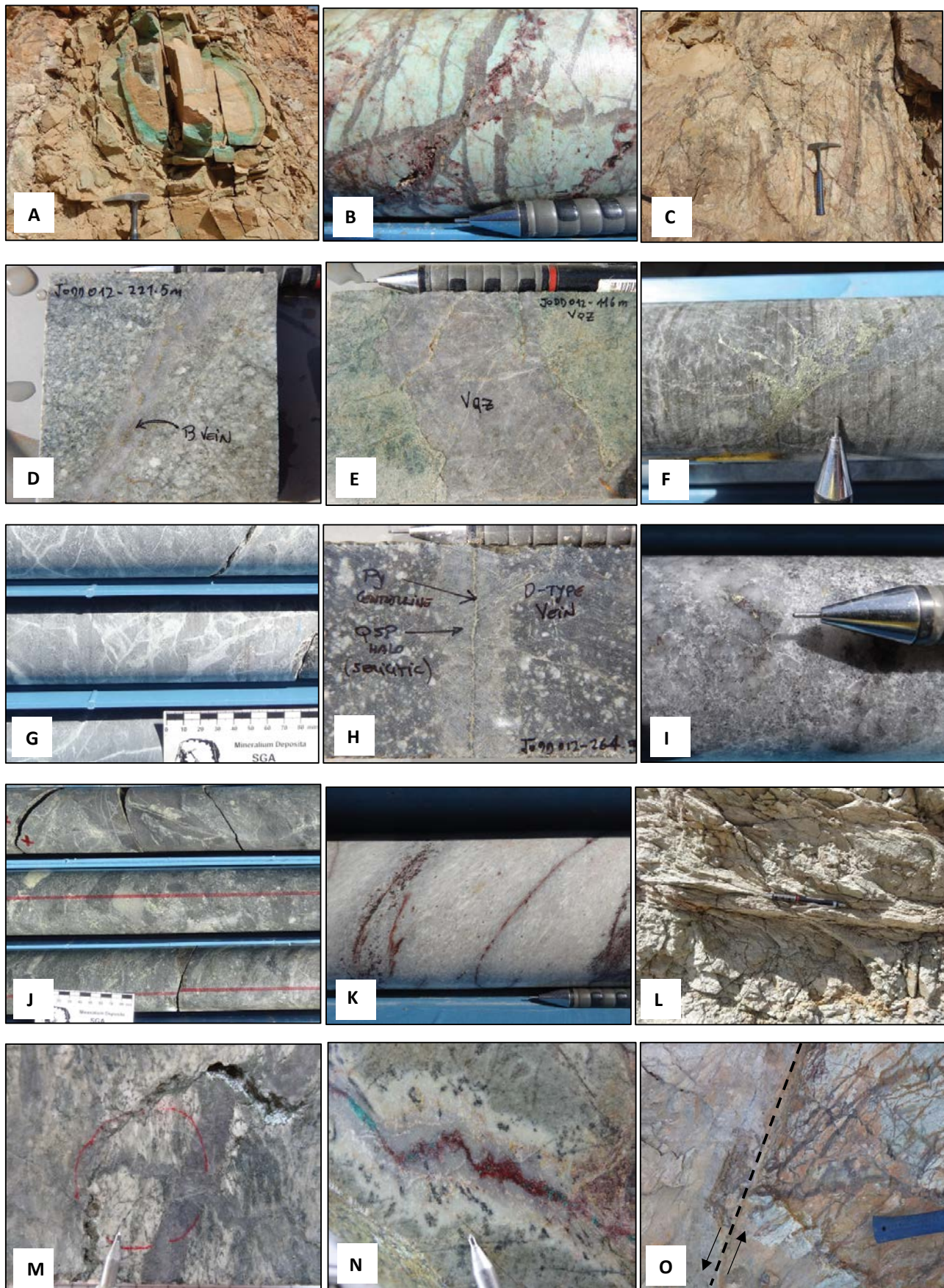
The two largest mineralized centers at Jebel Ohier have dimensions typical of porphyry deposits elsewhere (e.g., John et al., 2010). Malachite Mountain (1,600 × 700 m extent at surface) and Quartz Knob (600 × 500 m) both have a core of intense A-type stockwork veining and an outer zone of weak stockwork veining. In addition, less intense A-vein stockwork development is present in a 1,000- × 500-m zone

to the east of Malachite Mountain (delineating the Alfrasco deposit), in several areas to the south and west of the Quartz Knob-Malachite Mountain trend, and at Jebel Ohier North. Beyond these zones, weak A-vein stockwork veining transitions, across a relatively steep gradient, into phyllic alteration that is dominated by D-type veins. The intense central A-vein stockwork domains typically have two to three mutually crosscutting dominant (primary) quartz-sulfide vein orientations in any given outcrop, and numerous subordinate vein orientations (Fig. 5C). A-vein abundances in the most intense stockwork domains range from 5 to 20% of the rock volume. The outer weak A-vein stockwork domain not only has a significantly smaller total volume of A-type veins (typically <5%), but it also has fewer vein orientations with only one to three well-developed vein orientations discernible. Sugary textured quartz A-type veins are typically 0.2 to 2 cm thick (but can be up to 5 cm thick). They have slightly irregular to locally folded vein margins and are composed of sugary textured gray quartz with interstitial chalcopryite ± pyrite. Most of the A-type veins that form the proximal stockwork display dominantly steeply dipping arrays (78°–88°) with subvertical vein set intersection lineations, suggesting that the Jebel Ohier deposit has remained close to upright without experiencing any significant postemplacement tilting. The dominant A-vein populations trend west-northwest (Fig. 4), subparallel to the Malachite Mountain-Quartz Knob trend coincident with a deep linear, NW-trending magnetic high recognized in ground magnetic surveys.

There are distinct domains where sheeted vein arrays predominate over stockwork arrays. In some instances, these sheeted vein arrays appear to reflect the attitude of formation of the veins (i.e., $\sigma_1 = \sigma_2 > \sigma_3$). Where this is the case, it is clear that there is a single dominant vein orientation, but there are also rare, mutually crosscutting, undeformed veins at a high angle to the dominant vein orientation. In other areas, however, vein arrays appear to have been rotated into parallelism by intense ductile deformation within either NE-striking sinistral shear zones or within a NW-striking flattening fabric and associated localized shear zones.

B-type quartz veins (as defined by Gustafson and Hunt, 1975) have orientations similar to those of the A-type veins but are less abundant. B-type veins are distinguishable by their distinctive center line comprising chalcopryite ± pyrite, planar vein margins, and more massive internal quartz textures than the ubiquitous sugary vein-fill quartz in A-type veins (Fig. 5D). Most B-type veins are between 0.5 and 2.5 cm thick and lack selvages, although in some instances the veins are lined by an assemblage of shreddy chlorite, K-feldspar, and sericite.

Informally termed VQZ quartz veins (± chalcopryite, ± pyrite) are a prominent feature of the porphyry copper deposit stockwork domains at Jebel Ohier. Their distribution and orientation is closely related to that of A-type veins, but they are an unusual vein style for a porphyry copper deposit in that they are between 5 cm and 3 m thick (most are 5–50 cm thick), with slightly irregular to undulating vein boundaries and a fractured massive quartz texture ± fine internal sulfide stringers (chalcopryite and/or pyrite) predominantly along fractures within the vein fill (Fig. 5E). Mineralized wavy quartz veins are interpreted as synchronous with the development of A-vein stockworks (or at least the last phase of A-type



veining) as thick wavy quartz veins in many outcrops horse-tail out into a sheeted array of thinner sugary textured mineralized A-type veins, and like the A-type veins, they are commonly crosscut by C- and D-type veins.

Irregular narrow sulfide-only C veinlets are not a volumetrically important mineralized vein set at Jebel Ohier, as they are recognized only sporadically in drill core. They predominantly (but not ubiquitously) crosscut A- and B-type veins and are typically thin (generally <5 mm wide) with narrow phengite alteration selvages. They form networks that commonly crosscut and displace A- and B-type veins (Fig. 5F). Vein fill is predominantly chalcopyrite (80–100% of vein fill) $\pm$ pyrite, $\pm$ bornite with little or no quartz or other minerals. Diamond drilling to date indicates that sulfide-only veins are distributed throughout the proximal stockwork domains and are locally present in abundance in some of the hydrothermal breccia domains (see below). Their spacing varies from >2 m to abundant (10–20 cm) within the proximal stockwork domain. Given their very high copper content, they are a significant contributor to overall grade wherever they are developed above trace abundance.

Anhydrite veins are irregularly developed throughout the proximal stockwork and breccia domains but tend to be most abundant and dominant toward the deeper parts of mineralized centers at Jebel Ohier. The anhydrite veins have several different morphologies (Fig. 5G), display slightly to highly irregular margins, and contain rare angular wall-rock fragments. Vein thicknesses (0.5–20 cm observed in drill core) are highly variable. They are also spatially associated with irregular tensile vein arrays, breccia A-vein arrays, and hydrothermal breccia zones. Together, these features may indicate supralithostatic pore fluid pressures intense enough to drive hydraulic brecciation (incipient to intense brecciation). Although most anhydrite veins are dominantly anhydrite-quartz $\pm$ chalcopyrite, they exhibit additional spatial and temporal relationships with chlorite, actinolite, epidote, molybdenite, and other sulfides (pyrite, bornite, etc.) as alteration halos, proximal alteration assemblages, or, rarely, vein fill.

D-type veins can be identified by their 0.2- to 2-cm-wide, gray to white bleached, texturally destructive, QSP alteration (phyllitic) halos around a central seam of pyrite-sericite-quartz of varying proportions (Fig. 5H). An enrichment of sericite and complete textural destruction of primary igneous textures and minerals in the alteration halo is diagnostic of a D-type vein (Gustafson and Hunt, 1975). Although they can contain

abundant quartz, most D-type veins are characterized by the absence of a sharp vein wall and are defined more by a stringer of pyrite-sericite-quartz. D-type veins at Jebel Ohier are predominantly north-northwest striking with steep dips, similar to the orientation of A-type veins.

Locally developed, mineralized magmatic-hydrothermal breccias (e.g., Sillitoe, 2010) form discrete subvertical breccia pipes or sheets that cut the Malachite Mountain stockwork. These siliceous pipes lie adjacent to intense ductile shear domains and typically comprise subangular to subrounded fragments of sericite-altered ID₁ and A-vein fragments with quartz-sericite-anhydrite cement (Fig. 5I). Within mineralized quartz-rich breccias, pyrite and chalcopyrite cluster in the cement, replacing and interstitial to anhydrite and quartz grains. Locally, bornite can be relatively abundant (up to 1% of total rock volume) in some of the chalcopyrite-rich zones. These magmatic-hydrothermal breccias contrast with chlorite-epidote-rich tectonic breccias that appear to postdate most, if not all, stockwork mineralization and commonly comprise monomict to polymict breccia clasts that are variably angular to rounded and contain evidence of ductile flattening and shearing (Fig. 5J).

There are uncommon quartz-molybdenite veins, as well as rare epidote-chalcopyrite, actinolite-chlorite-chalcopyrite (-bornite), and magnetite-only veins at Jebel Ohier, but their genetic and temporal relationship to the main mineralizing event remains poorly understood due to limited examples. Sulfide mineralization is observed within A- and B-type quartz veins and as C-type veins, as well as disseminated in proximal halos to these veins, particularly in zones of high vein density. Highest Cu grades (in places showing a close correlation with elevated Mo of up to 120 ppm) are spatially associated with the aforementioned steep to irregular magmatic-hydrothermal breccia pipes.

Structural evolution

No premineralization structures have been observed in outcrop. Deformation at Jebel Ohier includes both brittle and ductile features that deformed, and locally displaced, mineralized rocks and some of the late dikes. At the prospect scale, there are domains with variably penetrative, NW-striking foliation. This foliation is interpreted to be the result of post-mineralization pure shear flattening (domained and partitioned by variable rock rheologies), with minor subparallel simple shearing (commonly but not always sinistral). The

Fig. 5. Examples of vein style, mineralization, and deformation at Jebel Ohier. (A) Malachite staining in mafic dike within stockworked diorite. (B) Oxidation of sulfides in intensely stockworked diorite (JODD_001 47.5 m). (C) NW-oriented A-vein array in outcrop on west flank of Malachite Mountain. (D) B-type vein with chalcopyrite nests along center line in potassic-altered diorite (JODD_012 221.5 m). (E) Example of VQZ vein in chlorite-sericite-altered diorite (JODD_012 116 m). (F) Chalcopyrite-pyrite bearing C-type vein cutting across brecciated A-type vein (JODD_002 293.1 m). (G) Intense network of anhydrite veins in chlorite-sericite-altered diorite (JODD_002 363.8–364.5 m). (H) Pyrite-bearing D-type vein exhibiting phyllic quartz-sericite-pyrite (QSP) alteration halo in chlorite-altered diorite (JODD_12 264.3 m). (I) Anhydrite cement-hosted disseminated bornite (purple; intergrown with chalcopyrite next to pencil tip) surrounding hydrothermally brecciated A-vein fragments (JODD_002 303.9 m). (J) Tectonic breccia composed of variably altered diorite fragments, quartz-anhydrite breccia and mafic dike intervals (JODD_001 183–184 m). (K) Pure shear fabric transposing (oxidized) D-type vein in sericite-altered diorite (JODD_002 87.4 m). (L) Exposure of sinistral D₂ shear zone with S-C fabrics in stockwork-hosting diorite, east flank of Frank's Ridge. (M) Example of folded A-type veins with strong axial planar cleavage (trending north-south in image; JODD_003 162 m). (N) Example of asymmetrically refolded B-type vein, showing penetrative (NW-trending in image) S₁ fabric overprinted by (north-south in image) S₂ crenulation cleavage (JODD_003 15 m). (O) Example of late brittle fault in outcrop truncating A-vein stockwork in ID₁ (north flank of Malachite Mountain).

NW-striking penetrative fabric at Jebel Ohier contrasts with a dominant NE-trending penetrative fabric to the east and west of the prospect. Bierlein et al. (2016a) interpreted this to reflect rotation of the regional fabric in the prospect area, related to a younger deformation event. An important set of major NNE-striking sinistral strike-slip shear zones and faults that significantly displaced mineralized rocks have also been identified. These include the Central Wadi shear zone to the west of the prospect (Bierlein et al., 2016a; Fig. 2). The exact timing of deformation and the nature of the local kinematics and far-field tectonic regime have not been determined, but relative timing has been inferred from overprinting relationships between the various structure sets and intrusive suites.

Detailed mapping identified the earliest recognized post-mineralization deformation at Jebel Ohier as a NE-SW-directed shortening event. This predominantly pure shear flattening event produced a locally penetrative, ductile, subvertical NW-striking schistosity or fine slaty foliation. The stockwork vein arrays were deformed and reoriented parallel to the fabric in areas where S_1 is intensely developed. Mineralized veins were deformed by, rather than controlled by, D_1 structures, demonstrating that D_1 postdates porphyry mineralization. The S_1 was cut by both ENE-trending DGC dikes and the NWD swarm, indicating that D_1 flattening predated both of these dike swarms. Localized sinistral (and subordinate dextral) simple shear zones and brittle faults are developed within the broader pure shear flattening foliation domains and also cut less deformed (otherwise unfoliated) host-rock sequences. The extent to which the host sequence has been deformed by the D_1 event is difficult to determine with any confidence due to the lack of layered stratigraphy within the project area. The only indicator of strain intensity is provided by the predeformation quartz stockwork vein arrays (Fig. 5K). However, these are not uniformly developed and, as such, are an unreliable direct indicator of strain intensity and cannot be used to infer the presence of any large-scale folding. The two recognized porphyry centers (Malachite Mountain and Quartz Knob) do, however, have a marked asymmetry, such that the central A-vein stockwork domain has an apparent northwest-southeast elongation of about 3:1 (Fig. 6A). Although undeformed upright porphyry deposits generally have equant (near circular) surface expressions (e.g., John et al., 2010), ultimately the shape of the porphyry center reflects the near-field stress regime at the time of magma emplacement. Given that the observed D-vein geometries indicate that the Jebel Ohier porphyry stockworks have not been appreciably tilted, we infer that the elongation of the Jebel Ohier stockwork zones is a result of northeast-southwest D_1 flattening, which, in turn, led to the deformation and apparent realignment of A-type veins into parallel to the locally penetrative S_1 foliation (Figs. 5M, N, 6B). In the absence of evidence for pervasive reorientation or systematic, symmetrical folding of A-type veins, however, an alternative explanation for the observed west-northwest to east-southeast elongation of the porphyry at Jebel Ohier could be a combination of multiple porphyry centers intruded along a preferred, preexisting structural trend, as suggested by processed gradient array induced polarization chargeability data over part of the Jebel Ohier project area (Fig. 6C). In such a scenario, the controls on dominant NW-striking vein orientation would be mainly of a synmineralization nature, with the

mineralized centers experiencing localized postmineralization reorientation of some vein domains as a result of asymmetric simple shearing. Some of this reorientation is likely related to flattening associated with cleavage formation.

The voluminous postmineralization DGC intrusions, which overprint all porphyry-related veining and alteration, are steeply dipping and largely strike east-northeast, implying a period of post- D_1 south-southeast to north-northwest extension. This event was followed by emplacement of the less voluminous NW-striking dike swarm, an event that implies east-northeast to west-southwest extension or possibly mild northwest to southeast compression (σ_1) accompanied by weak northeast to southwest (σ_3) compression with magmatic overpressuring.

D_2 shear zones are characterized by subvertical to moderately steep foliations with intensely developed S-C fabrics (Fig. 5L). Shear zones and individual shear planes are locally anastomosing, with sinistral simple shear deformation and displacement of stockworks, hydrothermal alteration domains, and DGC-series dikes. DGC dikes are locally boudinaged with D_2 shear fabrics wrapping around boudins and locally juxtaposing realigned A-vein stockworks within the shear fabric. Many D_2 shear zones have strong subhorizontal mineral elongation lineations, consistent with D_2 structures being dominantly strike-slip with little if any dip-slip component. Two major N- to NE-trending sinistral shear zones and numerous other minor NNE-trending D_2 shear zones have been identified in the project area. The roughly N-striking Malachite Mountain shear zone cuts the Malachite Mountain porphyry center, sinistrally displacing both mineralized and altered rock by approximately 250 m, whereas the NE-striking Quartz Knob shear zone is interpreted to have displaced the Quartz Knob porphyry mineralization center by approximately 150 m. Although individual fault displacements are comparatively small, combined sinistral displacements probably account for the apparent disconnect between the 110°-long axis trend of the elongated Malachite Mountain porphyry and the measured 135° (avg) strike orientation of the sheeted A-vein array that controls mineralization at Malachite Mountain. The D_2 deformation (cf. Fig. 5L) has also given rise to rare crenulation cleavages overprinting the penetrative NW-trending S_1 fabric and entrained A-type veins, as well as localized small-scale asymmetric folding of porphyry copper mineralization-related quartz veins (Fig. 5M, N).

Small-scale brittle faults are common in both drill core and outcrop, cutting vein sets with displacements typically on the order of centimeters to tens of centimeters (Fig. 5O). Where mapped, brittle faults have two main orientations that are similar to the two ductile shear fabrics: a subvertical to steeply dipping NW-striking set and a steeply SE-dipping set. No brittle faults with large offsets in excess of several hundreds of meters have been recorded at Jebel Ohier to date. However, their presence cannot be ruled out given the lack of lithological marker horizons.

Methodology

A suite of representative samples from each of the currently identified rock types has been investigated geochemically to further constrain their affinity. In contrast to the regional-scale work presented in Bierlein et al. (2016b), the current data set focuses entirely on the newly classified igneous units

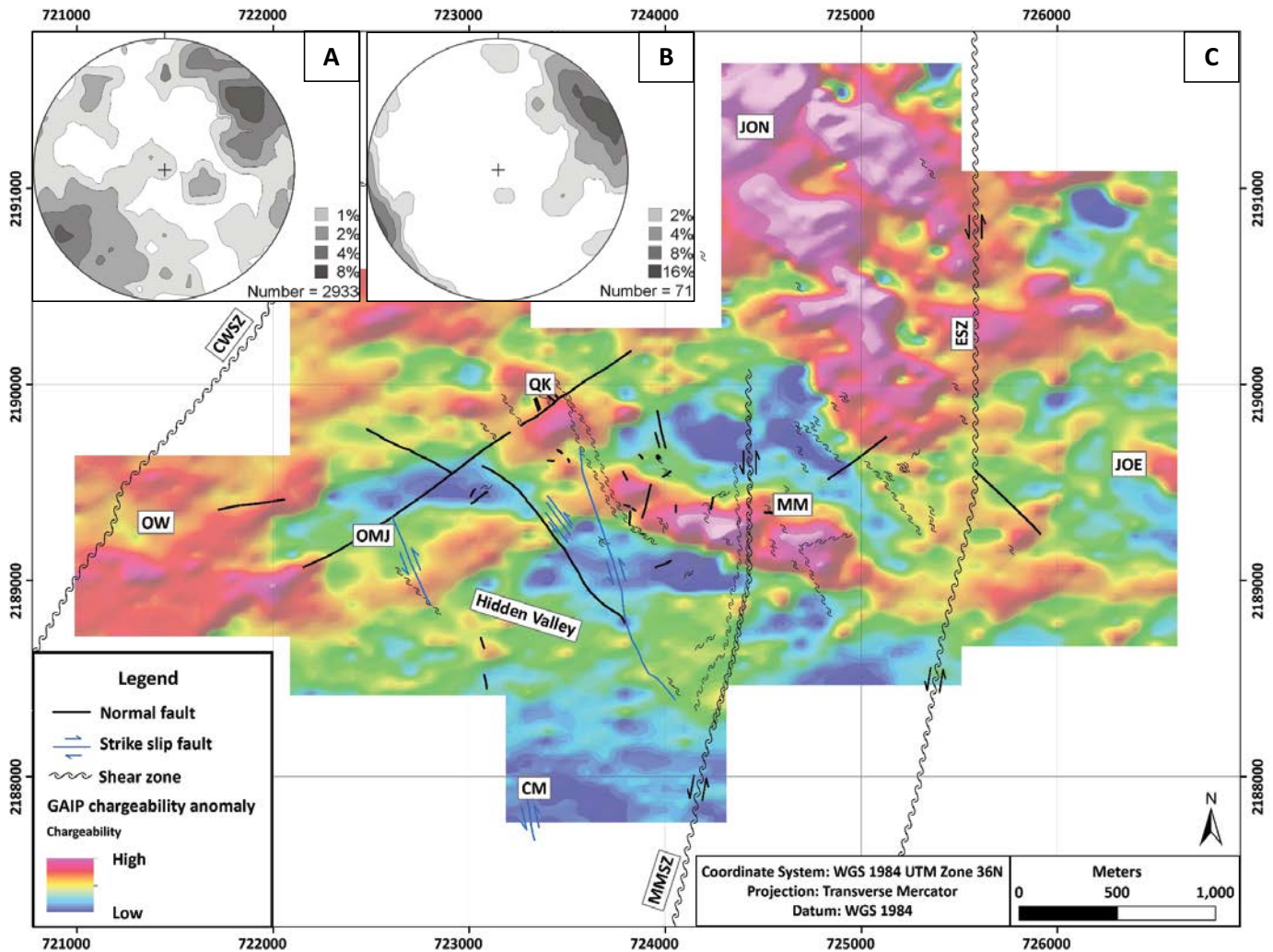


Fig. 6. (A) Contoured poles to planes of mapped A, B, and VQZ veins on the lower hemisphere of an equal-area stereographic net. The data have been weighted using a vein frequency qualifier recorded during mapping. (B) Contoured poles to planes of S₁ foliation surfaces on the lower hemisphere of an equal-area stereographic net and measured in outcrop from Malachite Mountain and Quartz Knob. The dominant populations of veins and S₁ surfaces trend northwest, subparallel to the Malachite Mountain-Quartz Knob trend, as well as a linear low-wavelength magnetic anomaly below Malachite Mountain and Quartz Knob observed in C. (C) Processed gradient array induced polarization (GAIP) chargeability data (for abbreviated location names, see caption of Fig. 2).

from Jebel Ohier (i.e., ID₁, ID₂, ID₃, QFP, FQP, DGC_bt, DGC_hb, DGC_MD, NWD) and, for the first time, includes unoxidized material from drill core. All 62 samples were examined and cleaned, with slabs prepared for chemical analysis by jaw crushing (2–5 kg) and milling in a tungsten-carbide mill. The pulverized samples, together with several blanks, duplicates, and certified reference material, were analyzed for 64 major and trace elements by ICP-optical emission spectrometry (ICP-OES) and MS methods using a four-acid digest (HNO₃, HClO₄, HF, HCl) at ALS Laboratories in Romania. Results are summarized in Table 3, with relevant classification diagrams shown in Figure 7.

In order to establish the absolute timing of mineralization at Jebel Ohier, three carefully selected samples of ID₂ were chosen from logged drill core intervals well below the base of oxidation, where crosscutting and relative timing relationships could be established unambiguously. In all three cases, intense

A-type veins in strongly potassic altered ID₁ have been cut by weak stockworks predominately composed of D-type veins but also containing minor A-type veins and disseminated trace chalcopyrite in less pervasively altered ID₂. These crosscutting, mineralization, and alteration features confirm that emplacement of ID₂ most likely occurred toward the final stages of mineralization and ore formation. This is further demonstrated by the observation that most of the A-type veins are truncated by the intrusive contact, but at least some A-type veins propagate across the contact. Our reasoning behind focusing on samples from mineralized ID₂ is based on the notion that while geochronological constraints from the ore-hosting ID₁ can only ever provide an indirect maximum age of mineralization (i.e., the time of emplacement of a premineralization intrusion), well-constrained U-Pb ages from an intrusive phase that conclusively correlates with the time of mineralization can provide the best approximation of a direct age for the ore-forming

Table 3. Representative Lithogeochemistry Data

Sample ID	FBRs-71	FBRs-74	FBRs-75	FBRs-86	FBRs-87	FBRs-88	FBRs-96	FBRs-98	FBRs-99	FBRs-100	FBRs-101
Latitude ¹	723624	721866	721867	724666	723890	722934	721523	726281	724008	724176	726113
Longitude ¹	2191312	2191600	2189450	2190791	2190379	2190403	2187014	2189463	2187225	2187622	2188762
Elevation (m a.s.l.)	579.4	521.4	587.4	555.0	541.3	533.1	537.3	650.9	599.3	632.4	563.9
Sample type ² Interval (core only; m)	S	S	S	S	S	S	S	S	S	S	S
Rock type	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID	ID ₁	ID ₁
SiO ₂ (%)	69.9	68.7	83.5	79.4	72.9	78.3	67.8	55.4	69.8	70.2	72.3
Al ₂ O ₃ (%)	17.05	17.9	13.25	12.45	13.2	18.3	16.85	18.5	17.8	26.4	12.2
Fe ₂ O ₃ (%)	2.51	2	1.44	1.23	3.77	2.04	2.9	9.21	2.99	0.77	7.73
CaO (%)	0.81	0.24	0.14	0.18	0.35	0.05	0.38	1.17	0.71	0.08	0.15
MgO (%)	0.24	0.57	0.01	0.24	0.65	0.01	3.15	4.16	0.84	0.01	0.63
Na ₂ O (%)	6.42	0.2	0.03	0.11	0.15	0.04	0.85	2.87	1.2	0.1	0.06
K ₂ O (%)	1.33	5.14	<0.01	3.57	3.92	0.07	4.18	1.8	3.1	0.05	3.81
Cr ₂ O ₃ (%)	0.006	0.004	0.01	0.004	0.003	0.008	0.005	0.021	0.005	0.006	0.008
TiO ₂ (%)	0.3	0.45	0.38	0.28	0.28	0.42	0.23	0.8	0.37	0.52	0.51
MnO (%)	0.01	0.01	0.02	0.01	0.04	0.02	0.03	0.09	0.04	0.01	0.03
P ₂ O ₅ (%)	0.08	0.07	0.19	0.02	0.01	0.14	0.05	0.03	0.14	0.02	0.06
SrO (%)	0.05	0.01	0.11	<0.01	0.01	0.07	0.01	0.04	0.05	<0.01	<0.01
C (%)	0.04	0.05	0.02	0.05	0.05	0.05	0.02	0.03	0.01	0.02	0.02
S (%)	0.13	0.16	0.1	0.05	0.04	0.11	<0.01	0.01	<0.01	0.04	0.01
BaO (%)	0.05	0.06	0.02	0.04	0.09	0.05	0.05	0.04	0.08	<0.01	0.09
LOI (%)	1.68	3.61	0.99	2.01	3.41	0.45	3.14	4.95	3.05	2.26	3.04
Total	100.44	98.96	100.09	99.54	98.78	99.97	99.63	99.08	100.18	100.43	100.62
Ba (ppm)	432	509	136.5	352	807	406	439	360	820	51.3	776
Ce (ppm)	17.3	18.8	13.7	12.5	8.5	18.7	45.1	18.9	30.7	31.4	5.7
Cr (ppm)	30	20	60	20	10	40	<10	120	10	20	30
Cs (ppm)	0.5	1.31	0.04	0.33	0.67	0.05	2.5	0.78	1.69	0.07	2.26
Dy (ppm)	0.69	1.07	0.41	1.67	0.71	0.55	5.88	7.66	2.26	1.71	1.56
Er (ppm)	0.38	0.55	0.22	1.41	0.64	0.39	3.47	5.13	0.98	0.85	1.16
Eu (ppm)	0.52	0.53	0.42	0.23	0.12	0.29	0.94	1.43	0.97	0.67	0.36
Ga (ppm)	17.6	20.4	8.9	5.7	24.5	27.8	18.2	21.3	24.5	30.3	16.2
Gd (ppm)	1.17	1.27	0.74	1.05	0.74	0.63	5.55	6.63	2.96	1.94	1.45
Hf (ppm)	2.6	2.4	2	3.9	3.5	2.7	6.9	2.5	3	4.4	2.4
Ho (ppm)	0.11	0.2	0.08	0.39	0.15	0.11	1.2	1.69	0.39	0.35	0.35
La (ppm)	8.6	8.7	6.9	7.5	4.5	10.2	21.6	8	14.3	13.8	3.8
Lu (ppm)	0.08	0.09	0.05	0.3	0.15	0.08	0.56	0.64	0.11	0.11	0.22
Nb (ppm)	2.3	2.1	1.9	2.9	2.6	2.2	5.1	2.4	2.2	3.1	2
Nd (ppm)	8.1	12	7.7	5.5	3.3	8	25.1	12.5	16.5	16.4	4.4
Pr (ppm)	2.07	2.68	1.72	1.4	0.86	2.22	5.68	2.61	3.82	3.83	1.04
Rb (ppm)	25.8	95.1	0.3	58.6	74.2	0.7	92.4	42.1	66.8	1.3	83.8
Sm (ppm)	1.56	1.93	1.3	1.18	0.64	1.05	5.75	3.92	3.6	2.75	1.16
Sr (ppm)	524	154	1,020	90	131	707	133.5	329	492	94.4	36.5
Ta (ppm)	0.3	0.1	0.3	0.1	0.1	<0.1	0.3	0.1	0.1	0.2	0.1
Tb (ppm)	0.16	0.17	0.07	0.21	0.1	0.06	0.94	1.18	0.44	0.3	0.25
Th (ppm)	0.88	0.75	0.64	2.76	2.1	0.57	3.81	0.65	0.88	1.18	1.46
Tm (ppm)	0.07	0.1	0.05	0.26	0.1	0.05	0.55	0.69	0.13	0.1	0.17
U (ppm)	0.53	0.34	0.21	0.87	0.86	0.45	0.81	0.88	0.67	0.75	0.71
V (ppm)	44	64	43	46	98	70	7	169	86	81	194
Y (ppm)	3.2	5.7	2.1	10	6.1	3.1	35	51.2	11.4	8.3	10.1
Yb (ppm)	0.4	0.6	0.33	1.91	0.89	0.36	3.54	4.56	0.84	0.76	1.29
Zr (ppm)	105	93	74	132	118	92	232	95	106	160	90
As (ppm)	1.4	5.4	6.9	0.6	1.6	64.5	0.4	0.9	1.2	3.5	2.2
Bi (ppm)	0.24	0.08	0.13	0.07	0.27	0.24	0.02	0.06	0.11	0.01	0.93
Sb (ppm)	0.06	0.1	1.3	<0.05	0.07	2.46	<0.05	0.06	0.09	0.19	0.12
Se (ppm)	0.9	0.4	<0.2	0.6	1	0.6	<0.2	<0.2	<0.2	0.2	1.4
Te (ppm)	0.05	0.22	0.23	0.03	0.09	1.52	<0.01	0.04	0.14	<0.01	0.84
Tl (ppm)	0.02	0.04	<0.02	0.02	0.03	<0.02	0.05	0.07	0.03	<0.02	0.04
Co (ppm)	1	<1	<1	<1	<1	<1	2	29	5	<1	22
Cu (ppm)	14	22	22	11	25	57	1	4,480	1,660	10	21
Mo (ppm)	<1	1	2	11	9	54	<1	<1	10	1	4
Ni (ppm)	1	<1	<1	<1	<1	3	3	34	3	3	7
Pb (ppm)	20	46	22	3	5	82	5	7	15	30	4
Sc (ppm)	3	5	2	7	5	3	5	17	4	6	15
Zn (ppm)	32	23	7	9	25	3	55	127	214	115	60
Au (ppb)	4	4	1	<1	3	42	<1	8	8	<1	46

Table 3. (Cont.)

Sample ID	FBRS-102	JODD_017	JODD_017	JODD_009	JODD_009	JODD_004	JODD_005	JODD_010	JODD_004	JODD_004
Latitude ¹	726719	724268	724270	724523	724516	723988	723413	723846	723979	723956
Longitude ¹	2188770	2189444	2189448	2189211	2189198	2189452	2189745	2189505	2189429	2189369
Elevation (m a.s.l.)	545.1	272.7	265.3	299.7	274.8	468.3	457.1	265.5	422.9	306.5
Sample type ²	S	C	C	C	C	C	C	C	C	C
Interval (core only; m)		454.3– 454.6	463.1– 463.3	462.6– 462.9	491.5– 491.9	162.7– 163	110– 110.2	430.9– 431.2	214.5– 214.7	347.3– 347.7
Rock type	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁
SiO ₂ (%)	70.1	64.6	62.8	47.7	68.2	51.5	52.5	74	68.3	54.1
Al ₂ O ₃ (%)	15.65	16.3	16.45	14.65	14.3	18.75	18.45	13	14.55	15.9
Fe ₂ O ₃ (%)	5.64	4.66	2.65	12.4	2.37	8.32	11.6	3.69	4.4	8.06
CaO (%)	0.34	3.5	3.95	8.78	3.29	2.02	3.15	0.41	1	7.14
MgO (%)	0.42	1.51	1.08	4.51	0.88	5.15	2.67	0.67	0.51	4.91
Na ₂ O (%)	0.16	5.33	5.85	2.97	4.95	4.05	5.54	0.23	0.17	3.31
K ₂ O (%)	3.78	1.52	1.31	0.46	1.19	2.41	0.79	3.74	4.53	1.77
Cr ₂ O ₃ (%)	0.007	<0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.02
TiO ₂ (%)	0.47	0.63	0.34	2.04	0.39	1.22	1.19	0.32	0.29	1
MnO (%)	0.02	0.09	0.05	0.19	0.03	0.07	0.06	0.01	0.01	0.14
P ₂ O ₅ (%)	0.08	0.17	0.12	0.34	0.12	0.21	0.28	0.03	0.1	0.24
SrO (%)	0.02	0.03	0.04	0.05	0.03	0.03	0.05	<0.01	<0.01	0.04
C (%)	0.04	0.13	0.12	0.87	0.19	0.09	0.09	0.13	0.19	0.33
S (%)	0.06	0.04	1.47	0.9	1.18	0.69	0.26	1.72	2.14	0.12
BaO (%)	0.06	0.07	0.03	0.02	0.03	0.03	0.01	0.13	0.06	0.04
LOI (%)	4	1.16	4.36	4.67	2.24	4.51	1.98	2.88	3.15	2.41
Total	100.75	99.57	99.03	98.79	98.02	98.27	98.28	99.11	97.07	99.08
Ba (ppm)	603	590	219	177.5	278	263	113.5	1,005	421	292
Ce (ppm)	21.6	31.6	16	23.3	25.9	9.3	14.8	22.2	3.2	28.9
Cr (ppm)	30	20	10	40	20	20	30	10	10	140
Cs (ppm)	0.76	1.08	0.43	0.11	0.12	1.83	0.44	0.58	0.6	0.29
Dy (ppm)	2.15	3.52	0.89	5.21	3.22	3.22	3.77	3.32	0.43	3.18
Er (ppm)	1.63	2.41	0.52	3.37	2.12	1.97	2.69	2.44	0.25	1.76
Eu (ppm)	0.47	0.83	0.62	1.91	0.76	0.84	1.1	0.51	0.16	1.05
Ga (ppm)	18.5	17.5	19.6	21.8	12.1	19.7	18.5	15.3	21.8	18.7
Gd (ppm)	1.98	3.87	1.55	6.23	3.01	3.12	4	3.34	0.4	3.7
Hf (ppm)	4.9	5.3	2.7	3.1	3.9	1.9	2.4	5.2	2	3.3
Ho (ppm)	0.49	0.8	0.19	1.13	0.71	0.69	0.95	0.8	0.09	0.72
La (ppm)	10.6	15.5	8.7	8.8	12.8	3.9	7	11.7	1.6	14.1
Lu (ppm)	0.3	0.35	0.09	0.42	0.38	0.34	0.39	0.43	0.04	0.26
Nb (ppm)	3.5	4.8	2.6	3.1	2.6	2.8	2.6	3.4	1.4	5.9
Nd (ppm)	11.2	17.6	8.5	18.1	13	7.5	9.7	11.8	1.9	16.8
Pr (ppm)	2.65	4.05	1.94	3.6	3.15	1.38	2.13	2.87	0.4	3.8
Rb (ppm)	85.7	28.8	27.6	9.8	20.1	58	17.9	51.6	64.1	32.4
Sm (ppm)	2.11	4.17	1.69	4.96	2.9	2.3	2.91	3.07	0.48	4.33
Sr (ppm)	207	342	466	474	331	324	487	35.2	94.3	460
Ta (ppm)	0.2	0.4	0.2	0.1	0.2	<0.1	0.1	0.3	0.1	0.4
Tb (ppm)	0.36	0.59	0.19	0.85	0.5	0.5	0.69	0.54	0.06	0.53
Th (ppm)	2.81	2.85	0.97	0.55	2.56	0.57	0.72	3.09	0.38	2.1
Tm (ppm)	0.24	0.31	0.08	0.46	0.34	0.31	0.39	0.37	0.04	0.24
U (ppm)	1.39	1.58	0.41	0.31	1.18	0.11	0.16	1.11	0.16	1.06
V (ppm)	120	59	53	388	49	253	101	42	69	179
Y (ppm)	13.2	20	4.7	31.6	19.8	18.9	22.4	20.5	1.9	20.2
Yb (ppm)	1.77	2.28	0.45	2.77	2.53	1.89	2.71	2.62	0.29	1.65
Zr (ppm)	184	233	105	110	133	70	87	180	80	130
As (ppm)	1	0.7	0.7	2.4	0.5	0.5	1	0.4	0.5	0.8
Bi (ppm)	0.12	0.03	0.08	0.07	0.01	0.14	0.05	0.14	0.97	0.02
Sb (ppm)	0.07	0.1	0.08	0.19	<0.05	<0.05	0.07	0.07	0.13	<0.05
Se (ppm)	2.2	0.2	0.6	1	0.3	3.1	0.9	2.6	7.7	0.2
Te (ppm)	0.11	0.02	0.06	0.17	0.03	0.15	0.06	0.09	0.24	<0.01
Tl (ppm)	0.07	0.09	0.03	<0.02	<0.02	0.25	0.03	0.07	0.07	<0.02
Co (ppm)	3	5	2	47	5	25	27	5	3	27
Cu (ppm)	200	56	1,620	265	695	5,890	2,080	8,410	18,950	76
Mo (ppm)	4	5	3	<1	20	2	4	25	3	2
Ni (ppm)	4	3	2	24	2	14	19	3	<1	49
Pb (ppm)	13	5	5	<2	4	19	5	5	122	6
Sc (ppm)	11	10	3	36	7	27	23	9	3	20
Zn (ppm)	32	73	118	97	34	158	179	32	87	79
Au (ppb)	<1	1	6	10	2	77	20	16	252	<1

Table 3. (Cont.)

Sample ID	JODD_002	JODD_004	JODD_006	JODD_004	JODD_015	JODD_016	JODD_025	JODD_023	JODD_010	JODD_014
Latitude ¹	724732	723979	723412	723950	724222	724048	723577	724747	723799	724405
Longitude ¹	2189279	2189429	2189664	2189353	2189252	2189239	2189886	2189248	2189400	2189316
Elevation (m a.s.l.)	237.4	423.1	340.3	274.1	411.6	441.1	412.3	563.2	457.7	210.4
Sample type ²	C	C	C	C	C	C	C	C	C	C
Interval (core only; m)	518.4– 518.7	214.7– 214.9	279.3– 279.5	384.3– 384.5	292.3– 292.7	213.4– 213.8	152.6– 152.9	150.3– 150.6	206.5– 206.8	551– 551.4
Rock type	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁	ID ₁
SiO ₂ (%)	62.3	57.4	61	66.6	63	45.4	52.8	66.7	61.6	51.3
Al ₂ O ₃ (%)	15.55	17.4	15.85	11.3	16.35	13.75	14.5	16.4	17.35	18.5
Fe ₂ O ₃ (%)	6.94	5.55	6.17	2.78	2.7	10.15	6.31	3.51	4	10.3
CaO (%)	4	5.68	5.5	4.82	3.83	9.02	7.01	1.26	4.29	4.41
MgO (%)	1.85	3.49	2.37	1	1.06	2.67	2.55	0.95	1.84	4.09
Na ₂ O (%)	5.26	4.2	2.32	1.87	5.01	3.6	2.96	6.44	5.41	2.23
K ₂ O (%)	1.04	1.4	1.24	2.44	1.66	1.11	1.96	1.03	0.97	3.33
Cr ₂ O ₃ (%)	0.01	0.01	0.01	<0.01	<0.01	0.01	0.01	<0.01	0.008	0.01
TiO ₂ (%)	0.56	0.61	0.75	0.29	0.35	0.89	0.69	0.34	0.6	0.87
MnO (%)	0.04	0.09	0.05	0.03	0.05	0.08	0.04	0.03	0.06	0.11
P ₂ O ₅ (%)	0.08	0.19	0.14	0.06	0.14	0.19	0.18	0.13	0.22	0.18
SrO (%)	0.03	0.08	0.03	0.03	0.06	0.05	0.02	0.03	0.11	0.04
C (%)	0.1	0.27	0.09	0.05	0.13	0.07	0.09	0.14	0.39	0.04
S (%)	1.26	0.06	1.83	3.49	1.65	4.02	3.6	0.61	0.01	1.72
BaO (%)	0.02	0.05	0.04	0.05	0.03	0.01	0.04	0.02	0.05	0.07
LOI (%)	3.94	2.67	4.4	6.39	4.72	5.38	6.51	1.62	2.8	3.86
Total	101.62	98.82	99.87	97.66	98.96	92.31	95.58	98.46	99.31	99.3
Ba (ppm)	188.5	358	286	409	233	103.5	367	149.5	365	635
Ce (ppm)	24.3	17.6	17.7	25.2	17.6	13.1	22.6	11.3	24.6	14.7
Cr (ppm)	40	40	30	10	10	50	20	10	30	40
Cs (ppm)	0.36	0.38	1.08	0.64	0.36	0.38	0.7	0.2	0.3	1.12
Dy (ppm)	3.77	1.44	3.48	3.33	0.83	3.17	3.62	0.65	1.04	2.9
Er (ppm)	2.46	0.87	2.1	2.1	0.52	2.17	2.48	0.42	0.46	1.86
Eu (ppm)	0.89	0.75	0.82	0.64	0.59	0.93	0.99	0.43	0.91	0.98
Ga (ppm)	15.6	17.2	16.1	12.6	18.3	14.4	17	18.2	18.9	20.9
Gd (ppm)	3.71	1.79	3.44	3.29	1.43	3.77	3.89	1.15	2	2.88
Hf (ppm)	3.8	2.2	3.5	4.1	2.4	1.7	2.9	2.8	2.6	2.1
Ho (ppm)	0.77	0.35	0.81	0.79	0.19	0.77	0.97	0.14	0.18	0.62
La (ppm)	12	8.5	8.7	12.8	8.9	6	10.8	6.1	11.6	6.8
Lu (ppm)	0.35	0.12	0.35	0.33	0.07	0.3	0.37	0.07	0.04	0.28
Nb (ppm)	2.6	1.4	3	3	2	2	3	2	1.6	2.1
Nd (ppm)	12.8	10	11.9	12.3	9.3	9.4	12.5	6.3	13.7	10.3
Pr (ppm)	3.06	2.29	2.59	3.13	2.28	1.92	2.94	1.45	3.2	2.06
Rb (ppm)	26.6	28.6	24	43.8	39.2	32.4	41.1	22.9	13.8	77.7
Sm (ppm)	3.36	2.41	3.22	3.15	1.85	3.17	3.52	1.22	2.67	2.68
Sr (ppm)	327	765	410	415	737	601	356	293	918	352
Ta (ppm)	0.1	0.1	0.2	0.2	0.1	<0.1	0.1	0.2	<0.1	0.1
Tb (ppm)	0.57	0.29	0.6	0.57	0.17	0.59	0.68	0.13	0.23	0.44
Th (ppm)	2.39	0.79	1.81	2.73	0.7	0.49	1.78	0.62	0.95	0.87
Tm (ppm)	0.36	0.12	0.28	0.33	0.06	0.31	0.35	0.06	0.05	0.25
U (ppm)	1.29	0.44	0.67	0.97	0.34	0.18	0.36	0.21	0.64	0.62
V (ppm)	146	135	139	46	30	201	124	59	63	242
Y (ppm)	22.8	8.4	17.9	19.5	5.2	18.6	21.2	4	4.8	17.6
Yb (ppm)	2.46	0.75	2.25	2.21	0.41	1.82	2.56	0.41	0.37	1.82
Zr (ppm)	130	75	125	153	99	61	126	86	103	70
As (ppm)	0.7	0.4	0.6	0.4	0.6	1.2	0.6	0.7	0.8	1.1
Bi (ppm)	0.02	0.01	0.01	0.2	0.04	0.11	0.17	0.19	0.02	0.24
Sb (ppm)	0.07	0.13	<0.05	0.08	0.07	0.1	0.13	0.05	0.1	0.13
Se (ppm)	0.4	0.3	<0.2	1.4	0.4	1.7	3.2	2.2	0.3	1.2
Te (ppm)	0.03	0.01	0.01	0.08	0.04	0.11	0.12	0.21	0.01	0.32
Tl (ppm)	0.08	0.04	0.03	0.09	0.04	0.06	0.08	0.03	<0.02	0.23
Co (ppm)	17	21	19	4	5	25	15	5	10	46
Cu (ppm)	499	44	51	5,130	1,090	5,050	5,430	3,760	23	1,730
Mo (ppm)	27	2	<1	20	16	<1	76	3	<1	20
Ni (ppm)	9	29	9	3	3	16	8	3	12	17
Pb (ppm)	5	<2	10	3	28	18	6	34	7	10
Sc (ppm)	16	11	19	7	3	26	18	3	5	25
Zn (ppm)	58	73	80	66	133	419	79	103	72	172
Au (ppb)	1	1	2	25	6	23	12	101	2	18

Table 3. (Cont.)

Sample ID	JODD_026	JODD_009	JODD_025	JODD_010	FBRS-103	FBRS-69	JODD_048	JODD_025	JODD_014	FBRS-70
Latitude ¹	723469	724506	723571	723831	726477	724284	722447	723562	724396	723964
Longitude ¹	2190015	2189181	2189867	2189472	2189601	2191491	2190055	2189844	2189297	2191351
Elevation (m a.s.l.)	352.3	242.9	448.9	326.7	641.8	547.1	-81.3	493.90	244.46	601.8
Sample type ²	C	C	C	C	S	S	C	C	C	S
Interval	264.0–	528.8–	110.8–	359.3–			624.6–	59.3–	511.2–	
(core only; m)	264.3	529.1	111.0	359.6			624.9	59.6	511.5	
Rock type	ID ₁	ID ₁	ID ₁	ID ₁	Dacite	ID ₂	ID ₂	ID ₂	ID ₂	ID ₃
SiO ₂ (%)	54.8	49.2	63.3	65.1	72.5	72.9	47.1	64.2	55	53.8
Al ₂ O ₃ (%)	14.75	18.1	17.15	14.85	14	16.4	18.4	17.5	16.75	15.55
Fe ₂ O ₃ (%)	11.45	11.1	3.36	2.53	3.13	1.52	10.8	5.98	8.03	9.18
CaO (%)	5.03	3.63	3.56	4.24	1.67	0.13	7.63	1.09	6.99	7.99
MgO (%)	3.51	5.18	1.08	0.78	0.64	0.58	4.99	1.51	5	5.45
Na ₂ O (%)	2.39	2.08	6.17	3.92	4.71	0.15	3.96	2.2	3.84	2.91
K ₂ O (%)	1.27	3.06	1.27	2.23	1.24	4.86	0.57	3.21	0.95	2.04
Cr ₂ O ₃ (%)	0.011	0.012	0.003	0.002	0.005	0.004	0.009	0.002	0.021	0.031
TiO ₂ (%)	0.8	0.84	0.36	0.31	0.28	0.32	0.87	0.37	0.88	0.99
MnO (%)	0.08	0.12	0.05	0.02	0.04	0.02	0.16	0.07	0.12	0.16
P ₂ O ₅ (%)	0.18	0.1	0.18	0.11	0.1	0.01	0.22	0.1	0.23	0.35
SrO (%)	0.03	0.03	0.06	0.05	0.05	<0.01	0.05	0.03	0.06	0.04
C (%)	0.03	0.04	0.09	0.06	0.04	0.06	0.15	0.09	0.21	0.05
S (%)	6.78	3.62	1.6	2.61	0.02	<0.01	0.61	1.61	0.15	0.01
BaO (%)	0.02	0.05	0.03	0.03	0.06	0.08	0.01	0.04	0.04	0.05
LOI (%)	5.52	5.24	3.74	5.7	1.82	2.45	3.58	4.04	2.25	1.6
Total	99.84	98.74	100.31	99.87	100.25	99.42	98.35	100.34	100.16	100.14
Ba (ppm)	157	491	294	286	586	737	133.5	410	400	418
Ce (ppm)	12.1	7.5	20.8	11.4	16.8	10.3	9.6	17	25.8	32.3
Cr (ppm)	60	70	10	20	20	10	50	10	120	190
Cs (ppm)	1.56	2.06	0.56	0.34	0.29	0.62	0.63	0.97	0.26	1.26
Dy (ppm)	2.85	2.95	1.25	0.89	1.08	1.2	3.3	1.37	3.34	4.69
Er (ppm)	1.86	1.77	0.63	0.46	0.6	0.84	2.27	0.87	1.87	2.9
Eu (ppm)	0.72	0.51	0.64	0.39	0.61	0.21	0.92	0.66	1.16	1.45
Ga (ppm)	19.4	19.7	22.4	18	18.6	16.2	18.8	23	19.3	17.2
Gd (ppm)	2.49	2.49	1.47	1.13	1.58	0.75	3.24	1.88	3.37	5.38
Hf (ppm)	1.5	1.5	2.4	2	2.6	3.8	1.8	2.7	2.9	3.3
Ho (ppm)	0.63	0.61	0.2	0.16	0.2	0.27	0.71	0.26	0.66	0.98
La (ppm)	5.4	3.4	9	4.7	8.4	5.5	4.3	7.6	11.9	13.5
Lu (ppm)	0.28	0.28	0.11	0.06	0.08	0.18	0.33	0.1	0.3	0.37
Nb (ppm)	1.6	1.5	3.4	1.7	2.5	2.8	1.8	2.4	2.7	3.4
Nd (ppm)	7.6	5.7	10.5	7.4	9.4	4.1	7.2	10.2	14.9	22.4
Pr (ppm)	1.66	1.13	2.62	1.56	2.21	1.18	1.32	2.26	3.37	4.8
Rb (ppm)	37.1	86.7	23.7	29.8	18.6	91.9	12.7	59.3	19.7	43.8
Sm (ppm)	2.13	1.87	2.35	1.5	1.76	0.87	2.28	2.65	3.42	5.43
Sr (ppm)	353	295	581	421	500	56.8	504	278	615	461
Ta (ppm)	0.1	0.1	0.2	<0.1	0.1	0.4	<0.1	0.1	0.2	0.4
Tb (ppm)	0.43	0.46	0.21	0.16	0.22	0.15	0.53	0.28	0.54	0.8
Th (ppm)	0.56	0.58	0.65	0.47	0.67	1.69	0.59	0.66	1.23	1.89
Tm (ppm)	0.24	0.28	0.1	0.07	0.07	0.16	0.31	0.11	0.25	0.4
U (ppm)	0.27	0.62	0.43	0.18	0.28	0.68	0.44	0.27	0.58	1.06
V (ppm)	209	279	53	47	56	48	215	53	164	237
Y (ppm)	16.7	16.6	6.1	4.4	6.5	7.4	18.8	7.3	18.8	26.7
Yb (ppm)	1.78	1.95	0.53	0.29	0.59	1.13	2.03	0.66	1.81	2.4
Zr (ppm)	49	43	93	61	99	150	59	98	115	133
As (ppm)	3.7	2	1.7	0.6	0.6	0.3	1.9	0.5	1.4	2
Bi (ppm)	0.16	0.1	0.15	0.42	0.03	0.05	0.02	0.31	0.01	0.02
Sb (ppm)	0.08	0.09	0.11	0.1	0.07	<0.05	0.18	0.09	0.18	0.06
Se (ppm)	1.9	2.7	0.6	2.5	0.3	0.2	0.3	2	0.4	<0.2
Te (ppm)	0.32	0.24	0.05	0.13	0.09	0.03	0.03	0.23	0.05	0.02
Tl (ppm)	0.27	0.5	0.03	0.03	0.04	0.04	0.05	0.06	0.03	0.24
Co (ppm)	50	57	5	3	5	<1	28	23	23	25
Cu (ppm)	180	1,120	435	6,610	1,140	22	716	2,750	60	20
Mo (ppm)	1	9	1	43	<1	4	<1	8	<1	1
Ni (ppm)	20	21	<1	<1	4	1	19	7	68	24
Pb (ppm)	9	18	33	19	9	7	9	8	4	4
Sc (ppm)	23	29	4	3	3	6	24	4	17	26
Zn (ppm)	68	255	156	179	58	16	140	379	87	93
Au (ppb)	5	10	4	37	18	<1	4	40	1	<1

Table 3. (Cont.)

Sample ID	FBRs-76	FBRs-80	FBRs-81	FBRs-85	JODD_048	JODD_012	JODD_025	JODD_026	JODD_009	FBRs-68
Latitude ¹	721686	722638	722133	724854	722445	724828	723557	723474	724566	721146
Longitude ¹	2189737	2188137	2188501	2190592	2190052	2189220	2189827	2190027	2189298	2189632
Elevation (m a.s.l.)	536.1	742.5	710.8	600.2	-63.3	537.6	524.3	330.1	461.8	526.6
Sample type ²	S	S	S	S	C	C	C	C	C	S
Interval (core only; m)					606.3– 606.6	168.1– 168.3	24.4– 24.6	289.5– 289.8	273.9– 274.2	
Rock type	ID ₃	ID ₃	ID ₃	ID ₃	ID ₃	ID ₃	ID ₃	ID ₃	ID ₃	FQP
SiO ₂ (%)	68.7	65.2	63.5	67.7	65.7	61.4	66.6	66.4	64	67.3
Al ₂ O ₃ (%)	15.65	17.2	17.05	14.85	16.45	17.4	17	16.9	16.25	14.95
Fe ₂ O ₃ (%)	3.08	4.17	4.55	3.95	3.18	4.3	2.9	3.31	3.44	4.05
CaO (%)	2.78	3.6	4.43	2.04	3.65	4.68	3.23	2.93	3.89	1.58
MgO (%)	0.96	1.3	1.06	1.05	1.49	1.94	1.25	1.15	1.77	1.14
Na ₂ O (%)	4.54	6.77	4.61	4.95	5.31	4.68	4.78	5.99	5.7	3.92
K ₂ O (%)	2.41	1.1	2.46	2.74	1.35	1.84	2.1	1.67	1.14	3.49
Cr ₂ O ₃ (%)	0.008	0.006	0.006	0.006	0.008	0.006	0.003	0.005	0.008	0.005
TiO ₂ (%)	0.29	0.41	0.44	0.37	0.41	0.57	0.43	0.35	0.48	0.51
MnO (%)	0.06	0.08	0.1	0.09	0.05	0.05	0.03	0.07	0.05	0.08
P ₂ O ₅ (%)	0.11	0.15	0.16	0.11	0.14	0.18	0.13	0.11	0.16	0.14
SrO (%)	0.07	0.09	0.06	0.01	0.09	0.11	0.12	0.05	0.09	0.01
C (%)	0.07	0.13	0.07	0.05	0.22	0.07	0.1	0.06	0.36	0.11
S (%)	<0.01	<0.01	<0.01	<0.01	0.12	0.1	0.01	0.27	0.04	0.01
BaO (%)	0.1	0.04	0.05	0.09	0.05	0.06	0.09	0.07	0.04	0.09
LOI (%)	0.75	1.05	0.98	0.71	2	1.01	1.35	1.18	2.28	1.58
Total	99.51	101.17	99.46	98.67	99.88	98.23	100.01	100.19	99.3	98.85
Ba (ppm)	925	355	412	745	490	522	782	749	376	754
Ce (ppm)	23.6	20.7	19.1	27.9	20.5	24.7	25	20.6	22	45.9
Cr (ppm)	40	30	30	30	40	20	20	20	30	20
Cs (ppm)	0.99	0.81	1.9	0.35	0.76	0.72	0.75	0.49	0.56	1.47
Dy (ppm)	1.07	1.71	1.58	2.58	1.05	1.07	1.04	1.43	1	5.41
Er (ppm)	0.43	1.1	0.92	1.46	0.38	0.58	0.48	0.74	0.45	3.6
Eu (ppm)	0.63	0.68	0.75	0.68	0.61	0.72	0.8	0.68	0.73	0.99
Ga (ppm)	18.9	19.1	18.6	16.5	20.8	20.2	22.3	21.5	20.7	16.1
Gd (ppm)	1.54	2.22	2.05	2.78	1.58	1.84	1.61	1.7	1.65	5.57
Hf (ppm)	2.8	2.7	2.4	4.2	2.2	2.4	2.9	3	2.6	8.6
Ho (ppm)	0.18	0.38	0.32	0.5	0.16	0.21	0.15	0.27	0.19	1.17
La (ppm)	12.2	10	9.2	14.1	10.2	12.5	12.3	10.1	10.1	20.3
Lu (ppm)	0.07	0.15	0.13	0.25	0.05	0.07	0.05	0.12	0.06	0.54
Nb (ppm)	2	2.8	2.7	3.5	1.4	1.9	1.5	2.6	1.1	7.1
Nd (ppm)	11.2	11.2	11.3	13.5	11	13	12.4	10.3	11.9	24.5
Pr (ppm)	2.71	2.56	2.38	3.38	2.59	3.04	3.09	2.51	2.8	6.01
Rb (ppm)	54.1	20.9	47.6	48.6	29.8	26.6	27.8	30.7	24.2	72.4
Sm (ppm)	2.14	2.53	2.13	2.7	2.04	2.34	2.29	2.01	2.31	5.78
Sr (ppm)	734	856	589	191	870	984	1,130	460	773	184.5
Ta (ppm)	0.2	0.1	<0.1	0.1	<0.1	<0.1	0.1	0.3	0.1	0.7
Tb (ppm)	0.16	0.27	0.25	0.43	0.2	0.23	0.19	0.26	0.21	0.9
Th (ppm)	2.07	0.95	0.88	3.51	1.35	2.17	1.64	1.14	1.04	5.57
Tm (ppm)	0.06	0.14	0.14	0.25	0.05	0.07	0.07	0.1	0.08	0.56
U (ppm)	1.53	0.58	0.46	1.94	0.8	1.06	0.94	0.66	0.62	3.16
V (ppm)	38	69	73	52	63	75	53	61	65	53
Y (ppm)	5	9.3	9	14.4	4.6	5.7	4.3	8.1	5.2	32.1
Yb (ppm)	0.39	0.89	0.91	1.52	0.41	0.47	0.33	0.77	0.35	3.33
Zr (ppm)	94	89	80	140	85	85	102	111	95	319
As (ppm)	0.9	5.8	2.8	0.8	1.8	1.2	0.8	1.3	0.9	1
Bi (ppm)	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.01
Sb (ppm)	0.11	0.23	0.26	0.09	0.14	0.11	0.1	0.17	0.13	0.11
Se (ppm)	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	<0.2	<0.2	<0.2	<0.2
Te (ppm)	0.02	0.02	0.01	0.01	0.05	0.01	0.01	0.04	<0.01	0.01
Tl (ppm)	0.11	0.03	0.08	0.22	0.06	0.07	0.04	0.12	0.02	0.24
Co (ppm)	5	8	9	5	9	11	7	5	7	7
Cu (ppm)	7	1	1	20	55	97	27	12	181	31
Mo (ppm)	1	1	<1	1	<1	<1	<1	<1	<1	<1
Ni (ppm)	4	2	4	2	9	11	6	<1	14	1
Pb (ppm)	12	2	7	2	9	11	8	6	2	7
Sc (ppm)	3	5	7	6	5	6	4	5	5	9
Zn (ppm)	51	60	57	51	75	62	83	55	57	62
Au (ppb)	<1	<1	<1	1	2	2	<1	1	3	2

Table 3. (Cont.)

Sample ID	FBRs-72	JODD_009	JODD_019	JODD_009	JODD_010	FBRs-82	FBRs-83	FBRs-84	FBRs-97	JODD_028	JODD_014
Latitude ¹	722712	724567	723356	724563	723778	721985	721716	724836	725634	723679	724412
Longitude ¹	2191547	2189301	2190078	2189291	2189346	2188304	2188660	2190363	2187176	2189726	2189328
Elevation (m a.s.l.)	526.0	467.7	44.4	448.9	557.6	635.7	564.9	573.3	651.5	315.0	187.3
Sample type ²	S	C	C	C	C	S	S	S	S	C	C
Interval (core only; m)		267.0– 267.3	583.3– 583.5	288.9– 289.1	91.3– 91.5					279.9– 280.0	578.0– 578.4
Rock type	FQP	FQP	QFP	MD	MD	MD	DGC_bt	DGC_bt	DGC_bt	DGC_bt	DGC_hb
SiO ₂ (%)	70.1	73.5	73.9	52.8	50.9	53.2	65.4	66	67.8	67.4	60
Al ₂ O ₃ (%)	14.05	13.05	12.7	16.35	16.75	19	16.5	16	16.25	16	15.8
Fe ₂ O ₃ (%)	3.54	1.84	2.03	9.43	8.07	7.41	3.09	3.08	2.83	2.94	5.62
CaO (%)	2.7	1.36	1.47	7.31	8.33	7.59	3.41	3.34	3.27	3.49	4.93
MgO (%)	0.58	0.44	0.25	3.98	5.84	2.66	1.25	1.34	1.33	1.27	2.51
Na ₂ O (%)	3.33	3.71	3.45	3.9	3.51	3.95	4.79	4.65	4.89	4.87	4
K ₂ O (%)	2.35	4.11	3.65	1.66	1.34	1.86	2.11	2.16	1.98	2	1.73
Cr ₂ O ₃ (%)	0.004	0.007	0.006	0.012	0.026	0.01	0.005	0.008	0.007	0.009	0.009
TiO ₂ (%)	0.31	0.16	0.19	1.76	0.87	1.28	0.42	0.38	0.37	0.35	0.94
MnO (%)	0.07	0.04	0.03	0.14	0.14	0.11	0.05	0.06	0.04	0.04	0.08
P ₂ O ₅ (%)	0.06	0.03	0.03	0.52	0.19	0.43	0.14	0.12	0.12	0.11	0.19
SrO (%)	0.03	0.02	0.01	0.07	0.06	0.08	0.1	0.09	0.1	0.09	0.06
C (%)	0.3	0.24	0.1	0.04	0.18	0.11	0.08	0.04	0.09	0.15	0.17
S (%)	<0.01	0.01	0.14	0.02	0.02	<0.01	0.01	<0.01	<0.01	0.03	0.01
BaO (%)	0.08	0.06	0.09	0.05	0.04	0.07	0.08	0.09	0.07	0.07	0.05
LOI (%)	2.05	1.4	0.95	0.89	2.11	1.47	0.91	0.71	1.29	1.29	2.08
Total	99.25	99.73	98.76	98.87	98.18	99.12	98.26	98.03	100.35	99.93	98
Ba (ppm)	675	593	815	501	282	547	709	786	605	622	448
Ce (ppm)	26.7	32.2	37.2	52.7	18.1	39.7	20	23.7	19.7	19.9	33.4
Cr (ppm)	10	30	30	80	140	50	30	40	20	40	40
Cs (ppm)	0.98	0.62	0.33	0.84	0.54	0.88	0.52	0.71	0.28	0.37	0.41
Dy (ppm)	3.03	1.87	2.11	6.9	2.86	4.4	1.06	1.22	0.91	0.83	3.18
Er (ppm)	2.07	1.01	1.53	3.65	1.65	2.52	0.55	0.55	0.35	0.36	1.84
Eu (ppm)	0.69	0.61	0.35	2.08	0.99	1.55	0.61	0.62	0.57	0.56	1.13
Ga (ppm)	15.9	14	14.1	24.2	15.9	20.1	19.4	19.5	17.1	18.9	19.2
Gd (ppm)	2.8	1.92	2.14	7.54	3.14	5.62	1.78	1.62	1.28	1.29	3.6
Hf (ppm)	4.3	3	4.7	6.4	2.1	4.5	2.2	2.9	2.3	2.5	4.1
Ho (ppm)	0.66	0.4	0.46	1.3	0.59	0.91	0.2	0.19	0.15	0.15	0.59
La (ppm)	13.6	16.5	17.7	22.4	8.2	17	9.7	12.2	9.5	9.9	15.9
Lu (ppm)	0.39	0.18	0.26	0.51	0.23	0.32	0.06	0.07	0.06	0.06	0.24
Nb (ppm)	2.9	4.5	4	6.1	1.9	4.4	1.9	1.8	1.3	1.4	4.5
Nd (ppm)	12.3	12.2	15.4	32.5	12.3	24.2	11	12.4	10	10	17.5
Pr (ppm)	3.25	3.49	4.01	7.06	2.49	5.38	2.42	2.9	2.33	2.39	4.21
Rb (ppm)	61.9	80.6	63.3	36.4	29.1	46.2	37.5	41	27.4	35.8	35.3
Sm (ppm)	2.71	2.67	2.67	7.57	2.94	4.86	2.19	2.15	1.61	1.76	3.63
Sr (ppm)	265	154	147	621	476	749	942	817	745	788	525
Ta (ppm)	0.4	0.6	0.4	0.4	<0.1	0.1	<0.1	<0.1	0.1	0.1	0.4
Tb (ppm)	0.47	0.3	0.37	1.11	0.47	0.8	0.17	0.23	0.18	0.16	0.53
Th (ppm)	2.83	6.02	5.34	3.14	0.76	2.28	1.73	2.03	1.29	1.58	3.98
Tm (ppm)	0.33	0.19	0.24	0.51	0.26	0.43	0.06	0.08	0.05	0.05	0.22
U (ppm)	1.19	3.38	2.92	1.42	0.39	1.15	1.15	1.21	0.88	1	1.93
V (ppm)	31	15	16	284	160	169	55	51	47	50	120
Y (ppm)	18.9	12	14.1	36.3	15.7	23.9	5.2	5.7	4.2	4.4	17.5
Yb (ppm)	2.22	1.26	1.67	3.3	1.71	2.34	0.53	0.47	0.39	0.41	1.53
Zr (ppm)	166	90	146	264	78	169	87	96	87	88	165
As (ppm)	1.5	0.6	0.3	1.3	1	1.6	0.8	0.3	0.3	0.9	1.2
Bi (ppm)	0.01	0.12	0.02	0.01	0.01	0.03	0.05	0.04	0.11	0.04	0.02
Sb (ppm)	0.13	0.05	0.08	0.06	0.06	0.14	0.07	<0.05	0.06	0.09	0.09
Se (ppm)	<0.2	0.2	<0.2	0.4	<0.2	<0.2	0.3	<0.2	<0.2	0.2	<0.2
Te (ppm)	0.01	<0.01	<0.01	<0.01	0.03	0.01	0.02	0.03	<0.01	0.01	<0.01
Tl (ppm)	0.1	0.03	0.03	0.1	<0.02	0.07	0.05	0.1	<0.02	0.03	0.1
Co (ppm)	3	1	3	26	34	20	7	7	7	5	16
Cu (ppm)	<1	2	17	153	21	108	41	14	48	3	31
Mo (ppm)	1	2	1	1	<1	<1	<1	<1	<1	<1	<1
Ni (ppm)	<1	7	<1	40	84	28	7	10	7	8	24
Pb (ppm)	7	12	5	6	7	6	11	6	8	4	6
Sc (ppm)	6	2	2	21	22	14	4	5	4	4	12
Zn (ppm)	43	24	15	100	98	79	58	48	59	50	64
Au (ppb)	<1	1	1	1	1	<1	<1	2	2	<1	1

< = below detection limit, LOI = loss on ignition

¹UTM zone 36N²S = surface, C = core sample (depth = top of interval)

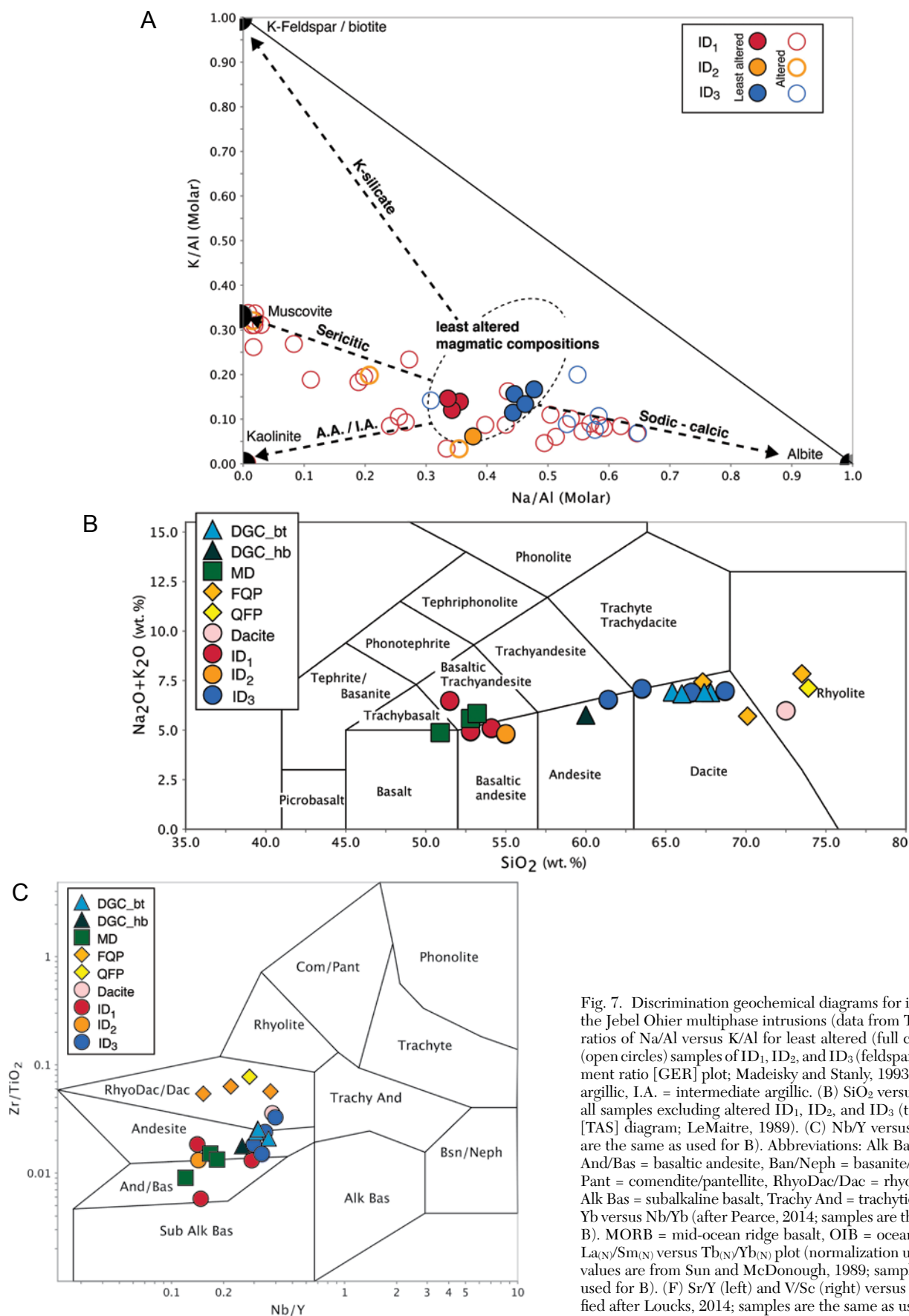


Fig. 7. Discrimination geochemical diagrams for igneous rocks from the Jebel Ohier multiphase intrusions (data from Table 3). (A) Molar ratios of Na/Al versus K/Al for least altered (full circles) and altered (open circles) samples of ID₁, ID₂, and ID₃ (feldspar Na-K general element ratio [GER] plot; Madeisky and Stanly, 1993). A.A. = advanced argillic, I.A. = intermediate argillic. (B) SiO₂ versus Na₂O + K₂O for all samples excluding altered ID₁, ID₂, and ID₃ (total alkali vs. silica [TAS] diagram; LeMaitre, 1989). (C) Nb/Y versus Zr/TiO₂ (samples are the same as used for B). Abbreviations: Alk Bas = alkaline basalt, And/Bas = basaltic andesite, Ban/Neph = basanite/nephelinite, Com/Pant = comendite/pantellite, RhyoDac/Dac = rhyodacite/dacite, Sub Alk Bas = subalkaline basalt, Trachy And = trachytic andesite. (D) Th/Yb versus Nb/Yb (after Pearce, 2014; samples are the same as used for B). MORB = mid-ocean ridge basalt, OIB = ocean island basalt. (E) La_N/Sm_N versus Tb_N/Yb_N plot (normalization using C1 Chondrite values are from Sun and McDonough, 1989; samples are the same as used for B). (F) Sr/Y (left) and V/Sc (right) versus SiO₂ (wt %; modified after Loucks, 2014; samples are the same as used for B).

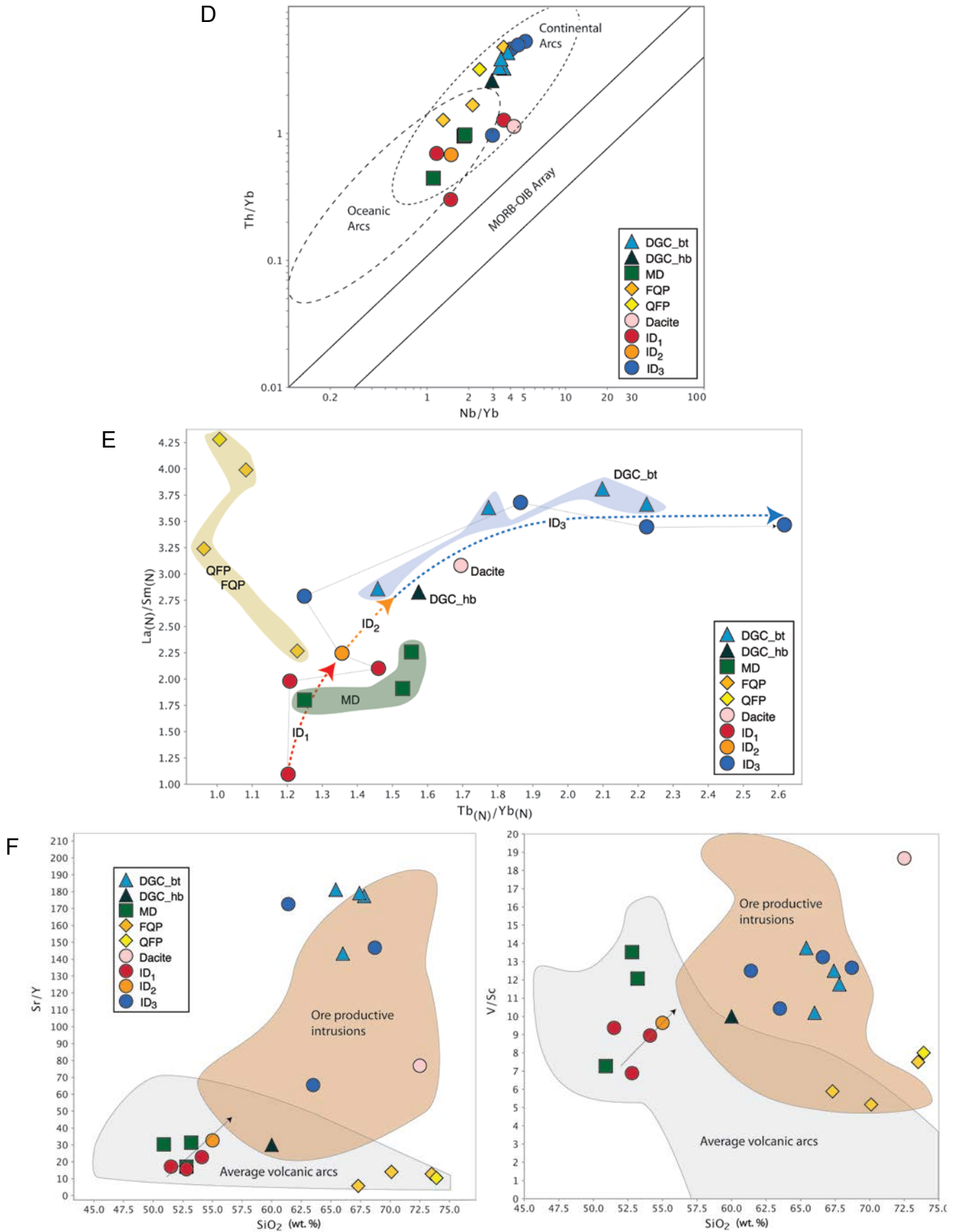


Fig. 7. (Cont.)

event itself. The fourth sample was taken from an interval of unaltered DGC_bt in drill core to ascertain the relative timing between mineralization and the bulk of postmineralization magmatism at Jebel Ohier. A fifth sample was collected from surface exposure of intensely A- and B-veined dacite in the Alfrasco deposit east of Malachite Mountain, where no diamond drill core was available. Inclusion of this sample was intended to test the temporal relationship between the mineralized dacite and the ore-hosting ID₁ and ID₂ to the west.

Zircon grains were separated from the five samples at the Curtin SelfFrag facility, using electric pulse disaggregation and conventional magnetic and heavy liquid techniques. Final mineral separates were handpicked, best-quality, non-magnetic grains. Zircon from the samples and zircon standards (TEMORA, BR266, and OCG zircon, and 610 glass fragments) were mounted and polished in 24-mm-diameter epoxy discs and gold coated. Zircons were then studied by cathodoluminescence (CL) imaging using a MIRA3 scanning electronic microscope (SEM) and analyzed by the SHRIMP II ion microprobe at Curtin University. Ion microprobe analytical methods broadly follow those described by Compston et al. (1984) and Williams (1998). A series of standard analyses were interspersed between analyses during each session. All isotopic measurements were reduced by off-line computer programs using standard techniques. Pb/U ages were normalized to a value of 559 Ma determined by conventional U-Pb analysis of standard zircon BR266, or 561.3 Ma for M257, or 416.78 Ma for Temora 2 (Black et al., 2003; Stern and Amelin, 2003; Nasdala et al., 2008). The measurement of ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²³⁵U ages requires normalization to results of the standard analyses, and the results were corrected for the uncertainties associated with the measurements of the BR266 standard (App. 1). Because of the low U and Th contents of many of the zircons analyzed, the ²⁰⁸Pb correction method was used where possible to correct for common Pb, rather than the ²⁰⁴Pb method, which is sensitive for low U and young zircons (Compston et al., 1984). Decay constants used are those recommended by the International Union of Geological Sciences (IUGS) (Steiger and Jäger, 1977). Errors cited for individual analysis include errors from counting statistics, the common-Pb correction, and the U-Pb calibration error based on reproducibility of U-Pb measurements of the standard and are at the 1σ level. Weighted mean values given on pooled analyses are at the 95% confidence level. Error ellipses for individual analyses shown in Figures 8A to E are shown at 1σ uncertainty. Where possible, concordia ages are used, as they combine the information from the ²⁰⁶Pb/²³⁸U or ²⁰⁷Pb/²³⁵U and ²⁰⁷Pb/²⁰⁶Pb ages. The concordia age ellipse is at the 95% confidence level. The ages in the text are the ²⁰⁶Pb/²³⁸U dates for Paleozoic and Neoproterozoic zircon, which are more precise than ²⁰⁷Pb/²⁰⁶Pb dates due to the lower content of ²⁰⁷Pb in these zircons. The ²⁰⁷Pb/²⁰⁶Pb ages are used for zircons older than 1.0 Ga.

Results

Geochemistry

The units making up the Jebel Ohier multiphase intrusion comprise predominantly subalkaline diorites to granodiorites (Table 3). Variable types and intensities of hydrothermal alteration (i.e., sericitic, intermediate argillic, and sodic-calcic

alteration), as well as abundant A-type stockwork quartz veins, are evident in ID₁ and ID₂. To better constrain the original magmatic compositions, elemental gains and losses were examined in order to screen the least altered samples. The alteration types and intensity present in these samples are illustrated in a Na/Al versus K/Al molar diagram (Fig. 7A), where gains and losses of Na and K relative to a more conservative element such as Al can be readily visualized. In this diagram, only a few of the ID₁, ID₂, and ID₃ samples plot close to inferred least altered compositions (full circles). The rest of the samples (open circles) either have mild gains of K and losses of Na due to sericitic alteration, gains of Na and losses of K due to sodic and/or sodic-calcic alteration, or both losses of K and Na caused by intermediate and/or advanced argillic alteration. Whereas the least altered samples of the pre-synmineralization ID₁ and ID₂ intrusions identified in the Na/Al versus K/Al molar diagram plot mostly in the basaltic-andesite (diorite) field of the total alkali versus silica (TAS) diagram of Le Maitre (1989; Fig. 7B), the least altered samples of the postmineralization ID₃ intrusions plot in the andesitic and dacitic fields (granodiorite). Similar compositions are inferred for ID₁, ID₂, and ID₃ intrusions using immobile element compositions (Winchester and Floyd, 1977; Fig. 7C), which are typically not highly susceptible to mobilization during hydrothermal alteration and weathering. The samples of the Jebel Ohier multiphase intrusion delineate a well-defined calc-alkaline trend centered on an evolving oceanic to continental arc setting (Pearce, 2014; Fig. 7D), with the more evolved postmineralization intrusions plotting solely into the continental arc field. The temporal evolution from ID₁ to ID₂ and ID₃ is also marked by a progressive depletion of mid and heavy rare earth elements (REEs) relative to light REEs, as illustrated by progressively higher La_(N)/Sm_(N) and Tb_(N)/Yb_(N) ratios (Fig. 7E). Similarly, there is a progressive increase in Sr/Y and V/Sc with fractionation, with highest ratios in the ID₃ samples (Fig. 7F). The dacite wall rock from Jebel Ohier East is more felsic than the ID₁ wall rock at the main Jebel Ohier deposit and plots close to the dacite-rhyolite boundary on the TAS diagram (Fig. 7B). This dacite has rare earth compositions similar to those of the ID₁₋₃ suite of samples, suggesting a possible genetic connection (Fig. 7E). The postmineralization granitic intrusion, QFP, and FQP have distinct rhyolitic compositions (Fig. 7B, C) and high La_(N)/Sm_(N) and low Tb_(N)/Yb_(N) ratios (Fig. 7E), suggesting a genetic origin different from that of the slightly older Jebel Ohier multiphase intrusion. Whereas the much younger DGC suite of rocks ranges from andesitic (DGC_hb) to dacitic (DGC_bt), the MD group of rocks (i.e., both DGC_MD and NWD) are basaltic-andesitic in composition (Fig. 7B, C). All of these younger intrusions have trace element compositions similar to those of the older Jebel Ohier rocks that they intruded (Fig. 7E), a phenomenon that might be explained by crustal assimilation. It is relevant to note that the DGC-bt samples, which are unrelated to porphyry copper mineralization at Jebel Ohier, show equally high Sr/Y and V/Sc ratios to the immediately postmineralization ID₃ intrusions (Fig. 7D).

Geochronology

Three samples taken from synmineralization ID₂ intrusions, as well as the sample from ore-hosting dacite at Jebel Ohier

East, bracket the age of mineralization at ca. 816 to 812 Ma. The fifth sample from DGC_bt gives a $^{206}\text{Pb}/^{238}\text{U}$ age of ca. 724 Ma (Table 2; App. 1).

Sample QFB1 is from a sericite-altered and intensely A/B-vein stockworked ID₂ dacite porphyry composed of abundant phenocrysts (plagioclase >> hornblende and biotite >> magnetite > ilmenite > apatite) in a fine-grained groundmass (feldspar > quartz >> hornblende and biotite). The zircons in this sample are large, up to 0.5 mm, equant, bipyramid prisms, which are mainly pink or colorless. CL images show oscillatory zoning in zircon grains with no inherited cores (Fig. 8A) and zircons with cores overgrown by low-U oscillatory rims. Sector zoning is visible in some zircons, which is typical of intrusive igneous zircons. Twenty-five zircons were analyzed from this sample, giving concordant dates clustered as a single population with a concordia age of 816.2 ± 3.4 Ma (Fig. 8A), if one clearly discordant analysis is excluded. This is considered to be the crystallization age, as rims overgrowing cores and cores all have the same age (App. 1).

Sample QFB2 was taken from an unaltered DGC_bt unit composed of abundant phenocrysts (plagioclase >> hornblende = biotite > quartz) in a fine-grained micrographic groundmass (quartz = K-feldspar >> hornblende, biotite, magnetite, ilmenite, apatite, anhydrite, titanite, apatite). The zircons in this sample are small (<15 μm) bipyramidal prisms, which are mostly pink or brown grains, mixed with a small number of lower-U zircon fragments, which are paler in the CL image (Fig. 8B). CL images show oscillatory zoning in the zircon grains with no obvious evidence of inherited cores. Most zircons appear to have very thin elevated-U rims and are overall higher in U and Th than the other samples documented herein. Thirty-one zircons were analyzed. A total of 21 analyses form a mostly concordant group that we consider a single population with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 723.7 ± 6.7 Ma. This age is interpreted to represent the crystallization age (Fig. 8B). The same age, within uncertainties, was obtained from all types of zircon. Four other analyses form a slightly older group with $^{206}\text{Pb}/^{238}\text{U}$ ages of 758 ± 15 , 759 ± 15 , 791 ± 16 , and 799 ± 17 Ma (inset in Fig. 8B). There is one reversely discordant grain with a $^{206}\text{Pb}/^{238}\text{U}$ age of 1458 ± 40 Ma (App. 1). This analysis could have overlapped a Pb-rich inclusion or an inherited Proterozoic grain, or may be a contaminant.

Sample QFB3 is from a massive crowded porphyritic ID₂ unit with anhydrite veins and composed of abundant phenocrysts (plagioclase >> hornblende >> titanite) in a fine-grained groundmass (feldspar >> others including trace zircon). The zircons are large, up to 0.5 mm, equant, bipyramid prisms, which are mainly pink or colorless. Many grains are fragments of larger zircons. CL images show oscillatory zoning or sector zoning in zircon grains with no obvious inherited cores and zircons with cores overgrown by low-U oscillatory rims (Fig. 8C). Twenty-one zircons were analyzed; these yield dates clustered as a single population with a concordia age of 812.6 ± 4.0 Ma (Fig. 8C). This figure is considered to represent the crystallization age, with rims overgrowing cores yielding identical ages (App. 1).

Sample QFB4 was taken from an ID₂ unit containing D-type veins that has cut an ID₁ containing A-type veins. Mineralogically, this sample is identical to QFB3. The pink to colorless zircon grains are moderate in size (100–250 μm),

show oscillatory zoning, and have no inherited cores. Twenty-seven zircons were analyzed from QFB4. The results were consistently discordant by a small amount, possibly due to undercorrection for common Pb. The analyses clustered as a single group, but a concordia age could not be obtained (Fig. 8D). The best estimate of the age, after exclusion of two reversely discordant analyses, is the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age, which is 813.1 ± 8.5 Ma (Fig. 8C). This age is considered to represent the approximate crystallization age, as rims overgrowing cores and cores all have the same age (App. 1).

Sample QFB5 was taken from an ID₂ unit with A-vein stockwork and disseminated chalcopyrite, with a clear contact against more intensely altered and stockworked ID₁. The presence of both magnetite and ilmenite in this sample suggests the magma was only weakly oxidized. Similar to samples QFB3 and QFB4, zircons in sample QFB5 are moderately large, up to 0.3 mm, equant, bipyramid prisms, which are mainly pink or colorless and are typical of intrusive igneous zircons. They show sector zoning with no obvious inherited cores and very thin high-U rims (Fig. 8E). Twenty-five zircons were analyzed and gave concordant dates clustered as a single population with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 814.1 ± 8.5 Ma (Fig. 8E). Rims and cores all have the same age (App. 1).

Discussion

Classification of Jebel Ohier as a porphyry-type deposit

In terms of their relative abundance, Precambrian-aged porphyry copper systems are exceptionally rare. This can be largely attributed to their comparatively poor preservation potential within shallow levels of active tectonic settings that are dominated by high uplift and erosion rates (e.g., Groves et al., 2005; Wilkinson and Kesler, 2007, 2009). Moreover, the majority of Proterozoic- and Archean-aged porphyry copper deposits have been subjected to significant overprint by deformation and high-grade metamorphism. Examples include Boddington (Yilgarn craton, Western Australia, Allibone et al., 1998), Troilus (Superior craton, Canada, Goodman et al., 2005), the Dienemera, Gongondy, and Mont Biri occurrences in the Gaoua district (Birimian, Burkina Faso, Le Mignot et al., 2017), and Aitik (Fennoscandian Shield, Sweden, Wanhainen et al., 2003). In each case, attribution of the mineralization to a porphyry copper-style deposit is not universally accepted (e.g., Laznicka, 2010) due to obscuring of porphyry mineralization characteristics by more recent geologic events. Consequently, the classification of several of these deposits remains contentious, especially where a subsequent mineralization event obscures features of the original deposit.

In the same way, the recognition of such a deposit for the first time in the Arabian-Nubian Shield contradicts the commonly held belief that this resource-rich region was too ancient to hold much potential for the existence, and preservation, of porphyry deposits. The exceptionally well preserved K-silicate to sericitic alteration zonation patterns with spatial dimensions consistent with more recent porphyry copper deposits elsewhere (e.g., Cooke et al., 2005; Garwin et al., 2005; Sil-litoe, 2010, and references therein), the presence of abundant diagnostic A- and D-type veins and magmatic-hydrothermal breccias, and crosscutting relationships with porphyritic dikes revealed in drill core (which was not available for previous

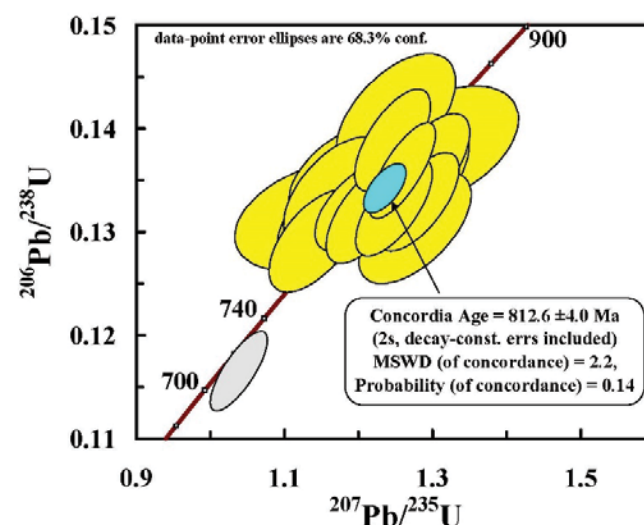
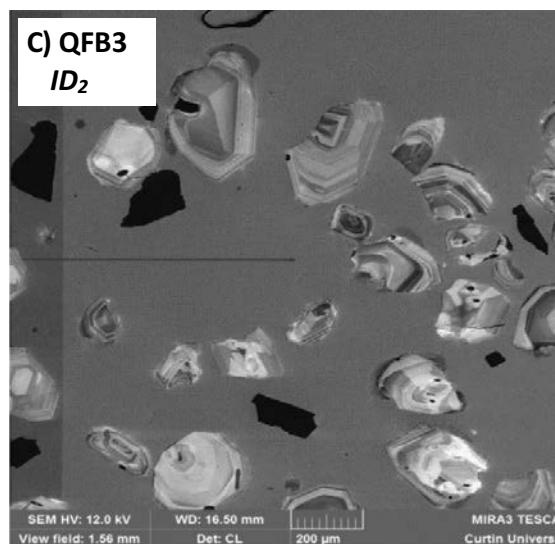
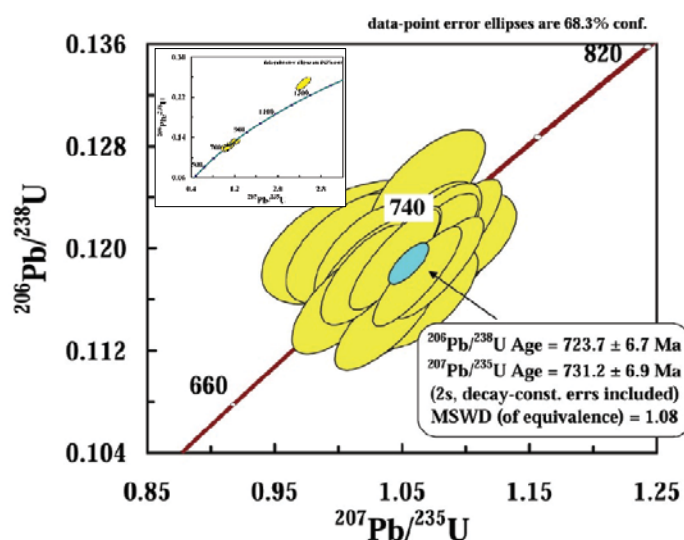
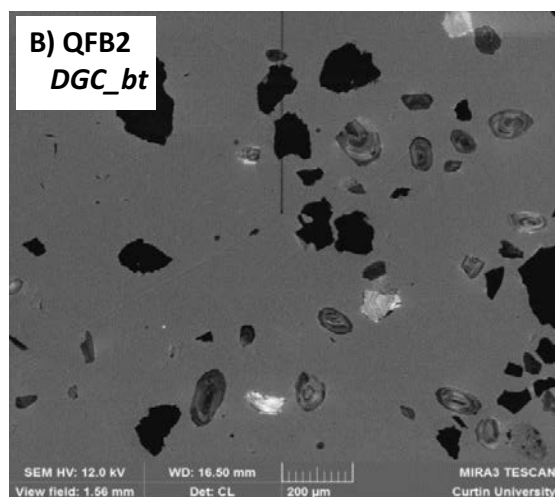
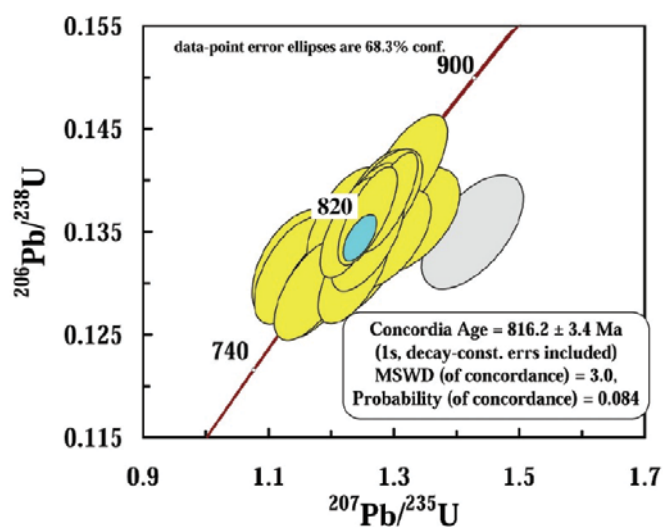
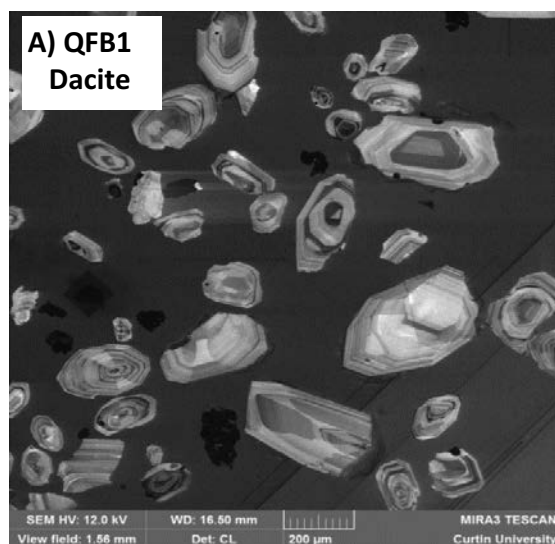


Fig. 8. (A-E) CL images of zircons in QFB1 to QFB5 (left side) and $^{207}\text{Pb}/^{235}\text{U}$ versus $^{206}\text{Pb}/^{238}\text{U}$ plots for SHRIMP U-Pb analyses (right side). MSWD = mean square of weighted deviates. Inset in (B) shows the $^{207}\text{Pb}/^{235}\text{U}$ versus $^{206}\text{Pb}/^{238}\text{U}$ age range for all 25 analyses of QFB2.

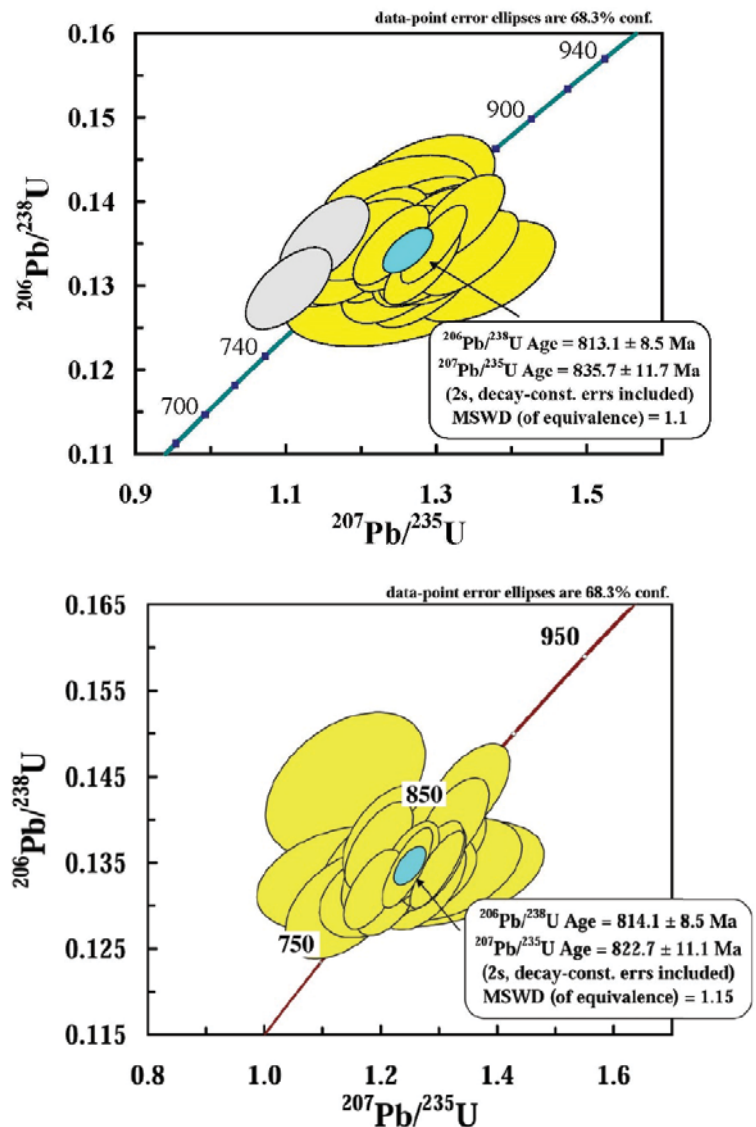
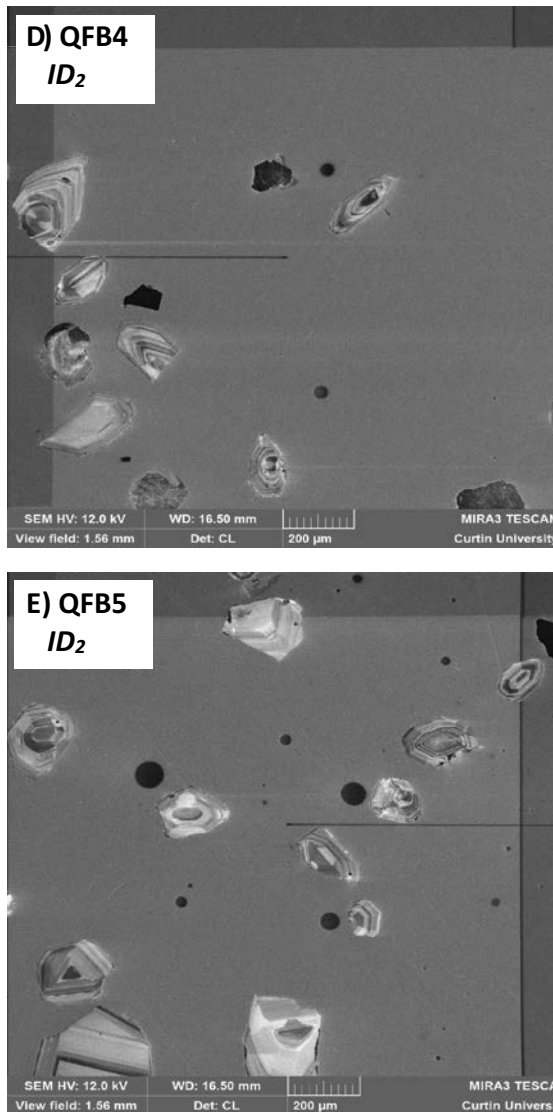


Fig. 8. (Cont.)

studies) documented herein all provide compelling evidence that Jebel Ohier is a Neoproterozoic porphyry copper deposit. This conclusion has significant implications for porphyry prospectivity throughout the Arabian-Nubian Shield.

Tectono-magmatic origin of the Jebel Ohier intrusions

Lithogeochemical data presented herein reinforce previously published constraints on the nature and petrogenesis of the rock units hosting Cu-Au mineralization at Jebel Ohier. The data demonstrate these units represent bimodal calc-alkaline arc material (Fig. 7D). Their compositions are compatible with the gradual evolution of a subduction-related juvenile volcanic island arc within the geodynamic framework generally proposed for the wider Gebeit-Gabgaba terrane portion of the Arabian-Nubian Shield (e.g., Johnson et al., 2011, and references therein). Furthermore, the data are in agreement with those of Bierlein et al. (2016b), who demonstrated (on the basis of petrographic, geochemical, and isotopic evidence) that the intrusive system responsible for Cu ($\pm$ Au) mineralization

at Jebel Ohier was derived from a distinct, calc-alkaline magma source characterized by high oxygen fugacity and relatively high water contents. This is important, as hydrous and oxidized subduction-related magmas are demonstrably responsible for the vast majority of productive porphyries globally (e.g., Richards, 2003; Cooke et al., 2005; Loucks, 2014). A high magmatic oxidation state and/or high water content due to hornblende fractionation (at the expense of plagioclase production; Richards et al., 2012) is reflected by relatively high Sr/Y and V/Sc ratios in ID₁, ID₂, and particularly ID₃ samples from the Jebel Ohier multiphase intrusion (Fig. 7D, E). REE patterns in these units are also akin to those of ore-related Tertiary porphyries in the Escondida area in northern Chile, in that they are characterized by variable but consistent enrichment in light REEs and overall depletion in the middle and heavy REEs (Richards et al., 2001; Bierlein et al., 2016b). Importantly, the ID₁, ID₂, and ID₃ units at Jebel Ohier lack negative Eu anomalies typical of upper crustal material and evident in samples from dioritic-dacitic units from elsewhere in the

Gebeit terrane (Bierlein et al., 2016b). The similarly depleted middle and heavy REE signature favors the interpretation of hornblende fractionation (i.e., hydrous magma), rather than garnet fractionation (i.e., thickened crust). This trace element signature and genetic interpretation have been reported for intrusions associated to much younger porphyry copper deposits elsewhere (e.g., John et al., 2010; Richards, 2011). A similar evolution is inferred by a progressive increase in Sr/Y and V/Sc with fractionation (Fig. 7F). A high Sr/Y ratio could be interpreted to be caused by petrogenesis from a hydrous magma that resulted in inhibition of plagioclase fractionation and enhanced crystallization of hornblende-titanite-zircon (e.g., Sisson, 1994; Klein et al., 1997; Richards, 2011). Similarly, fractionation of garnet in thickened crust has been proposed to explain the increased Sr/Y ratios (e.g., Hamilton, 1981; DeBari and Sleep, 1991; Chiaradia, 2009). High V/Sc ratios have previously been interpreted as resulting from an increase in the oxidation state of the magma due to either the inhibition of magnetite fractionation and/or the decrease of the magnetite-melt partitioning coefficient of vanadium as oxidation increases (Toplis and Corgne, 2002). Both of these ratios are the highest in the post-Cu-mineralization ID₃ intrusions that immediately follow the ID₂ ore-forming intrusions and plot well inside the field for ore-productive intrusions defined for younger porphyry copper deposits elsewhere (Fig. 7F; Loucks, 2014). In at least some of the more recent porphyry copper deposits of the Andes, intrusions emplaced after Cu mineralization, and also those intrusions that are only affected by sericitic alteration, show higher Sr/Y and V/Sc ratios than the ore-related intrusions (e.g., Haquira East; Cernuschi, 2015). Nonetheless, the pre- to synmineralization intrusions (ID₁ to ID₂) at Jebel Ohier form an apparent trend toward higher Sr/Y and V/Sc ratios as SiO₂ increases, approximating the field of ore-productive intrusions (Fig. 7F) in the same way as more recent pre- to synmineralization intrusions elsewhere (Cernuschi, 2015). All these observations suggest that the petrogenesis of ore-productive Neoproterozoic magmas capable of giving rise to porphyry copper deposits may in many ways be similar to the petrogenesis of their Phanerozoic equivalents. The geochemical similarities between the precursor premineralization ID₁, synmineralization ID₂, and postmineralization ID₃ porphyries support a model whereby each of these units represents a distinct stage in the evolution of a parental magma chamber that gave rise to the porphyritic intrusions that both host and intruded the Jebel Ohier porphyry deposit.

There is a strong genetic link between the formation of significant porphyry Cu mineralization and the occurrence of fertile (i.e., hydrous, metal-enriched) arc volcanism (e.g., Sillitoe, 1998; Kerrich et al., 2005; Richards et al., 2013; Correa et al., 2016). Some authors have argued that the metal endowment of the parental magma is less significant than the duration of magmatic activity and intrusion volume involved. For example, Chelle-Michou et al. (2017) hypothesized that any normal hydrous arc-related magma could give rise to hydrothermal fluids capable of forming large porphyry Cu deposits (>20 Mt Cu), provided the magmatic activity exceeded 1 m.y. and involved large volumes of magma (>1,000 km³). The onset of voluminous and/or intense magmatic activity capable of producing a porphyry Cu ± Au deposit is typically triggered by a relatively sudden and pronounced change in the tectonic regime due to

crustal thickening, transient changes in the angle of subduction, periodic extension, megathrust earthquakes and catastrophic mass wasting, or topographic and thermal anomalies on the downgoing slab (Tosdal and Richards, 2001; Cooke et al., 2005; Loucks, 2014; Richards, 2018). However, Park et al. (2019) showed that for giant porphyry Cu deposits (i.e., >1 Gt Cu), the Cu and Au grades are positively correlated, regardless of the tonnage of each deposit or the specifics of their tectonic setting. These authors argued that because of this correlation, duration and volume of magma activity cannot represent primary controls on the ore grade. Instead, Park et al. (2019) argues that a critical factor controlling the size and grade of a porphyry system is represented by a combination of chalcophile element fertility and efficient transfer of metals from the melt to the fluid. Park et al. (2019) showed that the higher the Cu and Au contents of the ore-associated magma at the time of volatile saturation, the higher the tenor of the ore for a given fluid/melt partition coefficient for Cu and Au. Therefore, a magma with high chalcophile element fertility can produce an economically significant porphyry deposit even if the volume is smaller and duration of the magmatic activity is shorter-lived. However, the eventual Au grade of the porphyry deposit is controlled primarily by variations of the interval between sulfide saturation and fluid saturation and by differences in the partitioning coefficient into immiscible melts between Au and Cu (e.g., Mungall and Brennan, 2014). Numeric modeling by Park et al. (2019) showed that if sulfide and fluid saturation in a sulfur-undersaturated melt occur at ~70 and 80% fractionation, respectively, the 10% fractionation interval is enough to deplete the melt in Au without removing significant amounts of Cu. The result is a Cu-only porphyry copper deposit (i.e., Au <0.05 ppm), such as is the case of Jebel Ohier.

Age of the Jebel Ohier deposit

The new U-Pb ages from synmineralization intrusions tightly constrain the timing of deposit formation at Jebel Ohier, including the dacite-hosted stockwork mineralization in the Alfrasco deposit (to the east of Malachite Mountain). Within current uncertainties (i.e., ±5–10 m.y. on the weighted mean age for each sample), QFB1, QFB3, QFB4, and QFB5 are all the same age. There is a small spread in the weighted mean age measured for the different samples, from 816 to 812 Ma, but this age range, which is 5 m.y., is within the current uncertainty limits for low-U samples of this age (Williams, 1998). In contrast, the sample of DGC_bt (QFB2) yields a well-constrained age that places the bulk of the postmineralization intrusive activity ca. 90 m.y. after the ca. 816 to 812 Ma magmatic-hydrothermal mineralization event. As such, the emplacement of the DGC belongs to a distinctly different tectonic event in the evolution of the long-lived arc system. Based on analytical results from a granodiorite intrusion now understood to belong to the DGC suite, the ²⁰⁷Pb/²⁰⁶Pb age of ca. 730 Ma (obtained by laser ablation ICP-MS) for this surface sample was originally considered by Bierlein et al. (2016a) to represent the approximate time of mineralization at Jebel Ohier. A ca. 806 ± 7 Ma age obtained from a pyrophyllite-altered tuffaceous dacite unit by the same method was interpreted by these authors to represent the approximate formation age of a volcanic edifice that had preceded the emplacement of the ore-hosting diorite porphyry into the nascent magmatic arc. From our new geochronology

results, supported by detailed mapping, drill core logging, and 3-D geologic interpretation, it is now apparent that this dacite unit is analogous to the ID₂ that sample QFB1 was taken from. As such, the mineralized dacite in the Eastern extension zone represents a third porphyry center that is closely related in space and time to the Malachite Mountain and Quartz Knob porphyries.

Figure 9 illustrates the interpreted evolution and post-emplacement history of the Jebel Ohier porphyry copper deposit in the context of the Neoproterozoic-Tertiary development of the Arabian-Nubian Shield. The diagram shown in this figure brings together field observations, relative and absolute timing constraints discussed herein, and information from previous regional-scale studies. Johnson et al. (2011) bracketed the opening, inversion, and closure of the Mozambique Ocean from 800 to 650 Ma within the broader context of the Arabian-Nubian Shield orogenic cycle, with the oldest arc assemblages yielding formation ages of ~850 Ma (Johnson, 2014). The new data from Jebel Ohier strongly suggest that the basaltic-andesitic-dacitic volcanic rocks and ID₁ to ID₂ (and, most likely, ID₃) porphyry intrusions formed more or less contemporaneously during the evolving stages in the development of an intra-Mozambique Ocean island arc. Strongly positive initial ϵ_{Nd} and Nd model ages of about 0.9 Ga (Bierlein et al., 2016b) further support an island-arc setting for the Jebel Ohier magmatic complex, with only minor components of crustal assimilation involved in the formation of the arc assemblage. Consistent with the broader geology of much of the Arabian-Nubian Shield, and the Gebeit terrane in particular, a virtual absence of inherited (pre-Neoproterozoic) zircons in the U-Pb samples analyzed herein also confirms the predominantly juvenile (depleted mantle-derived) character of these units (Johnson, 2014). It has to be emphasized, however, that the tectono-magmatic and geodynamic evolution of individual accretionary terranes within the Arabian-Nubian Shield remains poorly constrained, with large tracts of the geologic assemblage requiring much more detailed study.

On the matter of preserving a ca. 816 to 812 Ma porphyry deposit, Bierlein et al. (2016b) speculated that relatively rapid accretion of the Gebeit terrane to the stable continental margin of the Saharan Megacraton some 20 m.y. after the deposit formed (e.g., Abdelsalam and Stern, 1996) may have aided in the prevention of excessive uplift, erosion, and/or structural dismemberment. However, the general lack of inherited zircons in the samples from the DGC and the petrogenetic characteristics of this composite unit preclude the incorporation of substantial volumes of pre-Neoproterozoic crustal material. Furthermore, a review of available geochronologic and isotopic data by Johnson (2014) has placed the western margin of the Arabian-Nubian Shield in the area of the N-striking, sub-vertical arc-continental Kerf suture, with accretion between the Arabian-Nubian Shield and the Saharan metacraton (reflecting terminal collision of the Arabian-Nubian Shield and western Gondwana blocks) not occurring until ~650 to 580 Ma (Fig. 9). The timing of the ca. 724 Ma magmatic event at Jebel Ohier coincides with the final suturing of the Gebeit and the Haya terranes along the NE-trending arc-arc Nakasib shear zone (Abdelsalam and Stern, 1993). From that time, tectonic burial and the emplacement of voluminous DGC

and associated mafic dikes into, and especially to the south of, Jebel Ohier (Fig. 2) during an interval of increased volcanism, may have played a significant role in preserving the porphyry deposit (e.g., Khashgerel et al., 2009; Fig. 9). In this regard, these rigid postmineralization intrusive bodies, while diluting mineralization, may also have afforded protection from the effects of structural overprint and extensive erosion of the ancient porphyry deposit. Likewise, the large mass of DGC situated to the south of the area is likely to have acted as a buttress for Jebel Ohier during periods of far-field stress reorientation in conjunction with movement along major syn-collisional structures such as the Hamisana, Oko, and Nakasib shear zones after ca. 724 Ma (e.g., Abdelsalam, 2010). This notion is also supported by the overall geometry of the Jebel Ohier porphyry, as deduced from drill holes and the detailed analysis of principal vein orientations, which suggest that the mineralized porphyry has remained in more or less an upright position since its formation. It is likely that much of the missing part of the Jebel Ohier porphyry copper deposit (estimated to be ~1 km; cf. Bierlein et al., 2016b) was eroded following the cratonization and rapid unroofing of the magmatic arc hosting the Jebel Ohier porphyry copper deposit between ca. 580 and 540 Ma (Fig. 9; Johnson et al., 2011). This was followed by postamalgamation pervasive extension and the deposition of Paleozoic sandstone units above the deeply weathered Proterozoic basement throughout wide parts of the shield. Rifting in northern Sudan probably commenced as early as the Jurassic and culminated in the opening of the Red Sea rift at about 30 Ma (Sultan et al., 1993; Cochran and Karner, 2007). Rapid uplift gave rise to a renewed cycle of erosion and weathering at Jebel Ohier that continues to the present (Fig. 9).

Conclusions

Jebel Ohier is an exceptionally well preserved Neoproterozoic porphyry copper deposit situated in the Red Sea Hills of northeastern Sudan. The deposit is hosted by a laterally extensive (>5 × 3 km), fine- to medium-grained, calc-alkaline dioritic intrusion, which, in turn, has been intruded by a series of syn- to postmineralization diorite to granodiorite porphyry dikes. Several intermediate to felsic dike-like intrusions cross-cut the porphyry copper deposit prior to the emplacement of a voluminous DGC. Mapped hydrothermal alteration associated with the porphyry copper deposit at Jebel Ohier and a spatial zonation pattern that transitions from proximal K-silicate-dominated, to sericitic, and out to distal propylitic alteration are akin to that documented in many analogous settings elsewhere. Mineralization is associated with stockwork development, with three distinct centers of intense A-type veining recognized to date. Highest copper grades correlate well with A-vein abundance, with chalcopyrite (±bornite) mineralization present within A- and B-type quartz veins, as well as sulfide-only C-type veins, and as disseminated sulfides in proximal halos to these veins. Locally, magmatic-hydrothermal breccias are important from a Cu grade viewpoint. Although the deposit has been affected by both brittle and ductile deformation, overprinted by regional-scale greenschist facies metamorphism, and subjected to repeated periods of uplift and partial erosion, the postmineralization evolution of Jebel Ohier has done relatively little to obscure, let alone obliterate, the original deposit. The emplacement

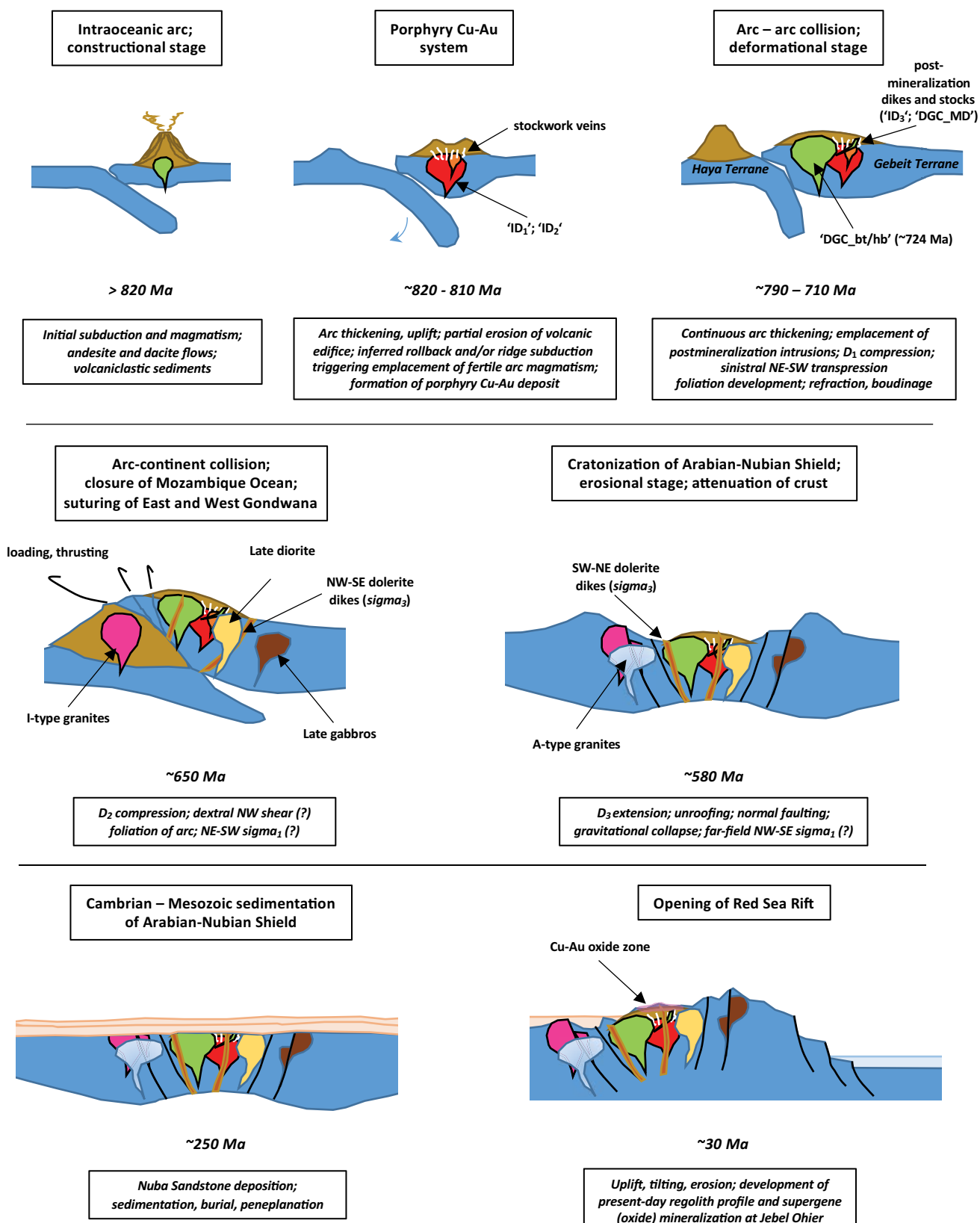


Fig. 9. Cartoon diagram showing the interpreted evolution of Jebel Ohier based on field observations and new geochronological constraints, placed in the broader context of the Gebeit terrane and the development of the Arabian-Nubian Shield (based on age data and geologic interpretations presented in Johnson et al., 2011, and Johnson, 2014).

of a series of postmineralization dikes and the DGC might have played a major role in preserving the relatively ancient porphyry deposit.

Four samples from intrusive units hosting mineralization at Jebel Ohier, including three samples from synmineralization intrusions, yielded a weighted mean age range of ca. 816 to 812 Ma. When viewed in the context of available geochronologic data sets for the Arabian-Nubian Shield (e.g., Johnson, 2014), the new age data for Jebel Ohier suggest that it formed from a productive magma during the early stages of an immature intra-Mozambique Ocean island arc. A fifth sample demonstrates that emplacement of the DGC did not occur until some 90 m.y. later, possibly during the final suturing of the Gebeit and the Haya terranes.

Jebel Ohier is a rare example of a Precambrian porphyry copper deposit and represents the first confirmed example of this globally important source of copper in the Arabian-Nubian Shield. Although its preservation was perhaps aided by several serendipitous circumstances, there is no reason to believe that Jebel Ohier remains the only porphyry deposit preserved in what is essentially an ancient equivalent of the southwest Pacific region, an assemblage dominated by intra-oceanic island arcs and known for hosting some of the world's largest porphyry deposits (e.g., Cooke et al., 2005; Garwin et al., 2005). As such, the discovery of Jebel Ohier has significant ramifications for porphyry Cu exploration both elsewhere in the Red Sea Hills and in other parts of the Arabian-Nubian Shield. Moreover, geochemical analysis demonstrates that the petrogenesis of fertile Neoproterozoic magmas capable of producing a potentially economic porphyry Cu deposit may be akin to the petrogenetic makeup of far more recent (i.e., Tertiary) ore-productive porphyries.

Acknowledgments

We are grateful to the Sudanese government and QMSD Mining Co. Ltd. management for their support and the permission to publish this work. Mohammed Salah Ahmed Elemam is thanked for his skillful assistance with drafting. A big thank-you must go to the Sudanese contingent of QMSD geologists and field hands for their passion, enthusiasm, and hard work (there are too many to mention—you know who you are!). Thorough reviews by Dr. B. Zoheir and Mr. N. Grumbley are gratefully acknowledged. The late Prof. J. Richards provided extensive editorial comments and constructive feedback. His diligent efforts significantly improved the quality of the manuscript. We are profoundly saddened by Prof. Richards's untimely passing, and that we lost the opportunity to thank him for his immense contributions to the understanding of porphyry Cu systems in general and for his staunch support and encouragement to publish our work in particular. Prof. D.R. Cooke's comprehensive review of a revised version of the submission and his editorial efforts are acknowledged with sincere thanks. We also thank Prof. L. Meinert for his editorial leadership.

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