**Chapter 6**

**Hydrothermal Mineral Deposits in Volcano–Sedimentary Environments**

**6.1 Introduction**

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| * ***3. Hydrothermal deposits****:* ore minerals precipitated from high-temperature aqueous fluids of different origins. *(a) Deposits in orogenic environments* Orogenic gold deposits Carlin-type gold deposits Iron oxide-copper-gold (IOCG) deposits *(b) Deposits in volcano–sedimentary environments* Volcanogenic massive sulfide (VMS/VHMS) deposits Sedimentary exhalative (SEDEX) deposits Mississippi-Valley Type (MVT) deposits Red-bed copper deposits |

Mineral deposits of volcano–sedimentary environments, island arcs, and midocean ridges are of great economic importance in extracting many metallic elements, such as Cu, Zn, Pb, Au, Ag, and other economically important metals. The components of these volcano–sedimentary associations are derived mainly from submarine volcanic sources called *volcanic exhalations*, which are precipitated in volcano–sedimentary or sedimentary basins, and are therefore referred to as *double-origin deposits*. This group of mineral deposits includes a number of ores, including *volcanogenic massive sulfide* (VMS) *deposits* (or *volcanic-hosted massive sulfide* (VHMS) *deposits*), *sedimentary exhalative* (SEDEX) *deposits*, *Mississippi Valley–type* (MVT) *deposits*, and *red-bed* *deposits*, which are all major sources of base-metal sulfides. Hydrothermal mineral deposits in volcano–sedimentary environments represent the dominant source worldwide of Pb, Zn, Cu, Co, and U and are significant sources of Ag and, to a lesser extent, Au. The major types of ore deposits are those of base-metal sulfide deposits. Mineral deposits in volcano–sedimentary basins are either syngenetic, which are formed at the same time of sedimentation of the host rocks, or epigenetic, which are formed after sedimentation of the host rocks. Most host basins were not sites of magmatic activity during mineralization. Neither magmatic hydrothermal fluids nor magmatic heat-driving fluid flow are thus considered to be factors in the formation of these mineral deposits in sedimentary basins. Instead, metal-carrying solutions migrate long distances through the sedimentary rocks of the basin and in some cases also through underlying basement (Ridley 2013). The hydrothermal fluids in volcano–sedimentary basins are at relatively low temperatures, ranging ~100–150 °C, but sometimes reaching up to ~250 °C. Efficient transport and precipitation of ore minerals from migrating low-temperature fluids are required for specific geochemical environments. Hydrothermal fluids of nonmagmatic origin in the volcano–sedimentary basins are called *basinal fluids* and include seawater and meteoric water origin that have infiltrated from above into the basin, as well as the connate and diagenetic waters that are derived from within the basin itself. The metal contents of seawater and meteoric waters are low; however, their metals are most probably have been dissolved into the basinal hydrothermal fluids either during fluid circulation or via diagenetic reactions. In either case, these fluids are derived by leaching of the sedimentary rocks in the basin or from underlying basement rocks. There are empirical relationships between the type of hydrothermal mineral deposits in the volcano–sedimentary basins and the type of sedimentary rocks that form the major aquifers in the sedimentary basins (Fig 6.1). The Zn-rich deposits occur in carbonate-dominated sequences, while the Pb-rich deposits are found in close association with sandstones, and the Cu-rich deposits commonly associated with sequences of either continental red-bed sandstones or oceanic basaltic lavas, or both (Fig 6.1, Ridley 2013). These relationships suggest that the metal content of the fluid is mainly controlled by metal availability in specific rocks of the volcano–sedimentary basin. For example, in Zn-rich deposits, Zn would be potentially released from limestone via replacement of calcite by dolomite. In the case of Pb-rich deposits, Pb can be in relatively high concentrations in feldspars of clastic sediments, and these are replaced in many basins by clay minerals during diagenesis, potentially releasing Pb. On the other hand, in Cu-rich deposits, Cu can be concentrated via adsorption onto hematite or iron hydroxide coating of quartz grains in red-bed sandstones and these coatings may be dissolved during syndiagenetic fluid flow. Copper can be also sourced from ocean-floor basalts to form VHMS (VMS) deposits, and may thus also be sourced from mafic rocks interbedded with sedimentary rocks in the volcano–sedimentary basin, most likely when primary mafic silicate minerals are replaced by lower-temperature hydrous minerals such as chlorite and epidote (Ridley 2013). The base-metal sulfide mineral deposits in volcano–sedimentary basins may be syngenetic, syndiagenetic, or epigenetic, where the ores have the following common characteristics (Ridley 2013): (1) Hosted in sedimentary and/or volcano–sedimentary basins. (2) “Syngenetic ores are generally stratiform and stratabound. Syn-diagenetic and epigenetic ores are generally stratabound.” (3) Mineral deposits of these types are formed at relatively low temperatures between approximately 60 and 250 °C. (4) In many cases, the ore fluids have salinity higher than seawater. (5) Many ores have an intimate relationship with either abundant sedimentary organic matter or with migrated hydrocarbons (oil or gas). The classification of these volcano–sedimentary base-metal deposits are based mainly on the metal content, host-rock type, and the timing of mineralization relative to sedimentation. The main classes of volcano–sedimentary mineral deposits can be categorized under the following types: (i) ***Volcanogenic massive sulfide (VMS) deposits*** (or *volcanic-hosted massive sulfide* (VHMS) *deposits*): These are mainly found as stratabound and sometimes-stratiform bodies of hydrothermal massive sulfide ores. The VMS deposits occur in a variety of tectonic settings but are typically related to precipitation of metals from hydrothermal solutions circulating in volcanically active submarine environments. They are polymetallic deposits, containing variable metal sulfides such as Cu, Zn, and Pb, in addition to Au and Ag; where the host rocks are submarine volcanic rocks and/or deep-sea sedimentary rocks intercalated with volcanic rocks. There are some geological and geochemical criteria for targeting VMS mineralization (Gibson et al 2007), which can be summarized as follows: (1) VMS deposits commonly occur in clusters that define the VMS districts. VMS districts occur within large volcanic edifices, calderas, and crustal structures. (2) Some of the largest deposits (>50 Mt ore) may be associated with a major long-lived crustal structure, or with thick successions of volcaniclastic rocks, or occur in more-stable rifted continental margin settings. The large deposits tend to be associated with widespread, low-temperature alteration systems, felsic volcaniclastics and thin, but laterally extensive Fe and Fe-Mn formations. (3) Deposits associated with mafic-dominated terranes tend to be Cu- and Cu-Zn-endowed. Continental margin or successor rifted arc-hosted deposits with felsic volcaniclastic–sedimentary host rocks have a higher Pb-Zn endowment. (4) Strongly metamorphosed deposits commonly found in Archean or Proterozoic terranes tend to have coarser-grained sulfides and consequently metal recovery is commonly better than for the finely crystalline sulfides in some less metamorphosed districts. Recrystallization can also mechanically purify deposits of metals such as Hg, As, and Sb. (ii) ***Sedimentary exhalative (SEDEX) deposits***: In contrast to the VMS deposits, SEDEX deposits are dominated by Zn-Pb (with lesser Cu, but commonly Ba- and Ag-rich) hosted in sedimentary rocks of early Proterozoic to Mesozoic age. Barite can also be accumulated near SEDEX deposits. SEDEX deposits are also related to hydrothermal fluids venting onto the sea floor, but without an obvious or direct link to volcanism. (iii) ***Mississippi Valley–Type (MVT) deposits***: These occur as epigenetic Pb-Zn sulfide deposits in solidified carbonate rocks, at up to ~10 wt%, with equal grades of Pb and Zn metals. MVT deposits can contain other metals as byproducts, including one or more of Ag, Ge, Cd, Cu, barite, or fluorite. (iv) ***Red-bed copper deposits***: These occur as large, laterally extensive, stratabound Cu deposits, with Co and minor amounts of Ni, Ag, Zn, Pb, and U as important byproducts. This deposit type provides ~30 wt% of the world’s Cu supply. The host rock of this deposit type is largely red-bed sandstones overlying black shales of shallow marine or lacustrine origin. It is thus distinct from those of MVT and SEDEX deposits. In the Arabian–Nubian shield (ANS), the mineral deposits of volcano–sedimentary environments are essentially found in many places of various tectonic settings including volcano–sedimentary associations, island arcs, and mid-ocean ridges. Most of these mineral deposit types are represented by VMS deposits, and to a lesser extent, sometimes by MVT deposits and stratabound/stratiform red-bed base-metal hosting deposits. Following is a detailed description of most famous localities of these types of mineral deposits and/or occurrences in the ANS, with the same approach used in the previous chapters starting with the Arabian Shield (Saudi Arabia and Yemen) and then the Nubian Shield (Egypt, Sudan, Eritrea, and Ethiopia). **6.2 Volcano–Sedimentary Mineral Deposits in Saudi Arabia**  There are numerous mineral deposits related to the volcano–sedimentary environments in the ANS, in general, and in the Arabian Shield of Saudi Arabia, in particular (Fig 6.2), including those of island arc and the mid-ocean ridge associations. These mineralizations are mainly represented by VMS and SEDEX mineral deposits/occurrences, which are found in several tectonic terranes of the Arabian Shield including: (1) the Midyan terrane in the northwest, (2) Jiddah terrane in the central-western shield, (3) the Asir terrane in the southwest, (4) the Afif–Ar Rayn terranes in the northeastern Arabian Shield, and (5) the Al Amar terrane in the eastern Arabian Shield (Fig 6.2). Following are detailed descriptions of the well-known deposits and/or occurrences of these deposit types. ***6.2.1 Volcanogenic–massive sulfide deposits***  Globally, VMS deposits are major sources of Cu, Zn, Pb, and Ag (± Au); they formed throughout the Earth’s history (see, e.g., Lydon 1988 2007; Hannington et al 2011). The VMS deposits form in a variety of tectonic settings, including back-arc, intra-arc basins, and mid-ocean ridges (Tornos et al 2015). The volcanic-arc assemblages of the Arabian Shield are highly favorable for polymetallic VMS deposits, which are concentrated mainly in the western juvenile arc-terranes in the shield that originated at convergent margins in intra-oceanic settings. The host rocks of these VMS deposits are mostly Cryogenian, ranging from ~850 Ma in the Bidah and Shwas districts to ~700 Ma in the Al Amar district (Johnson and Kattan 2012). Many of these mineral deposits are classic examples of VMS mineralization but some others are highly sheared and are of unknown or uncertain deposit type. The VMS deposits are hosted by bimodal mafic-to-felsic volcanic rocks, particularly where the volcanic sequences contain packages of exhalative carbonates and chert, and range in size from small-sized deposits (a few million tons) to large-sized deposits (>150 million tons) of mineralized rock. The most famous occurrences of classic large-sized VMS deposits include *Al Masane* and *Gebel Sayid*. Examples of smaller, but underexplored, VMS deposits are at *Umm ad Damar*, *Ash Shizm*, *Farah Garan*, and *Gebel Baydan*. Weathering zones of some VMS deposits, enriched in supergene gold, have been worked at Al Hajar and are being worked at Jadmah.  ***Volcanogenic massive sulfide deposits in the Midyan terrane:*** Cu-Zn mineralization is found in the *Ash Shizm* district, which is located to the northwest of the city of Al-Ula (Fig 6.2). The site is located within a volcanic assemblage, including diabase and metabasalt dykes, surrounded on three sides by a plutonic complex of gabbro, diorite, trondhjemite, and granite cut by porphyritic rhyolite dykes. The volcanic assemblage comprises four lithostratigraphic units (Sangster and Abdulhay 2005); the first three volcanic units are interpreted to be members of the Farri group, where a major unconformity separates these rocks from the uppermost unit, which is correlated with the dominantly sedimentary Al’Ays group. The main sulfide deposits and associated alterations consist of a funnel-shaped discordant chloritic alteration aureole extending upward from within Unit I to the top of Unit II. The aureole is ~150 m in width and ~300 m in height and terminates with a red jasper layer at the top of Unit II. A wide mineralization zone (~300 m) of disseminated pyrite surrounds the chloritic aureole at the lower rhyolitic lava facies of Unit II. The host rocks are completely transformed by intense alteration to massive chloritite containing veinlets, amygdules, and irregular spots of silica, epidote, and calcite. The red jasper layer forms a cap to the chloritic funnel-shaped alteration, and irregular patches of sericite occur within and toward the top of the chlorite zone. Sulfide mineralization occurs within the chloritite aureole as a stockwork that begins deep in Unit I as chlorite–sulfide veins. In Unit II, the stockwork increases in breadth to ~100 m and consists of sulfide-bearing veinlets accompanied by chlorite and epidote. The top of the stockwork penetrates a silicified and chloritized breccia containing disseminated sulfides. This is then capped by a band of magnetite-bearing red jasper up to 5 m thick, and at its base, the jasper is brecciated and cemented with pyrite, chalcopyrite, and galena. The entire mineralized complex strikes north/northeast parallel to a bounding fault on the west. The core and base of the stockwork contain mainly chalcopyrite grading upward and outward to increasing amounts of sphalerite, pyrite, and galena. A small body consisting of blocks and fragments of massive sulfide occurs on the footwall of the jasper layer. A second zone of alteration ~ 200 × 100 m in width is elongated in a north/south direction and located ~1.8 km NE of the main mineralization zone; it lies within the hornfels zone of a nearby granite body. Drill holes into this alteration zone yielded values up to 0.2 wt% Cu and 0.6 wt% Zn (Sangster and Abdulhay 2005). The principal ore minerals in Gebel Ash Shizm deposit comprise, in decreasing order of weight percent, chalcopyrite, sphalerite, magnetite, bornite, and minor/trace amounts of cobaltite, various tellurides and selenides, titanium-bearing minerals, enargite, and argentite. Supergene weathering mineral products such as malachite, native silver, and greenockite are also present. Gangue minerals are represented mainly by chlorite, epidote, quartz, calcite, muscovite, and sericite. The common presence of ancient workings, in addition to the piles of waste and slag in the area, indicate that this site was previously exploited. Studies confirmed that the exploitation process took place during the Abbasid state. The mineralization of Gebel Ash Shizm appears to possess many of the characteristics of a stringer zone or vent complex of the VMS deposit. The position of the deposit at the transition from a mafic to a felsic volcanic sequence and the association with synvolcanic faulting permit consideration of Gebel Ash Shizm as a VMS deposit (Sangster and Abdulhay 2005). Furthermore, the intense chloritic alteration surrounding an inner Cu-dominated stockwork zone and their abrupt termination at a lithostratigraphic contact marked by a layer of ferruginous chert (jasper) are all features found in the footwall feeder zone of a typical VMS deposit. The expected overlying massive sulfide body, however, is apparently missing from this deposit. There are three possibilities to explain the absence of a massive sulfide body here (Donzeau 1980): (1) breakup and destruction due to the unstable tectonic environment, (2) modern erosion, and (3) unsuitable depositional conditions at the seafloor. The presence of the small layer of massive sulfide fragments lying immediately under the red jasper layer suggests the first hypothesis may be the most tenable. The synsedimentary brecciation and downslope transport of massive sulfides have been documented in a number of deposits in the Japanese Kuroko ores, the Canadian Shield, and the Canadian Appalachians. The estimated ore reserves of Ash Shism mineralization are ~600,000 tons of ore, with an average grade of 2.84 wt% Cu, 1 wt% Zn, 0.14 wt% Pb, and 25 g/t Ag (Donzeau 1980).  ***Volcanogenic massive sulfide deposits in Jiddah terrane:***The VMS deposits in the west-central part (*Jiddah terrane*) of the Arabian Shield include *Gebel Sayid*, *Umm ad Damar*, *Gebel Shayban*, and *Gebel Baydan*. They are hosted by volcanic-arc rocks of the Arj, Mahd, and Samran groups (described in Chap. 2 of this book), and situated in the northern and northwestern parts of the Jiddah terrane (Fig 6.2), south of the Bi’r Umq suture. A similar zone of polymetallic Au-bearing VMS mineralization is present in the Ariab and Hassai districts, Sudan, representing a continuation of the Gebel Sayid–Gebel Samran–Gebel Shayban zone of mineralization along the Nakasib suture (Fig 6.2). The Gebel Sayid deposit is a typical VMS deposit, while Umm ad Damar is a mixed epigenetic–VMS deposit (Sangster and Abdulhay 2005). The two deposits are north and south, respectively, of a set of north/west-trending Najd-related sinistral strike-slip faults (Fig 6.3), and may be displaced parts of a single base-metal VMS-type province (Johnson and Kattan 2012). The host rocks of Gebel Sayid and Umm ad Damar deposits belong to the Arj group. They consist of several thousand meters of basaltic to andesitic lava, breccia, and tuff, laminated felsic tuff, pyroclastic rocks and volcaniclastic quartz keratophyre, chert, limestone, sandstone, and conglomerate. The Arj group is not directly dated but is older than tonalite, dated at 781 ± 8 Ma (Hargrove 2006), and older than the Mahd group, dated at ~770 Ma. *Gebel Sayid* lies within a semicircular belt of volcanic rocks ascribed to the Hulayfah group, Halaban group, and Arj group (Bournat 1981; Johnson and Kattan 2012) that folded around a granite–diorite complex (Fig 6.3). The Gebel Sayid mineralization is located at the top of a sequence of rhyolitic lavas and pyroclastic rocks, overlain by andesitic pyroclastic rocks and intercalations of flow rocks. The rhyolitic unit is intruded by diorite, granite, and granodiorite. The Gebel Sayid prospect consists of four sulfide bodies (referred to as orebodies 1–4, lodes 1–4, or deposits 1–4), three of which are overlain by an extensive chert unit, while the footwall rocks of the deposit comprise felsic tuff and breccia intensely altered to chloritite (Fig 6.4). The orebodies spread over an area of ~1000 m extending southwest/northeast and 400 m southeast/northwest (Fig 6.4). The hanging wall of deposits 1, 2, and 4 is a welded tuff or ignimbrite moderately altered to sericite and talc (Bournat 1981). Lenses of marble or dolomitic limestone are intercalated with the ignimbrite, and deposit 3 occurs stratigraphically higher, above the ignimbrite. The four sulfide bodies at Gebel Sayid occur at two different stratigraphic positions (Fig 6.4). Deposits 1, 2, and 4 comprise the main massive mineralization horizon; within these bodies a massive sulfide style of mineralization was distinguished, associated with chert, and composed chiefly of pyrite and sphalerite, as well as stringer ore in veins and veinlets of pyrite and chalcopyrite. Deposit 3 comprises two massive sulfide bodies ~10 meters thick composed of pyrite, pyrrhotite, chalcopyrite, and sphalerite. Lesser amounts of tellurides, native Au and Ag, electrum, and Sn-bearing minerals have also been recognized at the Gebel Sayid mineralization (Bournat 1981). The Gebel Sayid mineralization is blind and has no surface expression; the other deposits crop out and are marked by gossans cover. Massive sulfides make up the upper part of orebody 1 and 20% of orebody 4; Cu stockwork makes up all of orebody 2 and 90% of orebody 4. Orebody 3 comprises two massive sulfide bodies ~10 m thick containing pyrite, pyrrhotite, chalcopyrite, and sphalerite. Orebody 4 is the largest at Gebel Sayid, with a total resource estimate (measured + indicated) of 20.8 Mt, with an average grade of 0.8 wt% Cu, 0.2 wt% Zn, 0.3 g/t Au, and 9 g/t Ag (Equinox Minerals Limited website, April 2011). The estimated ore reserves of deposit 1 (Bournat 1981) found to contain 8 Mt ore, with average grades of 2.2 wt% Cu, 1.4 wt% Zn, 40 g/t Ag, and 0.5 g/t Au. Deposit 2 was estimated at 1.5– 2 Mt ore, with an average grade of 1.5–2 wt% Cu. The Riofinex study at 1977, reported combined reserves of deposits 1, 2, and 4 at 34.3 Mt ore, with average grades of 0.55 wt% Cu, and 6.8 Mt grading 1.12 wt% Zn. Pitre et al (1984) calculated ore resources of deposit No. 4 to be 16.9 Mt of 2.60 wt% Cu, and those of deposit 2 at 3.02 Mt of 3.13 wt% Cu. Indicated ore resources of deposit No. 1 were 3.7 Mt ore grading at ~2.12 wt% Cu and 1.35 wt% Zn. The Gebel Sayid deposit possesses many of the distinctive features of a proximal VMS deposit (Sangster and Abdulhay 2005). The extensive footwall Cu-rich stringer zone, surrounded by chloritic alteration, and overlain by a Zn-rich sulfide lens and a Si-rich chemical sediment all confirm the volcanogenic exhalative nature of this deposit. Recognition of these features at Gebel Sayid has resulted in a better understanding of the deposit model and constituted an important step in the exploration for other VMS deposits in the same group of rocks. The validity of this viewpoint has been confirmed with the discovery of VMS deposits in the Umm ad Damar area ~20 km southeast of Gebel Sayid. The *Umm ad Damar* mineralization covers an area of ~6 km southeast/northwest and 3 km southwest/northeast, 20 km southeast of Gebel Sayid (Fig 6.3). It is not as well-exposed as Gebel Sayid, but is notable for the large size of its ancient workings, slag piles, and mining village ruins and midden. The Umm ad Damar area is underlain mainly by volcanic rocks of the Arj group that the Metal Mining Agency of Japan (MMAJ 1999) team divided into four lithologic units, including (Sangster and Abdulhay 2005): (1) rhyodacite and rhyodacitic volcaniclastic unit, (2) dacite to dacitic volcaniclastic unit, (3) andesite flows and andesitic volcaniclastic unit, and (4) intercalations of jasper within all of the volcanic and volcaniclastic rocks. Andesite and andesitic volcaniclastic rocks of the Mahd group overlie the Arj group in the northwestern part of the Umm ad Damar area. Rocks of the Arj group have been regionally chloritized and epidotized with extensive shearing developed in the volcaniclastic rocks. Faults are dominantly northeast/southwest except for a northwest/southeast fault bounding the eastern edge of the prospect area (Fig 6.3). The area also includes intrusive rocks of tonalite, diorite, quartz diorite, andesite, dacite, rhyodacite, and basalt. Four mineralized zones have been identified in the area, including Gebel Sujarah, the 4/6 gossan, the Umm ad Damar north prospect, and the Umm ad Damar south prospect (Sangster and Abdulhay 2005). According to the MMAJ (2001) team, VMS-style mineralization occurs in the Gebel Sujarah and the 4/6 gossan deposits. Massive sulfides are also found at the Umm ad Damar North Prospect deposit although most of the mineralization here is Cu-dominated vein style. Mineralization at Umm ad Damar south prospect is Cu-Zn vein style. At Gebel Sujarah, the mineralized zone is ~6 m thick and extends ~200 m along strike and at least 250 m down dip. It comprises several layers of massive and pebbly sulfides accompanied by a disseminated zone. The latter, which is mostly pyrite, extends >100 m into the dacite footwall. Thick jasper layers are developed in the hanging-wall dacitic volcaniclastic rocks. In the Umm ad Damar north prospect, eleven drill holes intersected mineralization thicknesses of 2.6–3.1 m and average grades of 1.87–2.17 wt% Cu. Mineralization occurred as a network of chalcopyrite–pyrite veins in fractured dacitic volcaniclastic rocks, intrusive dacite, and rhyodacitic volcaniclastic rocks near the western edge of a large diorite body. In the Umm ad Damar south prospect, eleven holes were also drilled and confirmed that mineralization extended ~300 m along strike (northeast/southwest) and ~300 m down dip. Mineralization occurs as chalcopyrite–pyrite–quartz veins and chalcopyrite–pyrite–sphalerite disseminations in rhyodacitic volcaniclastic rocks at the southwestern periphery of a tonalite–diorite intrusion. At the 4/6 gossan, mineralization is massive sulfide in rhyodacitic volcaniclastic rocks and consists of massive, siliceous, and pebbly ores containing chalcopyrite, sphalerite, and pyrite. Massive sulfide ranges up to 35 wt% Zn and averages 2.11 wt% Cu. Zinc grades in pebbly and siliceous mineralization range up to 9.8 wt% and Cu averages 1.24 wt% (Sangster and Abdulhay 2005). Three zones of mineralization are associated with a layer of basaltic tuff. Immediately below the tuff, a 3.7 m mineralized zone averages 2.17 wt% Zn, 0.96 wt% Cu, and 0.4 g/t Au. A second, lower, zone is 9.3 m thick, averaging 3.67 wt% Zn, 1.00 wt% Cu, and 0.4 g/t Au. Each of these two zones extends ~100 m along strike and >60 m and 120 m, respectively, down dip. Above the basaltic tuff, a 2.5 m thick mineralized zone extends ~100 m along strike and averages 3.99 wt% Zn, 0.69 wt% Cu, and 0.1 g/t Au. Precious metal contents are low in most cases (e.g., 0.4 g/t Au) but, exceptionally, reach >16 g/t Au and >440 g/t Ag. Although there is a debate about the mineralization style at the Umm ad Damar area, whether a vein-style mineralization (intrusion-related epigenetic veins) as at the north and south prospects or, alternatively, stockworks to an undiscovered VMS deposit (MMAJ team 2001), there appears little doubt the massive sulfide lenses at the Gebel Sujarah and 4/6 Gossan areas are, indeed, synvolcanic massive sulfides. The coexistence of jasper (chert) and Zn-Cu sulfides strongly correlate with the Gebel Ash Shizm and Gebel Sayid VMS deposits. The mineralization areas at *Gebel Shayban*, *Gebel Baydan*, and *Gebel Samran* are located between 150 and 200 km southwest of Gebel Sayid along the strike of the Bi’r Umq suture (Figs. 6.2, 6.5). The country rock consists of volcanic and volcaniclastic rocks assigned to the Samran group intruded by large arc-related plutons of diorite, quartz diorite, syntectonic tonalite gneiss, and post-tectonic granite (Kamil suite) (Fig 6.5). The Tharwah ophiolite is in the hanging wall of the suture zone. *Gebel Shayban* and *Gebel Baydan* are Cu-Zn ± Au deposits hosted by the Shayban formation (775 Ma), the middle of three formations assigned to the Samran group and correlative with the Mahd group. The Shayban formation consisting of andesitic to felsic volcaniclastic rocks, felsic lava, pyroclastic rocks, lithic arenite and conglomerate, and phyllitic to schistose metatuff, is inferred to comprise the remains of a number of closely spaced, possibly coalescent, volcanos in an oceanic arc or rift system (Roobol 1989; Hargrove 2006). The rocks are strongly folded, faulted, and metamorphosed to the greenschist facies. The Gebel Baydan has characteristics indicating that it is a VMS deposit. The primary mineralization at Gebel Shayban consists of massive and disseminated sphalerite, lesser chalcopyrite, and finely disseminated Au. The prospect was originally examined as a Zn prospect; its Au content came into focus as a result of work by Bureau de Recherché Geologique et Miniere (BRGM) in the 1990s. It has a resource of 8.7 Mt ore grading at 1.4 g/t Au, 16.4 g/t Ag, and 0.4 wt% Cu (Equinox Minerals Limited website, http://www.equinoxminerals.com/, accessed April 2021). Drill intercepts reach depths of >200 m, but mineralization is open down dip to the west. *Gebel Baydan* is also somewhat sheared but is clearly recognizable as an in-situ VMS deposit (Bellivier et al**,**  1999). It is preserved on the flank of a regional anticline and consists different parts of mineralization include: (1) lenses of massive sulfide, mainly sphalerite, with subordinate pyrite, tetrahedrite, chalcopyrite, galena, and possibly stannite, (2) stockworks, (3) disseminated sulfides, and (4) stratiform bodies and veins of barite–silica–carbonate containing disseminated pyrite, chalcopyrite, sphalerite, tetrahedrite, and galena. The host rocks dip moderately west and from bottom to top are a sequence of (1) andesitic lava and lapilli tuff; (2) rhyolitic lava and felsic–porphyry quartz-eye tuff; and (3) epiclastic rocks. Mineralization is in the felsic volcanic rocks. The hanging wall of the deposit is intruded by a thick granodiorite–quartz diorite sill. Gebel Baydan mineralization has a drill-indicated resource of 0.5–0.7 Mt of ore at ~16–17 wt% Zn and 1.5–2.5 g/t Au, plus Cu and Ag (Bellivier et al 1999). The *Gebel Samran* is a small Cu-rich occurrence of enigmatic deposit type composed of quartz veins and secondary Cu-mineral fracture fillings in a quartz vein/stringer zone in volcaniclastic rocks strongly sheared by southeast-vergent thrusts. The deposit was drilled in the 1960s and has an estimated resource of 0.9 Mt ore at ~2 wt% Cu with traces of Au. The characteristics of the Gebel Baydan and Gebel Shayban sulfide deposits with a massive, layered sulfide lens underlain by a stringer sulfide zone enveloped in a cone of Mg-metasomatized wallrock (Bellivier et al 1999) leave little doubt that the deposits are small, vent-proximal VMS deposits. This classification is further supported by the Zn-rich nature of the massive lens (Zn/(Zn + Cu) = 0.93) and its position near the transition from intermediate-to-felsic volcanics, features that are typical of VMS deposits in Precambrian island arc volcanic sequences. ***Volcanogenic massive sulfide deposits in the Asir terrane:*** In the south-central Arabian Shield of Saudi Arabia, there are two mineral districts in the northern part of the *Asir terrane*, hosted by north-trending structural belts of greenschist-facies Lower Cryogenian convergent-margin volcanic-arc rocks. They are the *Bidah* and *Shwas**districts* (Fig 6.2). The rocks in each structural district are folded about north-trending isoclinal axes and cut by numerous north-trending shears. Most mineral occurrences in the Bidah district are along or west of the Bidah fault (shear) zone, a prominent system of sinistral brittle–ductile shears along the axis of the Bidah structural belt (Johnson and Kattan 2012). The most prominent shear in the Shwas district is the Umm Farwah shear, a serpentinite-decorated subvertical brittle–ductile strike-slip shear along the western side of the district. The shear zone has both dextral and sinistral sense-of-shear indicators and is the approximate contact between the Shwas belt and the long-lived extensional Ablah basin. The Aqiq shear zone, another serpentinite-decorated structure associated with the Aqiq Ghamid occurrences, is a sinistral strike-slip shear between the Bidah and Shwas shears on the west side of the Ablah basin. The *Wadi Bidah* *mineral district* (WBMD) lies in the southwestern part of the Arabian Shield of Saudi Arabia, ~260 km southeast of Jeddah, and consists of a north-trending belt 70-km long and 20-km wide, between latitudes 20° and 21° north and longitudes 41° and 41° 30ʹ east (Fig 6.6). The WBMD has been repeatedly explored, but despite the common abundant indications of mineralization, no significant deposit has yet been discovered. There are many mineralization occurrences, expressed mainly as small gossans, and extend discontinuously over the course of 120 km along strike, where there are two types of mineralization: (1) stratabound VMS-type sulfide bodies containing Cu-Zn ± Au ± Ag and (2) Au-bearing quartz veins and stringers (Volesky et al 2003; Johnson and Kattan 2012; Volesky et al 2017). Sulfide bodies along the east side of the Bidah shear zone and the east side of Wadi Bidah make up the *Rabathan* mineralized area; other mineralized areas (*Shaib at Tare*, *Gehab*, and *Mulgatah*) are west of the main shear zone (Fig 6.6). The sulfide bodies in these occurrences are folded and sheared, which indicate that the deformation event was after the mineralization process. Two of these occurrences, Shaib at Tare in the north and Rabathan in the south (Fig 6.6), have been selected to be described here as representative examples of WBMD. The *Rabathan* occurrence lies on the strike of the main Bidah shear zone; it is hosted by sheared calcareous quartz schist (Bidah group) and cherty-ferruginous beds at the contact with Khumrah greenstone. The Rabathan deposit is found chiefly within the carbonate-rich (now metamorphosed to calc-silicate) portions of the stratigraphy. Sulfide mineralization are found as massive-to-submassive bodies and chiefly composed of pyrite and chalcopyrite with variable minor amounts of sphalerite, pyrrhotite, rutile, and magnetite. The ore minerals occur as (Koch-Mathian et al 1994): (1) banded sulfide layers intercalated with beds of quartz–chlorite–dolomite schist, (2) clastic sulfides comprising pyrite aggregates and fragments cemented by chalcopyrite, and (3) microbrecciated sulfides composed of fractured pyrite healed by chalcopyrite, quartz, and chlorite. Estimates of ore resources made at Rabathan, on two sulfide bodies, were, separately, ~1.5 Mt ore with average grades of 2.3 wt% Cu, 0.03 wt% Zn, 2.85 g/t Ag, and 0.16 g/t Au, and 0.6 Mt ore with average grades of 2.2 wt% Cu, 1.51 wt% Zn, 5 g/t Ag, and 4 g/t Au. The *Shaib at Tare*, *Gehab*, and *Mulgatah* occurrences consist of stratiform lenses of massive and disseminated pyrite, sphalerite, and minor chalcopyrite, with minor barite, in chlorite–sericite–quartz schist and chlorite schist with beds of hematitic and pyritic chert and marble, west of the main Bidah shear zone (Roubichou et al 1989; Volesky 2002). The Shaib at Tare sulfide bodies crop out as gossans, extending over a north/south strike length of ~600 m, where the Riofinex Geological Mission (1979a) estimated ore resources of ~2.4 Mt with an average grade of 0.37 wt% Cu and 0.5 wt% Zn. The Gehab mineralization was exposed as gossans over a strike length of 700 m; it has an estimated ore resource of ~1.4–1.9 Mt at 0.64–1.26 wt% Cu, 1.45 wt% Zn, 5.3 g/t Ag, and 0.09 g/t Au. The Mulgatah occurrence has a very small resource of ~140,000 tons to a depth of 100 m, with average grade of 0.28 wt% Cu, 0.87 wt% Zn, 1.5 g/t Ag, and 0.75 g/t Au (Riofinex Geological Mission 1979; Roubichou et al 1989). The *Shwas district* is located in the Shwas structural belt, a narrow structural domain between the An Nimas batholith on the east and the Shwas pluton and the Ediacaran Ablah group on the west. The layered rocks are similar in age to those in the Bidah belt, but the relationship between the two belts is not clear. They may be parts of a common Lower Cryogenian volcanic-arc assemblage, now separated by the younger Ablah group, or separate arcs that were juxtaposed during assembly of the composite Asir terrane. The Shwas belt contains greenschist-facies flows and pyroclastic rocks of andesitic, dacitic, and basaltic compositions; green and red, feldspathic to lithic wacke, tuff, pebble-to-boulder conglomerate; and thin grey marble. As in the WBMD, these rocks are the host for VMS-type precious- and base-metal sulfide deposits. Exploration in the district initially concentrated on base-metal targets but BRGM, in the 1980s, located significant Au and Ag values in gossans and supergene oxide zones. The largest Au deposit at *Al Hajar* Au mine consists of two bodies of supergene ore in a weathered zone that extends to a depth of 70 m overlying primary sulfide ore. A prefeasibility study completed by BRGM in late 1989 outlined mineable reserves of 5 Mt ore, with an average grade of 2.6 g/t Au and led to a successful trial heap leach test (Cottard et al 1994). Open-pit mining by Ma’aden and the production of Au by heap leaching began in 2000 and ceased in 2006 on exhaustion of the supergene reserves (SRK Consulting 2007). The open pit at the mine is now closed, but activity continues with use of the heap leach facility to reprocess previously stacked and leached materials, and to process new materials from *Jadmah*, a similar VMS/supergene deposit ~ 4 km west of Al Hajar Au mine(Fig 6.2). The primary mineralized zone (un-mined) at Al Hajar consists of low-sulfide stringers and disseminations of pyrite (3%–10%, locally 40%) with subordinate chalcopyrite. The ore is hosted by porphyritic rhyolite and dacite, and the weathering produced a variety of oxidized ores referred to as siliceous facies, ferruginous facies, and bleached facies. The *Jadmah* deposit consists of Au-Ag mineralization associated with siliceous–ferruginous gossans produced by the supergene oxidation of lenses of disseminated and massive pyrite, chalcopyrite, and sphalerite. The host rocks include quartz-eye rhyolitic tuff, subordinate dacitic tuff, chloritized rhyolite ash flows, and jasper in a regional succession of felsic to intermediate volcanic flows and tuffs. The estimated in situ ore resources of oxide ore indicated the presence of ~0.52 Mt ore, with an average grade of 3.1 g/t Au and 40 g/t Ag at a cut-off grade ~0.5 g/t Au (Ma’aden Exploration Department 1998). In the southeastern most part of the Asir terrane, there are significant convergent-margin volcanic-related sulfide mineralization, named the *Wassal Masane–Kutam mineral district* (Fig 6.7). The belt is underlain by spreading-center and convergent-margin arc rocks in the Malahah basin (Johnson and Kattan 2012). The *Al Masane* occurrence is a classic polymetallic VMS deposit, the *Al Halahila* and *Farah Garan* occurrences have some of the characteristics of VMS deposits, but their classification is not definitive (Sangster and Abdulhay 2005). The *Kutam* occurrence may be a VMS deposit but is highly sheared; it was described in Chap. 5 of this book under the section of shear-zone-associated mineral occurrences. The *Wadi Wassat* is a typical VMS deposit type in the possible extension-related basaltic–andesitic assemblage in the northeast of the mineral belt (Fig 6.7). The *Al Masane* occurrence was discovered in 1967 in a deeply incised wadi as outcroppings of gossans in a sequence of steeply west-dipping mafic tuff and lava, felsic tuff and lava, lapilli tuff, and black shale (Fig 6.8) (Fernette 1994). The Al Masane occurrence consists of six sulfide bodies, in which four of them (the Saadah zone) hosted by felsic tuff and lava unit, one at the contact between lapilli tuff and black shale (the Moyeath zone), one in the mafic tuff and lava (the Shann zone) (Fig 6.8) (Fernette 1994; Sangster and Abdulhay 2005). All sulfide bodies comprise stratiform lenses of massive pyrite, chalcopyrite, sphalerite, galena, and pyrrhotite, with subordinate-to-minor tellurides and sulfosalts. The Al Houra–Saadah bodies are Cu-Zn-rich, and the sulfide layers are interbedded with Mg-Mn carbonate, chert, and pyrite–talc rocks. Metal zoning is reported at Saadah with Cu toward the footwall and Zn, Au, and Ag toward the hanging wall. The Moyeath zone is Zn(Pb)-rich body. The Al Masane massive sulfide mineralization has total ore reserves (proved + probable) ~7.2Mt, with an average grade of 1.42 wt% Cu, 5.31 wt% Zn, 1.19 g/t Au, and 40.20 g/t Ag (Al Masane Al Kobra Mining Company website: www.arabianamericandev.net, April 2011, accessed on April 2021). The Al Masane mineralized zones represent typical VMS deposits based on the following observations (Sangster and Abdulhay 2005): (1) the submarine depositional environment of the enclosing host rocks, (2) the stratiform nature of the sulfide lenses, (3) the Cu-to-Zn zoning reported in the Saadah lenses, and (4) its overall Zn-rich composition. The *Al Halahila* occurrence is located in the eastpart of the Wassat–Al Masane–Kutam mineral district (Fig 6.7); it is exposed as north-trending gossans on the steep slope of a deeply incised valley. It consists of three discontinuous sulfide lenses in a steeply east-dipping sequence of dolomite–sericite–chlorite schist and martitic ironstone composed of quartz and hematite pseudomorphs after magnetite, enclosed in chlorite–sericite–pyrite schist and andesitic–dacitic tuffs to the east, and andesitic metatuff to the west. The mineralization comprises veins and disseminations of pyrite and lesser sphalerite, chalcopyrite, galena, and tennantite replacing dolomite as well as subordinate banded-to-massive sulfides. The steep terrane makes drilling difficult, so the size of the deposits is not properly known, but an indicated resource has been estimated (Parker 1982) to be 1.04 Mt , with an average grade of ~2.99 wt% Zn, 0.44 wt% Cu, 25.2 g/t Ag, and 0.45 g/t Au, to a depth of 100 m. The *Farah Garan–Kutam* belt is located in the southwest corner of the Malahah belt (Fig 6.7); it contains two significant polymetallic mineral deposits: *Kutam* and *Farah Garan* that are situated within 10 km of each other (Fig 6.7). The Farah Garan–Kutam belt is a part of the Malahah belt of Halaban-group rocks, which has been interpreted to be a possible back-arc rift assemblage metamorphosed to greenschist facies (Sangster and Abdulhay 2005). The local geology of Farah Garan area comprises a north trending, steeply west-dipping sequence of mafic and felsic volcanic rocks and a varied sequence of sedimentary rocks (Fig 6.9) (Doebrich 19 1989). The mafic group comprises intercalated pillow basalt, mafic agglomerate, and mafic lapilli tuff. The felsic volcanic rocks have been metamorphosed to quartz-eye sericite phyllite with quartz “eyes” (<10% of the rock) in a matrix of fine-grained quartz, sericite, feldspar, and minor chlorite, pyrite, carbonate, clinozoisite, and epidote. Sedimentary rocks are represented by a carbonatized phyllite unit, which is regarded as a clastic sedimentary unit and comprises a graphitic phyllite and quartz–chlorite–sericite phyllite unit. In addition to the volcanic and clastic sedimentary rocks, a distinct assemblage of intercalated cherty dolomite, talc, chloritite, chert, and sulfides was recognized, which are referred to as an exhalative unit. The cherty dolomite, in particular, is intimately associated with layered sulfides. There are three layered sulfide-bearing units in the Farah Garan occurrence, and are referred to as the east, south, and west exhalative units (Fig 6.9). The highest-grade sulfides are contained within the south unit, which has been penetrated by two drill holes (Fig 6.9). The Farah Garan mineralization consists of banded and disseminated pyrite, sphalerite, chalcopyrite, tetrahedrite–tennantite, and galena in a sequence of exhalative cherty dolomite, talc, chloritite, and chert, that interfingers with felsic and mafic metavolcanic, volcaniclastic, and subordinate metasedimentary rocks. The rocks are steeply dipping and strongly folded, and the stratigraphy is severely disrupted, but it is believed that the felsic–metavolcanic rocks were originally below and the mafic–volcanic rocks above the sulfide mineralization. Drill holes intercepted sulfides over true thicknesses of as much as 31 m. A general upward metal zoning was reported in the area comprising an increase in Zn/(Cu ± Pb ± Zn) ratios and decrease in Cu/(Cu + Pb + Zn) ratios. The prospect has not been sufficiently drilled to yield an adequate resource estimate; however, estimated resources based on two drill holes were 0.23 Mt ore, with an average grade of 2.5 wt% Zn, 0.9 wt% Cu, 33 g/t Ag, and 2.8 g/t Au (Doebrich (1989). The lack and difficulty of drilling, inadequate sampling of fresh sulfides, and poor surface exposure make the deposit-type classification uncertain, but Sangster and Abdulhay (2005) tentatively classify the deposit as VMS type. ***Volcanogenic massive sulfide deposits in Afif terrane:*** In the north-central shield (the *Afif terrane*), the VMS deposits occur in the *Nuqrah district* at *Nuqrah North* and *Nuqrah South* as well as in the *Shaib Lamisah* occurrence in the southwestern part of the Afif terrane (Fig 6.2). The Nuqrah district is in the northwestern part of the Afif terrane, east of the suture between the Afif and Hijaz terranes (Fig 6.2). The Nuqrah belt lies within the Hulayfah group of volcanic and volcano–sedimentary rocks. This group comprises two formations; the lower, or Afna formation, is mostly andesitic with basaltic flows with subordinate mafic tuff, breccia, and agglomerate. Units of rhyolitic–andesitic quartz crystal tuffs are found near the top of the formation. The upper, or Nuqrah formation, is a sequence of alternating volcanic and sedimentary rocks (Fig 6.10). The site of the Nuqrah deposits is marked by ancient pits and trenches extending several hundred meters along strike (Sangster and Abdulhay 2005). Nuqrah south occurrence consists of sulfide ore in a steeply northwest-dipping zone of carbonaceous–graphitic tuffite and chert enclosed in dolomitic marble (Fig 6.10). The footwall consists of rhyolitic tuff, while the hanging wall is of andesite, basalt, and tuffite. The Nuqrah north occurrence is hosted by similar rocks, including basalt, rhyolitic tuff, graphitic tuff, dolomitic marble with graphitic intercalations, and lenses of black chert and dacite. Mineralization at both occurrences consist of Ag- and Au-rich massive, stringer, and disseminated sulfides. The sulfide lenses are layered parallel to axial plane schistosity. Primary bedding consists of millimeter-spaced alternations of sphalerite-, pyrite-, chalcopyrite-, and galena-rich laminae and graphitic laminae. Cubanite (Cu2Fe4S5) and mackinawite (Cu2Fe4S7) form exsolution phases in chalcopyrite. Other minerals occurring in trace amounts are boulangerite (Pb5Sb4S11), bournonite (PbCuSbS3), alaite (PbTe), tetradymite (Bi2Te2S), tetrahedrite, freibergite, native gold, electrum, hessite (Ag2Te), empressite (AgTe) molybdenite, siegenite [(Fe, Co, Ni)3S4], melonite (NiTe2), and frohbergite (FeTe2). The estimated ore resources for the Nuqrah south body range from 0.241 Mt ore, (grading at 13.8 wt% Zn, 2.0 wt% Cu, 6.3 wt% Pb, 14.4 g/t Au, and 554 g/t Ag) to 1 Mt (grading at 7.6 wt% Zn, 1.2 wt% Cu, 3.44 wt% Pb, 5.86 g/t Au, and 235 g/t Ag) (Bour 1972). Resource estimates for the Nuqrah north body ranges from 0.225 Mt ore (grading at 8.2 wt% Zn, 1.0 wt% Cu, 2.2 wt% Pb, 2.3 g/t Au, and 303 g/t Ag) to 0.30 Mt ore (grading at 6 wt% Zn, 0.75 wt% Cu, 1.22 wt% Pb, 2.5 g/t Au, and 332 g/t Ag) (Delfour 1975). Although the mineralization types have been compared to VMS deposits, the association with carbonate beds and the very high Ag content differentiate the Nuqrah ore from typical Precambrian VMS deposits, and Sangster and Abdulhay (2005) suggest that the deposits may be epigenetic carbonate replacements (MVT) rather than classic VMS bodies. The *Shaib Lamisah* occurrence is located just east of the ophiolite-bearing suture at the southwestern edge of the Afif tectonostratigraphic terrane. The Shaib Lamisah area is underlain by volcanic arc rocks of early Hulayfah age (780 to 730 Ma) belonging to the Hijaz orogenic cycle (Viland 1986). Early Hulayfah volcanic units comprise a varied assemblage of mafic-to-intermediate volcanic rocks with minor felsic components, some of which were deposited under subaerial conditions. The volcanic rocks are associated with fine-grained clastic sedimentary rocks dominated by calcareous and pyritic black shales and carbonate lenses. The volcanic and sedimentary rock assemblage is crosscut by intrusive bodies ranging in composition from mafic to highly evolved magmatic differentiates. The mineralized unit is composed of soapstone (tremolite and calcite), black crystalline marble (limestone or dolostone), pyritic black shale, massive or laminated gray chert, intermediate tuff, and intrusive metadiorite. Footwall black shale, normally up to 15 m thick, thins and grades northward to calcareous tuff.

Sulfide layers at Shaib Lamisah are roughly parallel to bedding in tremolite–carbonate “soapstone”, as irregular patches in dolomitic marble, and as massive sulfide containing carbonate “clasts”. Strong shearing has resulted in veinlets of segregated sulfides and recrystallization of chalcopyrite and pyrite. Pyrite, chalcopyrite, and sphalerite are the main components of the sulfide mineralization. Trace amounts of pyrrhotite, native bismuth, molybdenite, mackinawite, cubanite, and arsenopyrite were also observed. Gangue minerals are mainly carbonate, quartz, and tremolite. The estimated ore resources based on five diamond drill holes (Elsass et al 1983) at the Shaib Lamisah deposit found to contain ~ 1.4 Mt ore, with an average grade of 9 wt% Zn, 1.7 wt% Cu, and 9 g/t Ag. **6.3 Volcano–Sedimentary Mineral Deposits in Yemen**  The volcano–sedimentary mineral deposits in Yemen are mainly represented by Zn-Pb-Ag ± Cu occurrences, which are mostly related to the MVT environment. The most significant occurrences are widespread over an approximately 850 km long and up to 100 km wide rift basin of Jurassic age, which are not related to the Neoproterozoic ANS rocks. Thus, these mineral deposit types will not discussed in detail; however, it will just briefly be mentioned here for reference. Several carbonate-hosted Zn-Pb-Ag ± Cu occurrences are found along the rift, and one of the famous occurrences of these deposits is the Jabali Zn deposit.

As stated before in Chap. 2 of this book, the geology of Yemen comprises three main parts: (1) Precambrian basement rocks, (2) Jurassic pre-, syn-, and post-rift carbonate and clastic sedimentary rocks, and (3) Tertiary-to-recent sedimentary rocks and magmatic-associated rocks related to the opening of the Gulf of Aden and Red Sea rift (Menzies et al 1994). At the end of the Proterozoic age, the southern Arabian Peninsula underwent an extensional intraplate regime, characterized by extensive volcanism and magmatism. In the late Precambrian age, this extension caused uplift and erosion processes of the basement rocks, followed by the formation of several basins, related to major wrench-fault systems (e.g., the Najd fault system; Ellis et al 1996). These basins are filled by Paleozoic-to–early Mesozoic clastic sequences, deposited in marine epicontinental-to-deltaic environments, locally containing evaporites (Beydoun 1997). During the Triassic to the middle Jurassic periods, Yemen was part of the Afro–Arabian plate of western Gondwanaland, where the Jurassic breakup of Gondwana caused the separation of the Arabian plate from the original supercontinent (Bosence 1997;’Ahlbrandt 2002). The Mesozoic extensional tectonics of Yemen resulted in the formation of five sedimentary basins (Fig’ 6.11): (1) Siham-Ad-Dali', (2) Ramlat As Sabatayn (Sabatayn), (3) Say'un-Masilah, (4) Balhaf, and (5) Jiza'-Qamar (As-Saruri et al 2010). The Sabatayn and the Say'un-Masilah basins (Fig 6.11) are the only hydrocarbon-producing basins in Yemen. The Jabali mineral deposit is located on the western border of the Sabatayn rift basin.There are at least two rift-controlled basins of Jurassic age in Yemen, where most of the Zn occurrences are located at the margins of these rifts (e.g., the Sabatayn basin) or in rift-affected blocks. There are more than 100 known base-metal occurrences in Yemen, of which ~20 occurrences of them are of economic interest and considered to be prospects and/or deposits (Fig 6.12). Much of the exploration work during the 1980s was directed to the discovery of base-metal mineralization, in particular VMS deposits, which are known to occur in several localities of similar rocks in Saudi Arabia. The discovery of the Jabali Zn deposits in Jurassic carbonates led to an expansion of emphasis to include carbonate-hosted Zn-Pb deposits (known to be MVT deposits) (Christmann el al. 1989). Zinc-lead occurrences are widespread in Yemen; however, the most significant occurrences form an ~850-km-long belt in carbonate rocks within and adjacent to the Ramlat As Sabatayn rift basin. Mineralization is found in rocks ranging from Jurassic to Paleocene in age, and largely forms two sectors, located in the *Jabali* and *Tabaq* areas (Fig 6.12) (Yemen Geological Survey and Mineral Resources Board 1994 2009). The *Jabali* area comprises several ore mineralizations hosted by carbonate rocks of the Jurassic Amran group; it is located on the western flank of the Sabatayn basin, ~60 km northwest of the town of Marib. The Amran group directly overlies the Precambrian basement rocks, and is intruded by Tertiary igneous intrusions. Eight small-scale Zn-Pb occurrences were identified in the Jabali area, which were expressed on the surface as variously extended gossans containing limited Zn and Pb mineralization, hosted in dolomite breccias. The principal mineralization sites in Jabali area are *Barran*, *Al-Kwal*, and *Haylan* (Fig 6.12), which are grading at 16.5 wt% Zn and 6 wt% Pb, and by a very limited areal extension (Yemen Geological Survey and Mineral Resources Board 1994 2009).The *Tabaq* district is located ~360 km north/northeast of Aden, in the same rift system hosting the Jabali deposit of southern Yemen, and ~500 km east of the Jabali mining area (Fig 6.12). In the Tabaq area, nine small-scale Pb-Zn occurrences have been identified. Similar to the Jabali area, the mineralized occurrences at the Tabaq area are hosted in the Jurassic-to-Paleocene carbonate sequence, and are associated with zones of dolomitization and strong faulting. Maximum grades of 12 wt% Zn and 3.8 wt% Pb have been measured at Tabaq along a 30-m strike section, at Wadi Rama and Jabal Al-Jubal (Fig 6.12). The other two major occurrences of the area generally show lower grades. There is not enough mineralogical information for all of these minor occurrences (Yemen Geological Survey and Mineral Resources Board 1994 2009). Another base-metal mineralized district is located in the southwestern part of the Say'un-Masilah basin, in the Mukalla area named Al-Masylah and Ras Sharwyn occurrences (Fig 6.12). Mineralization of this district is fault-controlled, and consists of veins of barite and galena. A secondary nonsulfide Zn-Pb-Mn mineralization containing willemite, smithsonite, cerussite, descloizite, calcite, pyrolusite, and celestine, with anomalous grades of Ag, Cd, Ga, Ge, and Mo also occurs in this area. Following is a brief description of the Jabali Zn-Pb-Ag occurrence for reference of such MVT deposits to be compared with other volcano–sedimentary deposits in the ANS. \

***6.3.1 Jabali Mississippi Valley–Type Zn-Pb-Ag Deposit***

The Jabali occurrence is the most significant base-metal mineralization in Yemen (Yemen Geological Survey and Mineral Resources Board 1994 2009). The artisanal mine workings in the area are thought to be older than 2500 years. The Jabali MVT deposit was considered to be the greatest Ag mine in the Muslim world, with more than 400 furnaces producing “one camel load of metal” per week (Christmann et al 1989). The old mine workings extended over an area of ~10 ha, tracing cavities filled by relatively soft oxidized ore, locally rich in Ag. The ore was processed on site, where the waste dumps contain ~120,000 tons, with average grades of 24 wt% Zn, 3.5 wt% Pb, and 160 g/t Ag. It seems that the old artisanal metallurgical processes were not effective to extract the ore, since the remaining slags still contain ~23 wt% Zn, 6.5 wt% Pb, and 40 g/t Ag (SRK Consulting 2005). The site was rediscovered by BRGM and the Yemen Geological Survey and Mineral Resources Board (YGSMRB) in 1980. Between 1981 and 1986, an exploration and evaluation program based on 57 drill holes reported an accessible open-pit resource of 3.0 Mt ore, at ~15.2 wt% Zn, and an amenable by underground mining volume of 1.24 Mt ore at ~13 wt% Zn. The BRGM and YGSMRB during and after the period of exploration at Jabali area produced several scientific papers on the characterization and genesis of the deposit (Christmann et al 1989; Al Ganad et al 1994) and a Ph.D. dissertation (Al Ganad 1991). No further scientific publications on the Jabali mineralization has been produced in recent years, with the exception of Mondillo et al (2011 2014). The Jabali Zn-Pb-Ag deposit covers a total area of ~2 km2, striking in a northwest direction (Fig 6.13). The deposit is located in a small plateau on the eastern flank of a northwest/southeast-elongated mountainous area that is a segment of the western boundary of the Sabatayn basin, which extends for several square kilometers in the adjacent lowland. This mountainous area is called *Gebel Salab*. There is a small crest occurring on the northwestern part of the Jabali plateau called *Gebel Barrik* and a small valley named *Wadi Jabali* delimits this area from the southeastern part of the plateau, where the orebodies outcrop (Fig 6.13). The plateau is dissected by another valley (Wadi Khaynar) further southeast. These valleys vertically cut the mineralized formations, which are exposed along the valley flanks. There are small igneous sills and dykes cross-cutting the Jabali orebodies and their host sedimentary rocks at the mine site. The sedimentary rocks hosting the Jabali orebody belong to the Amran group, which directly overlie the Proterozoic basement rocks and are a maximum of 300 m in thickness (Al Ganad et al 1994; Beydoun et al 1998). At the mine site, the Amran group sequence subdivides into nine lithostratigraphic units (Figs. 6.13, 6.14), starting from the base upwards as: Unit 1 is ~10-m-thick sandstone and conglomerate overlying the late Proterozoic basement. Unit 2 is ~25 m thick, comprising gypsiferous mudstone overlain by and interbedded with dolomitized calcarenite, marl, and nodular limestone. Unit 3 is ~50 m thick and composed of micritic and biomicritic limestone, containing nodular concretions and chert layers. Unit 4 of ~15 m thick from micritic limestone and finely bedded lagoonal/lacustrine dolomite. Unit 5 is ~40-m-thick partly dolomitized calcarenite, overlain by coral-bearing oolitic and oncolitic limestone. Unit 6 is ~80-m-thick grading from greenish gypsiferous mudstone to micritic ammonite-bearing limestone interbedded with marls and calcareous sandstone. Unit 7 is ~80-m-thick massive bioclastic and biomicritic limestone that is partly dolomitized. This unit outcrops at the top of the plateau where the Jabali deposit is located, which clearly are affected by strong karstic erosion. Unit 8 is up to 30-m-thick black mudstone and argillite with gypsum crystals and dolomite intercalations, grading laterally to micritic ammonite-bearing limestone. Unit 9 is ~20-m-thick biomicrite with oncolites and bio-oocalcarenite with intercalations of gypsum and lenses of arkosic sandstone. The last two units (Units 8 and 9) outcrop along the Gebel Barrik crest, which constitutes a relief over the Jabali plateau. The Jabali Zn-Pb mineralization is mainly hosted by the dolomitized section of Unit 7 (Al Ganad et al 1994; SRK Consulting 2005; Mondillo et al 2011 2014), which partly outcrops in some places of the plateau. The majority of mineralized lithologies still occur in the subsurface, below Gebel Barrik (SRK Consulting 2005). The ore is almost completely oxidized, but in some places underneath Unit 8, primary sulfides have been partly preserved from oxidation by the impervious cover of black mudstone and argillites. The Jabali mineralization seems to be structurally and lithologically controlled, which is reflected in the morphology of the orebodies that are both tabular and parallel to the stratigraphy, and aligned vertically along fractures and faults and at the intersections of these structures. At the fault intersections, the mineralization forms big vertical bodies, comparable to chimneys. The stratiform bodies, parallel to the stratigraphy, occur in three different zones: The upper zone, which is a laterally extensive, and more sporadic lower and middle zones. These bodies are generally flat but, at the base of the Gebel Salab massif, along the northwest/southeast fault they dip towards the northeast at angles greater than 30° (Fig 6.13). The nonsulfide ore displays massive, semimassive, and disseminated character, and is characterized by vuggy–to–highly porous, brownish-orange–to–white Zn-bearing non-sulfide minerals (Fig 6.15) (Mondillo et al 2011; 2014). A porous cellular boxwork structure is accompanied by numerous cavities coated with Zn minerals, dolomite, and calcite that are quite widespread. The most common secondary Zn-bearing minerals is smithsonite, which is intimately intergrown with dolomite (Fig 6.15a). Fine-to-granular amorphous aggregates of hydrozincite have observed in outcrops (Fig 6.15b), but are very uncommon at depth and in drill cores. Lead is present both as cerussite and anglesite. The nonsulfide ore replaces primary sulfides (Fig 6.15c) and the dolomite host rock (Fig 6.15d), which is also dedolomitized and patchily replaced by calcite. Iron staining is common throughout the mining area, resulting in variable concentrations of goethite, hematite, and manganese oxyhydroxides. Silver is contained in Ag2S and as native metal. Gypsum is very common through the entire mineralized area (Fig 6.15e). Remnants of the primary sulfide association can be observed in outcrops and drill cores, and consist of sphalerite, galena, and pyrite/marcasite. Sphalerite occurs as two distinct generations, a first that is dark colored, and a second that is more abundant and represented by zoned euhedral-to-subhedral honey-colored or brownish-red crystals (SRK Consulting 2005). Sphalerite contains Fe, Ag, Cd, Cu, Ge, and Hg. Fluid inclusions of sphalerite have bimodal homogenization temperatures to the liquid between 60–85 °C and 85–110 °C and bimodal salinities of 10–14 eq wt% and 19–23 eq wt% NaCl, respectively (Al Ganad et al 1994). The Pb isotopic ratios for galena and cerussite, respectively, range between 18.85 and 18.95 206Pb/204Pb, 15.66 and 15.72 207Pb/204Pb, and 39.71 and 39.92 208Pb/204Pb (Mondillo et al 2011; 2014). These values are similar to the Pb isotopic composition of other Zn-Pb deposits of the Sabatayn basin and are interpreted as indicative of the contribution of an early Proterozoic crustal component (e.g., basement rocks of the basin) (Stacey and Hedge 1984; Al Ganad et al 1994). Regarding the genesis of Jabali Zn-Pb deposits, the basic geological concepts of Al Ganad et al (1994) have been confirmed in the reports of Allen (2000) and SRK Consulting (2005), but the genetic model for the primary and secondary mineralizations has remained an open matter and is still strongly debated. The Pb isotopic ratio of galena indicates a source of the metals from the basement (Al Ganad et al 1994). The sphalerite fluid inclusions, on the other hand, have a basinal character and show salinities and temperatures similar to many carbonate-hosted Pb-Zn deposits. Thus, the limited research on the genesis of primary sulfide ores of the Jabali Zn-Pb deposit support the hypothesis of a MVT mineralization in the broad sense (Al Ganad et al 1994). **6.4 Volcano–Sedimentary Mineral Deposits in the Eastern Desert of Egypt**  ***6.4.1 Introduction***

There are many volcano–sedimentary mineral deposits in the Central Eastern Desert (CED) and South Eastern Desert (SED) of Egypt, which are represented mainly by polymetallic VMS occurrences, including Hamama, Um Samiuki, Helgate, Maaqal, Derhib, Abu Gurdi, El Atshan, Egat, and Um Selimat. Except for the Hamama occurrence, which is located in the CED, all of other occurrences listed here are located within a small geographic area in the SED (Fig 6.16). Despite their existence in the Neoproterozoic basement rocks of the Eastern Desert, these VMS deposits/occurrences show distinct differences in their host rocks, structural evolution, and mineralogical, textural, and bulk geochemical characteristics. Based on these differences, VMS deposits/occurrences in the Eastern Desert of Egypt can be subdivided into three main groups with different characteristics (Abd Allah 2012; Morad and Helmy 2021) including, starting from the CED and progressing to the SED: The*Hamama west*, which lies in a wider area of Aton Resources Inc.’s Abu Marawat concession of the Abu Marawat mineral district in the CED. Mineralization at the Hamama West consists of primary hypogene sulfide mineralization overlain by an oxidized zone of Au-bearing gossans. The Hamama West mineralization is interpreted as being of VMS style, although it does not have the classic massive sulfide mounds to date. The*Um Samiuki mineral district* includes Um Samiuki, Helgate, and Maaqal occurrences. The sulfide mineralization of this district occurs as massive lenses and veins that extend tens of meters, where sphalerite, chalcopyrite, pyrite, and galena are the major sulfide minerals. Ore deposits characterized by Mn-rich sphalerite (up to 5.5 wt%) and has variable Fe content (ranging 0.5–4.5 wt%). The composition of galena is Ag- and Se-poor. Ag-rich tellurides are also recorded in these occurrences, which can be classified as Zn-dominated VMS. The*Derhib mineral district* includes occurrences at Derhib, Abu Gurdi, and Egat. The sulfide mineralization of this district is essentially located along major shear zones that intersecting ophiolitic mélange and island arc volcanic rocks. No primary structures and textures of the ores and host rocks have been preserved due to secondary deformations and metamorphism. Sulfide minerals are represented by chalcopyrite, galena, sphalerite, and pyrite. Sphalerite has high Cd content (up to 5.1 wt%) and is low in Mn content (<0.3 wt%). Galena is generally enriched in Se (up to 7.2 wt%). These occurrences are classified as Cu-dominated VMS type. The mineralogical and geochemical differences between these three VMS groups might reflect the differences in submarine tectonic environments and host volcanic rock successions. The Zn-dominated (and Pb-Ag ± Ba-enriched) Um Samiuki and Abu Marwat mineral districts are mostly similar to those of felsic island arc environments that are comparable with the Kuroko VMS–type of Japan. The Cu-dominated Zn-rich VMS mineralization of the Derhib mineral district is mostly similar to those hosted by a mafic fore-arc or back-arc ocean-floor environment classified under the bimodal mafic Cyprus-type VMS deposits. Following is a brief description of the VMS deposits/occurrences in the above-mentioned three mineral districts: Hamama (Abu Marawat), Um Samiuki, and Derhib, in terms of their host rocks, sulfide mineralogy, and geochemical characteristics.

***6.4.2 The Hamama west prospect (Abu Marawat mineral district)***

The majority of this section, especially the geology and mineralization, is mostly compiled from information supplied by the Aton Resources technical report ([Aton Resources technical Report, March 15 2020](https://www.northernminer.com/news/egypt-approves-aton-resources-mining-licence-for-hamama/1003814034/), accessed on April 2021). The Hamama west prospect is the only known VMS mineralization in the CED and is located ~450 km to the south/southeast of Cairo; it is located within the Aton Abu Marawat concession (Figs. 6.16, 6.17). The Abu Marwat concession lies between latitudes 26°18ʹ and 26°34ʹ N, and longitudes 33°19ʹ and 33°46ʹ E and covers a total surface area of ~738.8 km2. The Hamama west occurrence is located approximately between coordinates 26°20ʹ37ʺ N and 33°20ʹ33ʺ E (Fig 6.17). Historically, the ancient workings in the Hamama area are scattered over an area of ~5 km². The largest ancient workings concentrated at Hamama north, which known also as the Hamama I site (Klemm and Klemm 2013) that dated back to the New Kingdom and Ptolemaic periods, consisting of a 320-m-long zone of north/south-striking trenches, from which a significant amount of vein material has been excavated. Spoil and mine waste in the local area contains abundant specular hematite and red-brown gossan cover. At the Hamama east site, there is a regionally mineralized horizon at which a small adit has been driven, a few tens of meters into the side of the hill. This area is referred to as the Hamama II site, and suggested that it was utilized in the Early Arab Period (Klemm and Klemm 2013). Zinc and Cu mineralization occurs as stockworks or thin networks of veins, along with patches of gossanous materials. Next to this adit are collections of small rectangular huts that contain numerous shards of pottery, including occasional pieces of amphoras, where a little mine waste exists in this area. At the site of Hamama west, there is relatively little evidence of ancient mining, apart from a few very small pits within a gossanous zone, over a strike length of ~70 m. Several other small workings, possibly prospecting pits, are scattered around the area. They are usually associated with very small zones of quartz veining with staining of malachite and/or chrysocolla. In modern times, the Egyptian Geological Survey and Mining Authority (EGSMA) has carried out several exploration programs of geological traverses, trenching, and channel and lump sampling, with other national and international companies (including Minex, Centamin, Pharaoh Gold Mines NL (PGM), and, what was at the time Alexander Nubia (now Aton Resources)) from 1970 through 2007. Currently, Aton Resources has the sole right to explore and develop Au and associated mineral deposits within the concession area, where an exploration camp has been constructed at Abu Marawat and a smaller field camp at Hamama to conduct exploration activities, including detailed geological mapping over the entire Hamama area. A number of diamond drill holes were completed between 2011 and 2014 at the Hamama west, central, and east prospects. Diamond drilling was resumed again at the Hamama west site in March 2015 with an additional 70 diamond drill holes that were completed by the end of August 2016. Most exploration activities during this period were focused on the Hamama west site, although the Hamama central and Hamama east sites were also briefly drill-tested in 2015.

Geologically, the Hamama mineralization is essentially hosted by a sequence of volcano–sedimentary belts separated by narrow, sinuous belts of mafic and ultramafic rocks. These volcano–sedimentary belts are typically represented by calc-alkaline andesitic rocks with associated mafic-to-intermediate intrusive rocks (Fig 6.17), which are all regionally metamorphosed to lower greenschist facies, before being intruded by various tectonic or post-tectonic granitoids. The local geology at the Hamama occurrence consists of a sequence of intermediate-to-felsic lavas and tuffs, overlain by tuffaceous sedimentary rocks with minor thin beds of jasper, chert, and bedded pyrite (Fig 6.17). Numerous subvolcanic andesitic dykes and intrusives occur in the whole area, where they were subsequently folded and faulted during the Pan-African orogeny. Close to the Hamama west prospect, the entire rock package has been overturned, dipping to the north. Similarly, towards the Hamama central and Hamama east prospects, the rock units were overturned and their orientation changed to generally striking northeast dipping northwest. The main mineralized horizon and their host rocks dip from ~55° to nearly vertical. Stratigraphically, the footwall rocks of the Hamama mineralization are dominated by grey-to-green andesite lavas with interbedded tuffs (Fig 6.18). The andesite rock is mostly pillowed and is commonly porphyritic in texture and, where it is in proximity to the main mineralized zones, becomes more intensely altered to a chlorite–sericite zone and contains disseminated small pyrite crystals. The andesite unit is overlain by a sequence of felsic volcanic rocks, which represent the main mineralized horizon at Hamama west. At the Hamama west site, the basal unit is a semicoherent felsite (Fig 6.18), exhibiting various degrees of brecciation at a local scale. A package of medium-grey tuffs, which vary from moderately poorly sorted lapilli tuffs to laminated ash tuffs, is stratigraphically overlain by the felsic volcanic rocks. This felsic tuffs are found intimately together with the brecciated felsite zones; they mostly host the primary precious and base-metal sulfide mineralization. The stratigraphy of hanging wall consists of a sequence from fine-to-medium-grained felsic to intermediate tuffaceous rocks, with argillaceous or epiclastic sedimentary rocks. Drill holes in this area intersected clasts and small blocks of massive sulfide and vein material a few meters above the contact with the main mineralized zone, which are interpreted as minor slumping or talus features related to the sea-floor topography existing at the time of the deposition of these tuffs ([Aton Resources 2017 2020](https://www.northernminer.com/news/egypt-approves-aton-resources-mining-licence-for-hamama/1003814034/)). The hanging-wall unit is typically associated with thin beds of jasper and pyrite. The basal felsic tuffs or argillites grade upwards into a sequence of volcaniclastic rocks, which consist of darker grey-green tuffaceous sandstones and siltstones interbedded with purple cherty argillites and bright-red jaspers. The jaspilitic and tuffaceous sediments grade upwards into a distinctive massive, pale-green andesitic tuff unit, which rapidly grades upwards into fine-grained, featureless, massive tuffs. The mineralization at the Hamama occurrence consists of hypogene sulfides overlain byoxidized zone of Au-bearing gossans cover. Outcrop mapping and drilling have defined the deposit to date with ~800-m strike length and average width of ~60 m, outcropping at the surface, and an average drill-intersected depth of ~120 m below surface (Fig 6.18). The deepest drill hole to date has intersected the mineralized zone down to a depth of 275 m below surface. The hypogene sulfide mineralization at Hamama prospect is dominated by disseminated stringer and blebby pyrite, often associated with lesser amounts of sphalerite, and, rarely, chalcopyrite and galena. In the sulfide-rich zone, Au typically occurs as native grains that are interstitial to sulfide minerals, whereas Ag is mostly associated with sulfosalts and/or galena (Payne 2013). On a broader scale, zonation of the Au and Ag mineralization is unclear at the current level of drilling, but some shallow north-plunging trends are evident (which would therefore imply a steep-to-vertical control on mineralization at the time of deposition). At a smaller scale, there is some evidence of Au enrichment near the stratigraphic hanging-wall contact. Zinc commonly occurs throughout the deposit as disseminated mineralization into the footwall andesites. The alteration associated with sulfide mineralization is dominated by silica and carbonate especially ferroan dolomite. In some places, the original textures of the host lithologies have been completely obliterated due to the intense silica–carbonate alteration. The hypogene sulfide mineralization at the Hamama deposit is capped by an approximately 30-to-40-m-thick gossan cover of weathered and oxidized materials. This zone is quite variable and consists of ruddy to reddish-brown to yellow iron oxide and clay-rich materials. Gold and silver are commonly enriched in the uppermost 3–5 m of the profile. Zinc-bearing minerals are present in the oxide zone, related to the original distribution of sphalerite prior to the weathering events, and mostly at concentrations of >10 wt%. Minerals recognized in the oxide zone include limonite, hematite, smithsonite, malachite, and chrysocolla. Genetically, the Hamama mineralization has been variably described as a classic VMS deposit (Hall and McHugh 1989), a Au-rich VMS (Alexander Nubia Inc. 2015) and an orogenic precious/base-metals vein deposit (Voormeij 2015). The Aton Resources (2020) is interpreted the Hamama west mineralization as a *VMS–epithermal hybrid* subclass as it displays many of the characteristic features of the VMS style of mineralization. This distinct group of deposits has been variously described in the literature as “high-Au VMS” (Dubé et al 2007), “high sulfidation VMS” (Sillitoe et al 1996), and “hybrid VHMS–high-sulfidation epithermal deposits” (Large et al 2001). The world-class examples of this mineralization type include the LaRonde–Penna and Bousquet deposits in Quebec, the Eskay Creek deposit in British Columbia, and the Henty and Mount Lyell deposits in Tasmania. Such types of VMS–epithermal hybrid deposits are distinguished from the more “classic” VMS ones (e.g., bimodal mafic/felsic–Noranda type) by being relatively rich in precious metals and poor in base metals, having a higher proportion of volcaniclastic rocks to flows of bimodal characters (i.e., mafic/felsic volcanics), having anomalous geochemical signatures, and exhibiting alteration assemblages indicative of low-pH fluids. They essentially represent the shallow marine equivalent to subaerial epithermal systems (Dubé et al 2007). The hanging-wall stratigraphy, which in many places displays clear sedimentary textures, suggests a marine environment. The combination of the style of mineralization (footwall stringers), the presence of chemical sediments that occur at distinct stratigraphic breaks, and the style of volcanism are together indicators of a classic VMS environment. Alternatively, the advanced argillic alteration, colloform banded vein fragments, and vuggy silica with bladed quartz (after calcite) are suggestive of an epithermal style setting, with boiling of low-pH fluids. The anomalous geochemical signatures for As, Mo, and Sb are indicative of a magmatic volatile input. The abundance of pyroclastic rocks, especially towards the east, suggests a shallow marine setting. All of the above-mentioned features are likely indicators of a VMS–epithermal hybrid system, with fluids preferentially mineralizing a semiconsolidated pile of felsic volcaniclastic rocks with relatively high porosity.

***6.4.3 The Um Samiuki Mineral District***

The Um Samiuki mineral district includes several VMS occurrences, including the Um Samiuki (the largest VMS mineralization in Egypt), Helgate, and Maaqal occurrences. These mineral occurrences are hosted by a thick pile (>10 km) of volcanic rocks named the Shadli metavolcanic belt (SMB) that comprises rhyolites, andesites, basalts, and volcaniclastic rocks. The rocks of SMB were erupted in two magmatic bimodal cycles, the lower (older) Um Samiuki group, and the overlying (younger) Hamamid group (Searle et al 1978; Stern et al 1991; Noweir and Abu El-Ela 1991; Takla et al 1999). The SMB extends for >80 km in a northwest/southeast direction, an average width of ~25 km, and is flanked to the north and south by syntectonic granodiorite intrusions (Fig 6.19a). Both mafic and felsic volcanic cycles occur as alternating belts trending mostly west-northwest/east-southeast, and separated by tectonic contacts (thrusts and strike-slip faults; Fig 6.19b) (Faisal et al 2020). The lower metavolcanics group of Um Samiuki forms the main lithologic unit in the area, comprising >1000-m-thick massive, amygdaloidal, tholeiitic basalt, and andesite flows with minor intercalations of andesitic and rhyolitic volcaniclastic rocks (Fig 6.20). They have metamorphosed and occasionally pillowed in some horizons (Hafez and Shalaby 1983; Khudeir et al 1988). The lower Hamamid metavolcanics group, on the other hand, attains a maximum thickness of 2000 m. It is characterized by two distinct cycles of volcanism (cycles 1 and 2), in which each cycle commenced with the eruption of basic pillow lavas and terminated with thick beds of felsic lava and tuff (Searle et al 1978). The mafic rocks of cycle 1 are represented by massive pillow basaltic flows and agglomerates (Faisal e. 2020), whereas the felsic rocks of cycle 1 include dacites, rhyolites, and tuffs. The VMS sulfide orebody mainly is localized between the brecciated rhyolite and vent facies on one side and the tuffs of the felsic rocks on the other side (Fig 6.20). These felsic lavas were previously nonconstrained by age; however, recently they were dated using in situ U-Pb zircon dating to be ~695 Ma, and are characterized by subduction-related geochemical characteristics with significant enrichments in Zr, Hf, and Sm (Faisal et al 2020). The entire rock sequence of the SMB was later intruded by dolerites, biotite, and hornblende syntectonic granitoids, and lastly by the late- to post-tectonic muscovite granites (Figs. 6.19, 6.20). The last phase of igneous activity in the area is represented by various dykes and sills of Phanerozoic age, some of them related to the upper Cretaceous volcanic event of Wadi Natash area (Shukri and Mansour 1980). There are three well-known VMS occurrences in the Um Samiuki mineral district: the Um Samiuki, Helgate, and Maaqal prospects (Figs. 6.16, 6.19b). Following are brief descriptions of these occurrences in terms of their geology and mineralogy. The *Um Samiuki*prospect represents the largest VMS occurrence in the district; it was mined by ancient Egyptians and Romans for malachite. The Um Samiuki prospect comprises two separate occurrences of massive sulfide lenses at the top of cycle 1 rhyolitic breccia of the Hamamid group, which are known as the Um Samiuki west and Um Samiuki east mines (Fig 6.19b). The orebody in the western mine extends for ~90 m along strike with a maximum width of 20 m and continues to a depth of ~170 m. The orebody is made up of ~6-m-thick massive and semimassive sulfide zones extending vertically and laterally. The semimassive mineralized zone extends into a disseminated sulfide halo. The massive ore contains up to 70 modal % sulfides whereas the semimassive halo contains up to 30 modal % sulfides. In the western mine, one of the drill holes intersected a zone of ~11-m-thick sulfides grading at 21.7 wt% Zn, 2.2 wt% Cu, 0.5 wt% Pb, and 0.01% Ag (Searle et al 1978). In the eastern mine, the ore zone extends along the surface for more than 180 m with an average outcrop width of 10 m. The ore zone diminishes with depth due to tight cross folding and faulting. Sulfide mineralization comprises two separate large lenses, 35 and 25 m in length, respectively, with an average thickness of 2 m, as well as many small bodies (<2 m long). The massive sulfide ore of Um Samiuki prospect has variable mineralogical compositions; sometimes sphalerite-rich, bornite-rich, and pyrite-rich zones. In the sphalerite-rich ore, sphalerite forms the matrix hosting chalcopyrite and pyrite. In the bornite-rich zone, bornite constitutes ~40% modal, with lesser amounts of sphalerite, chalcopyrite, tetrahedrite–tennantite, and minor arsenopyrite and covellite. Covellite has been found to replace almost all other sulfide minerals along cracks. Pyrite is the main constituent of the pyrite-rich zone with lesser amounts of chalcopyrite and galena. Bornite, tetrahedrite–tennantite, chalcopyrite, and covellite are found to contain a high content of Ag, up to 1500 ppm (Shalaby et al 2004). The Ag-rich character of the Um Samiuki VMS is confirmed by the presence of several Ag-bearing minerals, including (Helmy 1996 1999; Shalaby et al 2004): hessite (Ag2Te), Au-Ag alloy, cervelleite (Ag4TeS), freibergite (Ag,Cu)10(Fe,Zn)2(Sb,As)4S13, acanthite (Ag2S), mckinstryite (Ag1.2Cu0.8S), benleonardite (Ag8SbAsTe2S3), stephanite (AgSbS), and native Ag. These Ag minerals are commonly associated with Ag-bearing bornite, tetrahedrite, tennantite, and chalcopyrite. The common gangue minerals associated with the Um Samiuki sulfide ores are represented by barite, calcite, rhodonite, tephroite (Mn2SiO4), rhodochrosite, spessartine, tremolite, diopside, talc, Mn-chlorite, and quartz. The United Nations programme (Searle et al 1978) prospected the Um Samiuki area geologically and geochemically, where a cumulative total of 806 m were drilled in six boreholes and tens of meters of tunnels and shafts were excavated in the western and eastern mines. The estimated ore reserves from these boreholes were <300,000 t, with average grades of 11.5 wt% Zn, 1.15 wt% Cu, 1.1 wt% Pb, and 0.01% Ag. The *Helgate* and *Maaqal* VMS mineralizations are also hosted by the SMB, which are about similar to those in the Um Samiuki prospect, which is represented by two major units: the lower and the upper metavolcanic units. The *Helgate* prospect lies on the eastward continuation of the Um Samiuki fault (Fig 6.19b). It is characterized by a number of highly contorted lenses of manganiferous carbonate (ankerite) in complex folded rhyolite and banded tuff and chert. The mineralization zone trends northwest with ~75° dips to the south. The underground extension along strike of the Helgate mineralization zone is ~60 m although surface indications appear to be approximately twice this length (Searle et al 1978; Abd Allah 2012). The thickness of the mineralized zone ranges 0.5–0.8 m in the form of concordant veins with the banded tuff and chert of the hanging wall. The geophysical data reveals that the orebody continues only for ~12 m farther to the southeast beneath the Wadi alluvium. To the north of Helgate prospect there is a vent area containing rhyolite breccia, mafic volcanic agglomerate, intrusive rhyolite, and a network of late basaltic dykes. Sulfide mineralization at the Helgate prospect comprises, in decreasing order of abundance, sphalerite, pyrite, chalcopyrite, and galena, without any Ag minerals identified. The common presence of micro- and cryptic layering of fine-grained thin layers of pyrite crystals suggest primary depositional textures. Gangue minerals are dominated by chlorite, quartz, and calcite. The estimated ore reserves are ~13,000 t, with an average grade of 13.6 wt% Zn, 2.9 wt% Cu, and 11.4 wt% Pb. The *Maaqal* prospect is located at the southern side of the meta-andesitic rocks of cycle 2 of the Hamamid group (Fig 6.19b). This prospect is characterized by a zone of intense deformation and brecciation, which is the main host for talcose rocks and sulfide lenses. The lithologic units exposed in the Maaqal area comprise lower pillow lava overlain by rhyolite flows and lapilli tuff and capped by banded tuff and chert. The contact between the footwall pillow lava and the hanging-wall lapilli tuff is marked by a talc-rich zone, along which massive sphalerite-dominated sulfide bands are stratified. Sphalerite is the dominant sulfide mineral, forming the matrix for other sulfides; it also forms small-scale bands interlayered with chalcopyrite bands. Pyrite, chalcopyrite, and galena represent the rest of the sulfide minerals in the Maaqal prospect. Chlorite, quartz, and calcite are the most common gangue minerals associated with sulfides. The estimated average assay of the Maaqal occurrence is ~13.6 wt% Zn, 2.9 wt% Cu, and 11.4 wt% Pb (Searle et al 1978).

***6.4.4*** ***The Derhib–Abu Gurdi Mineral District***

The *Derhib* and *Abu Gurdi* prospects are located in the eastern end of the SMB, at the northern side of Baranis-Aswan Road, ~ 60 km from Baranis (Figs. 6.16, 6.21). The Derhib–Abu Gurdi district is built up of late Neoproterozoic Pan-African metamorphic and magmatic rock assemblages, where the metamorphic rocks comprise gneisses/pelites and metavolcanics, which are intruded by syn- to late-tectonic magmatic granodiorite–tonalite and gabbroic rock assemblages (Ali-Bik et al 2020). The whole sequence is dissected by post-tectonic dykes and quartz veins and plugs. The Derhib area is well known for its talc mineralization, which has been exploited since 1953, where the talc mineralization is always encountered along shear zones separating Shadli metavolcanic rocks and ophiolites from the underlying metasedimentary rocks (Fig 6.22a). The Derhib area is covered by metasedimentary rocks, dismembered ophiolitic sequences (serpentinites, metagabbros, and metabasalts), bimodal mafic/felsic Shadli metavolcanic rocks, and younger intrusive granites and gabbros. The metasedimentary and the ophiolitic rocks are the oldest in the area and are extensively sheared and variably metamorphosed (Selim 1994). The VMS (Cu-Zn-Ag) mineralization occurs either as dissemination or as small massive sulfide lenses and veins along shear zones in talc tremolite rocks in the vicinity of ophiolitic fragments. The VMS mineralization in the whole area is commonly associated with malachite and azurite staining (Fig 6.22b, d), where these Cu-rich hydrous carbonates and talc constitute the surface or near-surface exposures as integral parts of VMS mineralization (Ali-Bik et al 2020). Small-scale VMS orebodies have been recorded at the Derhib–Abu Gurdi district, where talc and talc/malachite mineralization (alteration zones) are commonly distributed mainly along the east/west-trending shear zones. The treated remote sensing data revealed that there are several mineralization zones scattering throughout the area, which cover an area of ~14.38 km2, including the Derhib mine (Fig 6.23). These scattered small-scale lenses might represent parts of a fragmented large lens or represent small successive submarine hydrothermal vents in the area. The SMB, in general, experienced an alternating ductile/brittle deformation history. The role of subsequent structures in stretching and thinning, thickening, or even fragmenting the original sulfide ore lenses or beds is thus highly expected. Hence, the original geometry and architecture of mineralization systems at the Derhib–Abu Gurdi mineral district were most probably distorted and displaced (Ali-Bik et al 2020). However, VMS mineralizations in general tend to occur favorably within a single stratigraphic interval or a restricted number of horizons within the host volcanic sequences where ore deposition favorable horizons may represent a pause in volcanism, changes in volcanic compositions, or contacts between volcanic and sedimentary rocks (Lydon 1984; Evans 2009). In the *Derhib* area, sulfide mineralization is hosted either by mafic dykes, which are partially talcosed and contain disseminated sulfides (mainly chalcopyrite and sphalerite), or hosted by silicified talc tremolite rocks occurring as small black zones in talcose rocks, which are hosting disseminated and massive sulfides. At the Derhib and Abu Gurdi prospects, there are two modes of occurrence of sulfide mineralization: (1) Disseminated pyrite–chalcopyrite–sphalerite ore, where sulfides occur as grains interstitial to amphiboles, talc, and chlorites in mafic dykes and talc–tremolite rocks. The sulfide proportions vary from 3 to 18 modal % of the rock volume. This type is more common at depth in the Derhib mine. (2) Massive or vein ore type, which is composed of alternating bands of chalcopyrite and sphalerite enclosed in talc. These veins or lenses follow the structural direction of the shear zone and are encountered at depths of 21–35 m. The massive and disseminated sulfide ores in the Derhib mine consist essentially of, in decreasing order of abundance: chalcopyrite, pyrite, and sphalerite, with lesser amounts of galena and pyrrhotite (Abd Allah 2012). Covellite and magnetite are the major supergene sulfide and oxide minerals, respectively. The *Abu Gurdi* prospect is located to the southeast of the Derhib prospect (Fig 6.21), where the sulfide–talc mineralization occurs along shear zones separating the stratigraphically lower metasedimentary rocks from the upper metagabbros. Structural control of talc and base-metal sulfide mineralization is documented by the discontinuous occurrences along the shear zone. The sulfide mineralization at Abu Gurdi is encountered in only one place, where massive sulfide lenses are hosted in a talc-rich zone. The main shear zone in the area trends east/west and is 8 km long and less than 30 m wide. The talc-sulfide mineralization zone extends for ~180 m along strike and 6 m in width area in the central part of the shear zone. The mineralization zone is expressed on the surface by light-grey brecciated rhyolite and blue gossans with green malachite staining (Fig 6.22c,d). The sulfide minerals at Abu Gurdi prospect are represented by fine-grained pyrite, coarse-grained sphalerite, minor chalcopyrite, and galena.

The *Egat* and *Um Selimat* prospects are also talc-bearing base-metal sulfides that are located within the Derhib–Abu Gurdi mineral district (Fig 6.16). The *Egat* occurrence is a talc mine where the sulfide mineralization occurs as pockets in the lower levels of the mine. Talc is developed after metarhyolite along a megashear zone (~300 m long and 4–10 m wide) trending east/west and dipping 70° toward the south. Malachite-rich gossans cover is well developed along the shear zone. Due to its small-scale and low-grade mineralization, no further detailed studies have been conducted on the sulfide mineralization in the Egat area. The *Um Selimat* talc mine is located ~2 km to the northwest of the Derhib mine. Like the other talc mines in the area, talc is developed along the shear zones extending >1 km intersecting sheared and brecciated metarhyolite. In this megashear, isolated lenses of talc, carbonates and tremolite are encountered (Botros 2003), where discontinuous patches of primary sulfides and malachite are hosted in talc. Another base-metal sulfide mineralization in the area is the *El Atshan* prospect, which is also hosted in talc. It is located to the east of the Um Samiuki prospect, ~18 km west of the Red Sea coast (Fig 6.16). This prospect is one of the most productive high-grade talc ore in Egypt (Botros 2003). The talc deposit develops in a sequence of volcanic and volcaniclastic rocks of basaltic to rhyolitic composition. Talc ore develops along a major alteration zone cutting through basalt and rhyolite and extends for ~500 m in an east/west orientation. Talc is commonly associated with tremolite, chlorite, and quartz. Sulfide mineralization found as massive pockets in the deeper levels of the mine and are represented by malachite in the surface, whereas the hypogene sulfide mineralogy is dominated by chalcopyrite, sphalerite, and galena, which are mostly similar to the Derhib and Abu Gurdi prospects. **6.5 Volcano–Sedimentary Mineral Deposits in Sudan**

Volcano–sedimentary mineral deposits in Sudan are mainly represented by VMS deposits, which are located mainly in the Ariab mineral district of northeastern Sudan. The mining operations in the Ariab district is located in a remote area within the Red Sea State of Sudan, ~450 km northeast of Khartoum and ~200 km west of Port Sudan (Fig 6.24). The area is known variously as the *Hassai project,* the *Hassai* *region*, or the *Ariab mining district*. The Ariab mining district as a whole covers a surface area of ~20,000 km2. VMS deposits containing significant amounts of Cu, Zn, and Au were discovered in the late 1970s by the joint teams of the Geological and Mineral Resources Department (GMRD) of the Ministry of Energy and Mining of Sudan (now named the Geological Research Authority of the Sudan (GRAS)) with the BRGM of France. Despite the low interest in the VMS polymetallic deposits due to low base-metal prices, some drilling of these deposits was carried out as part of the definition of the oxide deposits to adequately define the limit of the resources close to the water table. In addition, several of the pits mined for Au were not closed, in anticipation of future mining of either the gold-and-sulfide bearing oxide sulfate material, or silica/barite rocks (SBR) or the VMS exposed at the bottom of the pits. With the increase in base-metal prices, the VMS deposits are now valuable targets.

*Historically*, the French and Sudanese teams conducted several exploration programs during the period from 1977 through 1981 for various metals (including W, Pb, Zn, Cu, Ag, Au, and Cr, among others) over five large areas in Sudan within the framework of a cooperation agreement (La Mancha Resources Inc. Technical Report 2009). One such exploration program focused on 17 gossans areas in the central part of the Red Sea Hills (in the Ariab–Arbaat area). These gossans are the weathering products of VMS deposits found at depth. The Au in most of the Ariab mining district is associated with these gossans. Exploration work covered most of the gossans in the Ariab district from 1981 to 1984. Initial work focused on the polymetallic potential of the underlying sulfide mineralization. In 1983, however, the discovery of noteworthy Au concentrations in SBR associated with the gossans at Hassai shifted the interest towards Au. Exploration efforts were then concentrated on the Ariab district from 1984 to 1987. Major trenching work was carried out on all known gossans in the region, including Hadal Awatib southwest, Hadal Awatib east, Talaiderut, Oderuk, Baderuk, and Adassedakh (Fig 6.24). All of these occurrences were eventually classified as Au deposits. In February 1985, sufficient data were collected at Hassai from surface trenching, percussion drilling, core logging, and pits to justify the installation of a pilot plant. In March 1987, the first Au production was started at Hassai (La Mancha Resources Inc. Technical Report 2009). In eight occurrences of these deposits (Adassedakh, Baderuk, Hadal Awatib west and east, Hassai south and north, Oderuk, and Talaiderut), Au is found to be associated with SBR and ferruginous gossans, which represent the near-surface expressions of underlying primary VMS mineralization. The mine production of the above-mentioned deposits began in 1991 and has yielded >2.127 Moz of Au to date. Some deposits (Adassedakh, Baderuk, Baderuk north, Dim Dim 4, Dim Dim 5, Hadal Awatib east, Hadal Awatib west, Hadal Awatib north, Oderuk, and Talaiderut Oderuk west) are almost exhausted; however, the Hassai north and Umashar deposits are still being mined. At present, Au from the oxidized part of VMS deposits is nearly depleted, and the existing pits are floored by massive sulfides. The location of the oxide deposits on surface exposures is an important guide to exploration; whenever Au grades are high in oxidized horizon, it is likely that high-Au grades will also be present in the primary sulfide ores. Geologically, the ANS rocks of the Red Sea Hills of Sudan are formed from the accretion of island arcs and back arcs onto the Nile Craton to the east (Deschamps and Lescuyer 2002). The two volcano–sedimentary series, the Ariab–Arbaat–Tokar to the south (Fig 6.25) and the Onib–Nafardeib to the north, display the same general geological history. Both of them have (1) a lower stratigraphic section of basaltic oceanic crust overlain by arc bimodal volcanic and siliciclastic rocks, (2) transpressional deformation that occurred during arc accretion and which produced high strain zones that bound and transgress arc subterranes, (3) predominantly greenschist facies metamorphism, and (4) syn- to late-tectonic magmatism. The granitoid–greenstone terrane of the Nubian shield is well endowed with VMS and vein Au deposits. In addition to those of the Ariab mining district in Sudan, there are three VMS deposits in the *Eyob district*, and six VMS deposits in the *Hamissana district*, but very little information is available about these VMS localities except those of the Ariab district. In addition to the above-mentioned VMS deposits in Sudan, there are four VMS deposits in the Bisha district, western Eritrea (Bisha, Bisha NW, Harena, Hambok); and three VMS deposits in the Asmara district of eastern Eritrea (Emba Derho, Adi Nefas, and Debarwa) (Barrie et al 2007), which will be discussed in the next parts of this chapter.

The whole Ariab district is underlain by transitional tholeiitic to calc-alkalic volcanic rocks and fine-grained siliciclastic rocks that stratigraphically overlie and are cut by syn- to post-tectonic mafic to felsic intrusions (Abu Fatima 2006). Regarding the mineralization age, the Pb isotope data for eight mineral separates (five galena, one cerussite, one anglesite, and one altaite) from seven deposits and one stratiform barite occurrence yield a model regression age of 702 ± 15 Ma (Barrie 2008). In general, the host rocks of VMS deposits of the Ariab mining district comprise bimodal volcanic, volcaniclastic and siliciclastic rocks, and late- to post-tectonic granites. Most of the VMS deposits occur within specific stratigraphic units, commonly associated with altered felsic tuffs. Following is a more detailed description of the most common VMS deposits in the Ariab mining district including the hypogene massive sulfides at depth as well as the supergene-oxidized zones.

***6.5.1 Oxidized surface zones (gossans)***

The oxidized surface exposures that underlain by the hypogene VMS deposits are rich in Fe and Mn oxides, oxyhydroxides, and quartz–kaolinite–barite Au deposits, which represent the main type of Au mineralization in the Ariab mining district. The area as a whole is characterized by Au enrichment in gossans and SBR, both of which are the weathering products of underlying polymetallic VMS deposits. The massive sulfide ores are volcanogenic in nature and represent an essential part from the Ariab Proterozoic greenstone belt. More specifically, most Au-rich VMS deposits are found within Unit D, the upper member of the differentiated felsic volcanic sequence of the Ariab volcanic series (Abu Fatima 2006). The typical surficial oxide–sulfate Au-bearing deposit in the Ariab area is shown in the diagrammatic representation (Figure 6.26), where >2 Moz of Au have been exploited since the beginning of mining activities in 1992. The hypogene VMS mineralization is described in more detail in the next section. The surface oxide–sulfate Au-bearing deposit represents the main source of ore at the Hassai deposit since mining commenced. However, only small resources of this deposit type remain and some of these are currently being mined. Other lesser important oxide–sulfate Au-bearing deposits require additional exploration. ***6.5.2 Hypogene Cu-Zn-Au-Ag volcanogenic massive sulfide deposits***  In general, as berifly mentiond earlier in this chapter, VMS deposits can be classified into five categories based on the host rock composition, from the most primitive to the most evolved in a chemical sense, they are (Barrie and Hannington 1999): mafic, bimodal mafic, mafic siliciclastic, bimodal felsic, and bimodal siliciclastic. The VMS deposits of the Ariab mining district are classified as bimodal-siliciclastic, similar to many of the large deposits in the Iberian pyrite belt, and to the nearby Bisha VMS deposit in western Eritrea. It is important to notice that the Ariab VMS deposits are mostly comparable with other large VMS deposits globally, in terms of their large size, commonly Cu-rich deposits, and their layered, relatively Zn-rich upward zoning. Furthermore, these large VMS deposits are relatively barren in pyritic zone in the central-middle mineralized zone. Most of the VMS mineralization in the Ariab mining district occurs as tabular bodies that vary from 0.3 to >25 m thick. In the case of Hadal Awatib, the VMS mineralization has been traced >2,500 m along strike. Sulfides are typically massive, fine-grained, layered, and locally brecciated, containing mainly pyrite, sphalerite, and chalcopyrite, with lesser amounts of pyrrohotite, galena, tetrahedrite–freibergite, and arsenopyrite. The identified hydrothermal alteration in the host rocks include proximal silicification and more distal chloritization, sericitization, and, in places, carbonitization (Abu Fatima 2006). The hypogene massive sulfides of the Ariab mining district are mainly pyrite-rich and are locally enrichin Cu and Zn in the form of chalcopyrite and sphalerite. The Pb content is characteristically very low; the Au content ranges 0.3–1.5 g/t. In addition, the high Zn values recently obtained (La Mancha Resources Inc. 2009) at the deposit of Onur is of particular significance in the Ariab district, where the ore grade reached up to 15.2 and 1.3 wt% for Zn and Cu, respectively, and 0.3 and 20 g/t for Au and Ag, respectively. In the following section, the exposed and easily accessible well-known Au-rich VMS occurrences of the Ariab mineral district will be summarized. ***Hassai South***: The Hassai south VMS deposit is located near the center of the Ariab mining district (Figs. 6.24, 6.25). It is a single large lens that has an extension of ~1000 m along strike, mining extended to a vertical depth of ~100 m, and the oxide zone ranging 4–35 m in thickness. Beneath the oxide-Au zone, ~42.1 Mt of Cu–Zn–Au (+Ag) massive sulfide has been estimated to a depth of 500 m (La Mancha Resources Inc. 2009). The geophysical signature, however, shows an up to 800 m in depth extension trending 60° toward the south. Although the Hassai VMS deposit is not thebiggest lens in the area, it is considered to be one of the main targets in the Ariab mining district. The Hassai VMS deposit is hosted by chloritic volcaniclastic and siliciclastic rocks (chlorite–quartz ± sericite ± carbonate ± iron oxide ± pyrite ± epidote ± incipient garnet) that have foliated and are transformed into phyllite and schist (Fig 6.27a). Minor lapilli tuffs are also present, as well as offsets of thin diorite dykes exposed in the pit walls mark minor cross-faults oriented north/south with small displacements of 10 cm to 1 m (Barrie et al 2016). The primary sulfide ore lies at a depth below the open-pit mine of the oxidized surface zone (Fig 6.28a) and contains significant Cu and Au grade, but mostly low Zn and Ag content. The mineralogy of the Hassai south VMS–oxide–Au system has been previously well-studied (Barrie and Kjarsgaard 2010), and numerous ore and gangue minerals have been identified. The ore minerals in the oxide-Au zone and in the SBR zone have native Au, electrum, anglesite, cerrusite, smithsonite, calaverite, petzite, tellurides of Pb, Ag, Bi, chalcocite, tenorite, malachite, azurite chrysocolla, and native Cu. Gangue minerals in the oxide-Au zone include kaolinite, gypsum, anhydrite, barite, jarosite, chalcedony, Fe-Ti oxides, epidote, chlorite, and sericite. In the hypogene and supergene massive sulfide ores, there are many ore minerals, including pyrite, chalcopyrite, sphalerite, marcasite, galena, clausthalite, tetrahedrite, tennantite, friebergite, arsenopyrite, polybasite, anglesite, altaite, tetradymite, tellurobismuthite, hessite, petzite, calaverite, electrum, cobaltite, magnetite, pyrrhotite, molybdenite, bismuthinite, mackinawite, bornite, covellite, digenite, cubanite, enargite, and several others (Barrie et al 2016). Furthermore, there are numerous significant stockpiles and Au-bearing tailings in the mining area. As of 2012, the total resources (measured, indicated, and inferred for oxide-Au and tailings in the Ariab district) were 1.80 Moz Au at an average grade of 2.58 g/t Au (Bosc et al 2012). ***Hadal Awatib***: The Hadal Awatib deposits are the largest VMS deposits in the Ariab Mining District. The Hadal Awatib area is located only 13 km east/northeast of the Hassai camp (Figs. 6.24, 6.25). The Hadal Awatib VMS deposit has an extension ~ 3.1 km along strike, folded and faulted where the important part remains unexplored. The width of mineralization zone is more than 100 m, and at least 500 m depth extension (La Mancha Resources Inc. 2009). The geophysical signature, however, shows that the deposit is up to 800 m depth extension trending mostly vertical or 80° southward. The Hadal Awatib deposit can be divided into 3 sectors (Fig 6.27b): (1) Hadal Awatib East, comprises the AB, CD open-pits and the Link. The outline of outcropping SBR and/or massive sulfide ore of the Hadal Awatib East is shown in red-dotted line (Fig 6.28b, c). (2) Hadal Awatib West with a single open-pit (Fig 6.28d). The Hadal Awatib West is one of the richest exploited (13.7g/t Au) and suggests that the sulfides below may be equally Au rich. (3) Hadal Awatib North, with the north open-pit, the Pipe and the Junction Au deposit (Fig 6.27b). About 1 Moz of Au have been exploited since the commencement of mining of the oxidized part of Hadal Awatib, with the highest grades recorded in the whole area (1,305 kt grading 13.7 g/t Au for 574 koz produced) so far (La Mancha Resources Inc. 2009; Barrie et al. 2016). Based on assays from historical drill holes on the Hadal Awatib East VMS lens, Au may have a lower average grade of about 1.1 g/t Au in comparison to that of Hassai deposits at 1.5 g/t Au. The average Cu content is about 0.9 wt.%, and the average Zn and Ag contents are higher than that of the Hassai deposit. In terms of the host rocks and size of the deposit, the Hadal Awatib VMS-–oxide–Au system is classified as a bimodal-siliciclastic subtype of VMS deposit (Barrie et al 2016). It is considered to be among the most extensive VMS deposits in the world, similar to the Kidd Creek, Ontario deposit, with a total length of 3.1 km and ~1 km depth, and Neves Corvo, being 3.45 km along strike (Rosa et al 2008). The Hadal Awatib VMS–oxide-Au deposits comprise a series of seven open-pit mines developed on a single, giant VMS system (Fig 6.27b). The host rocks include footwall-silicified and -sericitized, massive rhyolite and rhyolite breccia (C2 rhyolite); chloritized basalt–andesite flows, tuffs, and agglomerates; and hanging-wall felsic tuff, intermediate-to-felsic volcaniclastic rocks, and fine-grained siliciclastic rocks (Fig 6.27b). The whole package of VMS deposit and its host rocks have been folded along west-northwest/east-southeast-trending with the hanging-wall rocks extending to the north. The chloritic footwall rocks form the core of the principal west-northwest/east-southeast anticline; massive sulfide zones generally dip 65°– 90° to the north. The Hadal Awatib VMS deposit comprises three horizontally stratified zones (Barrie et al 2016): (1) surface oxide-Au zone ranging 80–120 m in depth, (2) supergene Cu-rich zone ranging 100–130 m in depth, and (3) a hypogene (unoxidized) massive-sulfide zone underneath. The massive and semimassive sulfides range in thickness from 10 to 100 m and ­­are mainly associated with chloritic tuffaceous rocks that commonly have stringer pyrite–chalcopyrite mineralization. The hypogene sulfide minerals are, arranged in decreasing order of abundance, pyrite, chalcopyrite, and Fe-poor sphalerite, with minor galena, tennantite, hessite, cobaltite, and electrum. The supergene sulfides comprise covellite and chalcocite, with lesser amounts of pyrite and chalcopyrite. The subhorizontal contacts between the ore types are transitional on a scale of meters to tens of meters, with the oxidized ore commonly occurring along fractures and fault planes that cut the supergene sulfide. In addition, the primary massive sulfide ore shows a stratified Zn-Cu zonation.

The *Hadayamet* deposit is located ~25 km toe east of Hassai camp (Figs. 6.24, 6.25). The Hadayamet VMS deposit has a horizontal extension of about ~300–400 m along strike, is at least 30–40 m in width, with a deep rooting of almost vertical dipping (La Mancha Resources Inc. 2009). This target was drilled in 2006, where two drill holes were carried out: (1) the ADAM 212 drill hole intersected 71 m of sulfide, dominantly pyrite, containing 1.4 wt% Cu, 2.4 wt% Zn, and 0.4 g/t Au; it includes 20 m, grading at 1.67 wt% Cu. The apparent thickness is ~71 m, since the drill hole intersects the north/south structure obliquely, and the real width may be in the range of 30–50 m. (2) The ADAM 213 drill hole, located 1 further to the east, crossing >60 m of pyrite stockwork, including 30 m of massive sulfide averaging 0.8 wt% Cu, 2.2 wt% Zn, and 0.3 g/t Au. The VMS deposit of Hadayamet is potentially of economic interest, but owing to the topography of the site, the deep part of this target is not easy to study and the structure of the deposit is not yet known in detail. The possible enriched zone is easily accessible (Fig 6.29a) and has not been drilled so far. As at the Hadal Awatib AB pit, a small amount of enriched material may be easily recovered by deepening the open pit.

***Taladeirut*** The Taladeirut VMS deposit is located only ~5 km northwest from the Hassai camp (Figs. 6.24, 6.25). The Taladeirut deposit has an extension ~300–400 m along strike (Fig 6.29b, black arrow), which is at least 15 m in width, and dipping at 80° eastward with unknown depth extension. Some historical drill holes show interesting sulfide mineralization demonstrating the potential of this target grading at 5.1 wt% Cu at 100 m. This intersection demonstrates the likelihood of supergene-enriched material in the upper part of the deposit.

***Oderuk*** The Oderuk VMS deposit is located only ~5 km southwest from the Hassai camp (Figs. 6.24, 6.25). The Oderuk deposit has an extension ~400–500 m along strike (Fig 6.29c), which is at least 15 m in width, and dipping at 80° eastward with unknown depth extension, but suggesting a deep-seated primary sulfide source. A drill hole intersection (ODE D058) at 6 m depth grading at 2.81 wt% Cu. This intersection demonstrates the likelihood of a supergene enrichment zone in the upper part of the deposit.

***Adassedakh*** The Adassedakh VMS deposit is a small open-pit mine located between Taladeirut and Oderuk (Figs. 6.24, 6.25) and was one of the richest oxides pits mined in the Ariab area. The VMS of Adassedakh site outcrops on floor of the pit (Fig 6.29d). The estimated length of the Adassedakh deposit ranges 100–150 m along strike (Fig 6.29d), is at least 15 m in width, and dipping at 80° eastward with unknown depth extension, but suggested a deep-seated primary sulfide source (La Mancha Resources Inc. 2009). The historical drill holes show some very interesting intersections in the upper part, where the drill hole ADS 26 at 5 m gave an average grade of 6.3 wt% Cu and 1.9 g/t Au. The drill hole ADS 24 at 15.5 m grades at 2.44 wt% Cu, 5.47 wt% Zn, and 2.27 g/t Au, and the drill hole ADS 25 at 15.2 m gaves an average grade of 3.25 wt% Cu, and 2.66 g/t Au. These three drill holes are interesting not only for their volumes of primary sulfide ore but mainly for the high likelihood of further enriched resources in the upper part immediately below the floor of the pit encountered locally in some drill holes.

***Onur*** Unlike other VMS deposits outlined above, the Onur deposit has not yet been exploited. However, a resource estimate was completed based on recent two drill holes that intercepted massive sulfides, which are significant because of the high Zn content. The drill hole ONU D015 at 93 m gave an average grade of15.12 wt% Zn,1.3 wt% Cu and 0.3g/t Au. The drill hole ONU D 008 at 89 m gave an average grade of 3.7 wt% Zn. Such high Zn grades are not frequent in the area and it was in fact the richest intersection ever reported in the Ariab area (La Mancha Resources Inc. 2009). The oxidized part of the Onur deposit has not been exploited so far. Resources (cyanidable Au and other indicated resources per NI43-101) have been evaluated at ~310,000 t of ore grading at 3.6 g/t = 210 kg Au.

***Other occurrences*** There are lesser or inconsistent zones of massive sulfide mineralization present below the several small SBR occurrences. Some of them contain interesting concentrations of base metals, mainly in the upper enriched supergene zone. These include *Medadip*, which is likely an extension of Hadal Awatib, *Dim-Dim*, *Abderrahman*, *Megzoub*, *Umashar*, and *Baderuk* (Figs. 6.24, 6.25). There is no more available information about these occurrences so far. **6.6 Volcano–Sedimentary Mineral Deposits in Eritrea**

The volcano–sedimentary mineral deposits in Eritrea are almost found in the western and eastern Nakfa terrane, which are represented mainly by VMS deposits that hosted by volcano–sedimentary rocks of a Neoproterozoic age. Eritrea has now emerged as having demonstrated potential to host significant VMS deposits after the discovery of Bisha, Harena, and Hambok VMS deposits in the western lowlands and the Koken deposit in the northwestern lowland. The Zara shear-hosted Au deposit and recent findings in Harab Suit and Seroa prospects also increase the potentiality of the country. Moreover, more find such as the Embaderho VMS deposit, in the VMS belt of the Asmara/Debarwa area, which includes Debarwa, Adi Nefas and Ketina and many other small prospects, has made the country to be known for this type of mineralization. Thus, nowadays there are so many exploration companies working in Eritrea having different concessions especially in the Neoproterozoic basement rocks that are concentrated in the western, northwestern, and eastern sides of the country (Fig 6.30). As stated in Chap. 2 of this book, Neoproterozoic basement rocks in Eritrea have been divided into four terranes on the basis of their stratigraphic and structural characteristics (Fig 6.31), including (Barrie et al 2007): (1) the Barka terrane to the far west (consisting mainly of metasedimentary and mafic gneisses), (2) the Hagar terrane to the north (principally mafic metavolcanic rocks, including ophiolite-like assemblages), (3) the Nakfa terrane, the largest of the four terranes (predominantly granitoid–greenstone belts and syn- to post-tectonic granitoid rocks), and (4) the Arig terrane to the east (composed mainly of granitoid and metasedimentary rocks). Almost all of the volcanic–sedimentary rocks of the Nakfa terrane strike in a north/south direction, and there is a significant volume of syn- to post-tectonic granite between the western and eastern halves. There are two main VMS mineralization districts in Eritrea: the *Bisha VMS district* (*Bisha*, *Bisha northwest*, *Harena*, and *Hambok*), and the *Asmara VMS district* (*Adi Nefas*, *Debarwa*, *Emba Derho*, and *Adi Rossi*) (Fig 6.31). The two VMS districts of Eritrea are entirely hosted by the western and eastern Nakfa terrane Proterozoic rocks, respectively. There are several indicators for the presence of massive sulfide mineralization in many areas of Eritrea including the north/northwest- to north/northeast-trending belt of gossans cover, exhalative cherts, and altered felsic rocks. The ore minerals of these VMS deposits are represented mainly by chalcocite and pyrite with minor amounts of sphalerite, chalcopyrite, and bornite. In Eritrea, there are two major belts of VMS deposit with Au and base-metal mineralization; one of them, the Asmara mineral district, passes through Asmara and includes Debarwa, Adi Nefas, Embaderho, and many other localities. It is roughly within a 50-km-wide belt over ~250 km along strike length, extending for >50 km north of Asmara and up to the Eritrean border to the south (Fig 6.32). The second major VMS belt, the Bisha mineral district, includes the Bisha and Harena VMS deposits in the western lowlands (Fig 6.32), has a world-class VMS deposit, and is under exploration for more deposits. There is a third belt of VMS indications farther north of Kerkebet, in Harabuit, and possibly in surrounding areas. There is a belt of Cu mineralization in Raba–Semait and sulfide-rich gossanous rock in Mt Tullului (Bedeho) in the Sahel, northern Eritrea, and in the Mt Seccar and Sheib areas in the eastern lowlands ([Mineral Potential of Eritrea 2012](https://www.eriswiss.com/mineral-potential-of-eritrea/)). Following are detailed descriptions of these VMS deposits in Eritrea, starting with the Bisha VMS mineral district and followed by the Asmara VMS district.

***6.6.1 Bisha Volcanogenic Massive Sulfide District***

The Bisha VMS mineralization is located in the western Nakfa terrane of western Eritrea (Figs. 6.30-6.32); it was discovered in 2003 after an initial drilling program intersected a substantial oxide-Au zone above massive sulfide mineralization. Further mineralization occurrences have been discovered at Bisha northwest, Harena, Hambok, and Yakob Dewar. Considering global ore resources identified at Bisha (39.0 Mt; Barrie et al 2007) and Hambok (40.7 Mt; Giroux and Barrie 2009), and particularly the high precious- and base-metal grades at Bisha, the economic viability of the district was found to be favorable, enabling it to be fast-tracked into production, which commenced in 2011 (Barrie et al 2016).

Geologically, the Bisha mine area is mostly covered by Neoproterozoic volcanic and sedimentary rocks of the Augaro–Adobha belt (Fig 6.31), which are metamorphosed at upper green schist to lower amphibolite facies. The lithology of the Bisha region is dominated by the Bisha gabbroic complex (BGC), a large (275 km2), a partly layered mafic intrusion consisting of cumulate gabbroic rocks, with lesser amount of gabbro–norite, pyroxenite, and ferroan gabbro containing up to 8 vol% Fe-Ti oxides (Fig 6.33) (Giroux and Ba 2009; Barrie et al 2016). The BGC is overlain by a sequence of layered volcano–sedimentary units comprising, from bottom to top, a lower sedimentary sequence of carbonates and fine-grained siliciclastic rocks, including siliceous iron formation; a volcanic sequence of mafic to felsic lapilli and ash crystal lapilli tuffs with intercalated minor mafic flows and hyaloclastite; and an uppermost sequence of fine-grained volcaniclastic and siliciclastic rocks (Fig 6.33). Rhyolite is the predominant volcanic rock type in the Bisha district, which is mostly tuffs, with minor blocky flows and agglomerates. Dacites comprise ~5% of the volcanic strata; in addition to other volcanic rocks including tholeiitic basalts. Neoproterozoic granite–syenite intrusions and minor mafic dykes/sills, and Cenozoic felsic and mafic dykes, are all cut from the older layered volcano–sedimentary rocks. Rhyolite porphyry and various types of granitic rocks are also found as quartz and feldspar phyric rhyolite/granite dykes, which is texturally and chemically distinct from the other felsic strata (NI 43-101 Technical Report Bisha Mine, SRK Consulting 2017). The footwall of VMS deposits at Bisha mineral district (including Bisha main, Harena, Bisha northwest, Hambok, and Asheli), are all hosted by bimodal mafic and felsic volcanic rocks, whereas the hanging wall is mainly felsic rocks (Fig 6.33). The footwall alteration is typically represented by strong quartz + chlorite alteration of tuffs, which may extend for tens of meters below massive sulfide rich zone. Below the footwall alteration zone, there is a thin, but variable (<3 m thick) zone of silicification and K-feldspar replacement (Chisholm et al 2003; Nevsun 2004). This zone is more variable in alteration intensity and thickness than the chlorite alteration zone, and, in some cases, is entirely absent. Hanging-wall alteration is typically represented by strong quartz + muscovite alteration of tuffs, which may extend for tens of meters above the massive sulfide rich zone. Carbonate, epidote, and albite alteration mineral assemblages are less common; they are sometimes weak and patchy, but in some other cases are intense and pervasive.

Following are brief descriptions of geology and mineralization of the principal VMS occurrences in the Bisha mineral district. The majority of this part is summarized from the SRK Consulting Report (NI 43-101 Technical Report Bisha Mine, SRK Consulting 2017).

***The Bisha main*** ***deposit*** The Bisha main VMS deposit comprises four massive sulfide lenses that extend ~1.2 km north/south trending along strike. The sulfide-rich lenses are variable in thicknesses that reach up to 70 m and extends to a depth of ~600 m below surface. The massive sulfide bodies comprise the southern and northern zones (Fig 6.34). The main part of mineralization in the southern zone strikes approximately north/south and dips steeply to the west, with strike and dip lengths of about ~600 m and 500 m, respectively. The main part of the mineralization in the northern zone also strikes approximately north/south and dips steeply to the west, with strike and dip lengths of ~500 m and 100 m, respectively.

The host rocks of the Bisha main deposit are strongly foliated rhyolite and rhyolite breccia interleaved with dark grey, thinly bedded mudstone and polymictic breccia. The environment of rhyolite association is typically of thick submarine domal lavas that have coherent cores and quench-fragmented margins. The footwall and hanging-wall rocks of the deposit are strongly altered. The massive sulfide intervals have gradational contacts with sulfide stringer both above and below. The Bisha main VMS deposit has been deeply weathered, where the weathering profile is complex and locally depends on the lithology and nature of the groundwater that is generated from oxidation of the massive sulfides. Weathering zones have of the Bisha main VMS deposits can be divided into six facies (Fig 6.35) including, from top to bottom: (1) surface gossans, (2) a near-surface oxide zone, (3) acid-leached zone (also known as an acid-soap zone), (4) a poorly consolidated pyrite-rich sand zone, (5) a supergene Cu-enriched zone, and (6) primary hypogene ore.

The zone of gossans cover is compositionally variable from highly siliceous-–ferruginous to massive goethite–hematite–jarosite (Fig 6.35). The near-surface oxide zone (saprolite) is up to 50 m deep and is composed of hematite, quartz, and clays; in places, the original rock textures are preserved. The saprolite zone is enriched in Au, Pb, Ba, and Mo, but depleted in Cu, Zn, Cd, and Co. The acid-leached (soap) zone is a white, light-yellow, or light-brown zone, and consists of clay, quartz, barite, galena, and pyrite and sometimes anglesite. Both the acid-leached and soap zones are depleted in Cu, Zn, Cd, Co, Fe, and Mn, but strongly enriched in Au, Ag, Pb, and Ba. They are poorly consolidated and their drill recoveries are generally poor (Fig 6.35). The supergene zone is up to 20 m thick, and has elevated Cu and Ba contents, but depleted in Zn, Cd, and Mn contents. Sphalerite and chalcopyrite in the supergene zone are replaced by chalcocite, covellite, digenite, and native Cu (Ashley 2013). The pyrite sand zone lies directly above the supergene zone and consists of unconsolidated recrystallized pyrite grains, where almost all of the Cu content has been remobilized from and redeposited in the supergene zone. In addition, some remobilization of Cu and Ba from the primary zone upwards into the supergene zone has occurred along steeply dipping basement structures. The primary (hypogene) zone represents the original massive sulfide deposit, where the mineralogy is essentially composed of pyrite and sphalerite, with minor chalcopyrite, covellite, pyrrhotite, and galena.

The estimated mineral ore resources and ore reserves at Bishmain as of 31 December 2016 follow (SRK Consulting NI 43-101 Technical Report 2017): the measured + indicated ore resources were ~34.91 Mt ore, with average grades of 0.6 g/t Au, 33 g/t Ag, 1.02 wt% Cu, and 4.18 wt% Zn. The inferred ore resources are ~33.97 Mt ore, with average grades of 0.8 g/t Au, 25 g/t Ag, 1.01 wt% Cu, and 4.74 wt% Zn. The proved + probable ore reserves of supergene sulfides were ~12 Mt ore, with average grades of 0.71 g/t Au, 17 g/t Ag, and 2.57 wt% Cu. The estimated ore reserves of hypogene sulfides were ~7.351 Mt ore, grading at 0.74 g/t Au, 50 g/t Ag, 1.14 wt% Cu, and 6.98 wt% Zn.

***The Harena*** ***volcanogenic massive sulfide*** ***deposit*** The Harena VMS deposit is located ~10 km to the southwest of the Bisha main deposit. The massive sulfide at Harena is a tabular body that is up to 60 m thick, extends ~900 m along strike, and dips ~60° to the northwest. The host rocks of the Harena deposit is a Neoproterozoic bimodal unit of basalts and rhyolite/dacite volcanic rocks. The stratigraphic succession at the Harena mine site comprises, from the bottom upwards: a lower footwall unit of rhyolite and dacite tuffs with an intense proximal chlorite–sericite–sillimanite alteration in the immediate footwall of the massive sulfide, and a distal silica–sericite ± biotite alteration; at least two stratigraphically distinct massive sulfide units with associated stringer mineralization on the southeastern or stratigraphically lower side; a hanging-wall unit of intercalated felsic rocks and fine- to medium-grained plagioclase–phyric mafic rocks—there is a distinctive felsic quartz breccia unit along the length of the mineralization, and the mafic rocks have a moderate silica-chlorite ± biotite alteration; and an upper sedimentary sequence of graphitic mudstone and greywacke.

The hypogene ore mainly comprises massive sulfide mineralization with subordinate semimassive sulfide within volcanic lithologies, which range in thickness from 0.4 to 100 m, averaging 19.8 m. The primary ore consists of fine- to medium-grained subhedral-to-anhedral pyrite with interstitial and/or enriched layers of sphalerite and chalcopyrite. The massive sulfide ore have a lensoidal to tabular shape, where the thicker parts of the ore elongated and plunging to the southwest. The primary massive sulfide units show typical VMS zonations from a Cu-Au-Ag rich base to a Zn-Ba rich top. The stringer or stockwork mineralization below the massive sulfide recorded in about half the drillholes; where present it is up to 58 m thick, with an average thickness of 6.6 m. The total mineralized package (massive sulfide + stringer) averages ~23 m thick. The weathering processes have produced a surface oxide layer of ~45–50 m in thickness with associated gossans cover overlaying a very thin secondary supergene zone, which grades downward into a primary massive sulfide. The oxide layerhas less Cu and Zn and greater Au and Ag than the primary mineralization. A 10-m-thick Quaternary alluvial sediment and soil almost completely covers the entire sequence at Harena site.

The estimated mineral resources at Harema as of 31 December 2016 were (SRK Consulting NI 43-101 Technical Report 2017): indicated mineral resources of the open pit are ~3.95 Mt, with average grades of 0.6 g/t Au, 28 g/t Ag, 0.87 wt% Cu, and 3.16 wt% Zn. The estimated inferred mineral resourceof open-pit oxide are ~0.12 Mt ore, with average grades of 2 g/t Au and 20 g/t Ag, while the inferred mineral resources of open-pit sulfide are ~1.92 Mt ore, with average grades 0.6 g/t Au, 28 g/t Ag, 0.87 wt% Cu, and 2.19 wt% Zn. The inferred mineral resources at underground sulfide deposits are ~23.02 Mt ore, grading at 0.8 g/t Au, 30 g/t Ag, 0.93 wt% Cu, and 4.96 wt% Zn.

***Bisha Northwest*** The Bisha northwest deposit is located to the northwest of the Bisha main site (Fig 6.36a), where it comprises a series of polymetallic massive sulfide lodes that have been defined over a strike length of ~800 m (Fig 6.36b), striking northeast, and dipping from 70° northwest to an almost subvertical direction. The deposit is thickest at the center, tapering to widths of less than 8 m at its strike limits; in cross section, it has a wedge shape that narrows down-dip. The thickness of the central portion of the deposit is >85 m wide. Drilling for resource estimation has effectively defined the deposit to a maximum of 250 m below surface, but the mineralized stringer vein system still exists at depths of >350 m below the surface. The Bisha northwest deposit is subdivided into three domains. (1) The northern main lode is the largest domain, being a Cu-rich massive- and semimassive sulfide ore that increases in Zn content northwards. (2) The southern lode is a Zn-rich, discontinuous massive- and semimassive sulfide body with a pyrite-dominated mineralization. (3) The eastern lode is a separate narrow VMS lode found on the footwall side of the northwest deposit. The eastern lode is poorly drill-defined, but carries appreciable Cu and Zn base-metal grades. It is still at its earliest stages of being defined and understood.

Similar to the Bisha main deposit, the Bisha northwest deposit has a Au-oxide cap and supergene Cu-rich zone. The oxide-Au cap is not as well-endowed as those in the Bisha main deposit in terms of Au, Ag, and Cu content, reflecting the overall lower grade of the underlying northwest primary mineralization. The oxide profile is still problematic due to core recovery problems during drilling, a problem also encountered across the Bisha main deposit. The unmined estimated mineral resources at Bisha northwest as of 31 December 2016 (SRK Consulting NI 43-101 Technical Ret 2017) follow: indicated mineral resources of the supergene zone were ~1.02 Mt ore, grading 0.2 g/t Au, 1/t and 1.47 wt% Cu. The indicated mineral resources of hypogene ore were ~2.53 Mt ore, grading at 0.3 g/t Au, 13 g/t Ag, 1.04 wt% Cu, and 1.08 wt% Zn. The inferred mineral resources of the oxide zone were ~0.50 Mt ore, with average grades of 3.7 g/t Au and 18 g/t Ag, while the inferred mineral resources of the supergene zone were ~0.10 Mt ore, grading at 3.7 g/t Au 19 g/t Ag, and 0.8 wt% Cu. The inferred mineral resources of the hypogene ore were 0.10 Mt ore, grading at 2.9 g/t Au, 15 g/t Ag, 0.9 wt% Cu, and 0.9 wt%.

***Hambok*** ***volcanogenic massive sulfide*** ***deposit*** The Hambok deposit lies within the Bisha VMS district in the western Nakfa terrane, and part of a sequence of Late Proterozoic mafic-to-felsic volcanic and sedimentary rocks including pelites, chert, and carbonate unit (Figs. 6.32, 6.33). One regionally extensive carbonate horizon that extends nearly the entire length of Eritrea passes east of the Hambok Bisha area through the Okreb Au mine area. This unit may correlate with a line of discontinuous carbonates on the western side of the Mogoraib River Exploration License (Fig. 6.33) between the volcanic sequence on the east and a turbidite siliciclastic sequence on the west. The Hambok deposit appears to occupy the eastern flank of a broad anticlinorium cored by basaltic rocks and ultramafic and granitic intrusions. The BGC, which as noted above is a major mafic intrusive complex, forms the core of a major regional anticline to the east of Bisha and Hambok, whereas a subordinate unnamed gabbro–diorite–pyroxenite intrusive complex forms the cores of an anticline between Hambok and Ashelli (Fig 6.33). The Ashelli and Mai Melih massive sulfide prospects appear to occupy the western flank of this anticlinorium. The top of the bimodal volcanic sequence appears to be marked by graphitic schists, chert and carbonate horizons, and pelitic sedimentary rocks. The Hambok VMS deposit is present within a sequence of chloritic, volcaniclastic rocks with lesser amounts of massive basaltic-to-andesitic lavas and felsic tuffs. Drilling to date shows that the sulfide body is a homoclinal lenticular body dipping steeply to the east; however, some structural complications may be present in the southern part of the body, where the dips are moderate. The Hambok VMS deposit comprises a primary Cu/Zn sulfide zone, forming the majority of the deposit, as well as a minor oxide-Au component. The primary massive sulfide mineralization is a single body with a faulted displacement at depth in the northeast of the deposit. The massive sulfide zones strike at ~15°, dipping steeply to the east, with overall strike and dip lengths of ~975 m and 400 m, respectively. The thickness of the massive sulfide ore varies from ~5.0 m up to 75 m. The mineralogy of massive sulfide ore has been found to contain pyrite, sphalerite, chalcopyrite, and magnetite as the major ore mineral constituents (Barrie 2007, Sanu internal memorandum). Minor and accessory ore minerals (0.5%–4%) are represented by galena, tennantite, digenite, and hematite. The main gangue minerals associated with the ore are quartz, sericite, Mg-chlorite, siderite, and feldspar. The Cu and Zn have a weak zonation throughout the Hambok deposit, with Cu increasing down-dip and to the west of the massive sulfide, whereas Zn has a tendency to be enriched up-dip and to the east. The best metal grades occur at the top, bottom, and edges of the thickest accumulation of sulfides, whereas the thick pyrite core of the massive sulfide mineralization is poorly mineralized. The preliminary estimated mineral resources at Hambok as of January 2009 were, at a 2 wt% Zn equivalent cutoff (Giroux and Barrie 2009): indicated mineral resources of ~10.7 Mt ore, with average grades of 0.2 g/t Au, 7.1 g/t Ag, 1.04 wt% Cu, and 2.21 wt% Zn. The inferred mineral resources were estimated to be ~15.9 Mt ore, grading at 0.2 g/t Au, 6.15 g/t Ag, 0.93 wt% Cu, and 1.77 wt% Zn. The estimated unmined mineral resources at Hambok as of 31 December 2016 (SRK Consulting NI 43-101 Technical Report 2017) were: indicated mineral resources of hypogene zone of ~6.86 Mt ore, grading at 0.2 g/t Au, 10 g/t Ag, 1.14 wt% Cu, and 1.86 wt% Zn. The inferred mineral resources of the oxide zone were ~20 Kt ore, grading at 1.57 g/t Au and 17 g/t Ag.

***Ashelli*** ***volcanogenic massive sulfide*** ***deposit*** The Ashelli VMS deposit is located ~10 km southwest of Hambok (Fig 6.33), hosted within a felsic volcanic sequence that was described in the Hambok site. Various lithologies outcrop in the area, with a general north/south strike and dipping steeply to the west. The lowest unit is composed of a series of mafic flows with strong carbonate and moderate chlorite alteration. This unit thickens to the south and tapers to the north, and is cut by several felsic and mafic dykes. It is overlain by a series of felsic flows, which have undergone moderate-to-strong sericite and chlorite alteration and are locally strongly foliated. This felsic suite includes a massive sulfide mineralization unit, a magnetite-rich siliceous chemical sedimentary unit, and an intermediate lava flows unit. The Ashelli deposit is a tabular, steeply north-plunging body that is ~400 m long, 100 m wide, and up to 30 m thick, composed of pyrite, sphalerite, and chalcopyrite. The top of the deposit is 60 m below surface. The host felsic suite is overlain by a siliceous chert horizon with associated thin marble beds followed by a thick sequence of finely laminated graphitic sediments and mudstone. This unit is strongly foliated and contains a graphitic horizon with a coarse boxwork texture after the oxidized pyrite (SRK Consulting 2017).

The estimated unmined mineral resources at Ashelli as at 31 December 2016 (SRK Consulting NI 43-101 Technical Report 2017) were: the inferred mineral resources of the low-grade ore were ~1.68 Mt ore, grading at 0.36 g/t Au, 28 g/t Ag, 1.9 wt% Cu, 5.2 wt% Zn, and 0.05 wt% Pb. The inferred mineral resources of the high-grade ore were ~0.72 Mt ore, with average grades of 0.39 g/t Au, 33 g/t Ag, 1.9 wt% Cu, 16.6 wt% Zn, and 0.14 wt% Pb. The total mineral resources were ~2.40 Mt ore, grading at 0.37 g/t Au, 30 g/t Ag, 1.9 wt% Cu, 8.6 wt% Zn, and 0.08 wt% Pb.

***6.6.2 Asmara volcanogenic massive sulfide district***

As mentioned earlier, the Nakfa terrain contains the Asmara greenstone belt VMS deposits (eastern Nakfa terrane) and the Bisha VMS deposit (western Nakfa terrane) (Figs. 6.30-6.32). The Asmara greenstone belt comprises several tectonostratigraphic blocks, including the Adi Neared block, the central steep belt, the Asmara syncline, and other blocks to the north. That part of the granitoid–greenstone belt in the vicinity of Asmara represents a moderately evolved belt typical of the granitoid–greenstone terrains of the ANS. The sequence is dominated by mafic-to-felsic flows and tuffs with a predominant calc-alkali affinity and lesser silisiclastic rocks, typical of moderately evolved island or continental arcs.

The *Asmara VMS district* of Cu, Zn, Ag, and Au deposits is located in close proximity to Asmara, the capital of Eritrea, within 15 km to the north-northwest and 30 km to the south-southwest (Figs. 6.31, 6.32). Individual VMS deposits and occurrences described following include *Debarwa*, *Emba Derho*, *Adi Nefas*, and *Kodatu*. The district also includes low-sulfidation epithermal gold deposits at *Gupo* and *Adi Rassi* in close proximity, accompanied by identical alteration and in the same host units, although these deposits are also described in the literature as orogenic deposits (e.g., Barrie *et al* 2016). Geology of the Asmara district (Fig 6.37) is generally east-facing, tightly folded approximately north-trending fold axes, generally dip to the east or east-southeast at 45º to 85º and are preserved at or below the lower greenschist facies. They consist primarily of a mafic–filsic bimodal suite of volcanic and derived volcaniclastic rocks overlain to the east by a metasedimentary sequence. The Neoproterozoic basement rocks are mostly covered by flat-lying Tertiary olivine basalts that are greater than 200 m in thickness. The basalts overlie a well-developed paleoweathering horizon along which locally thick laterite deposits have developed, and the underlying Neoproterozoic rocks are strongly saprolitized.

Three mineralized trends were described in the Asmara mineral district, all of them are trending north/northeast, these are (Barrie 2004): (1) the *Emba Derho trend* to the west of Asmara that includes the Dairo Paulos occurrence, the Woki Duba occurrence, and the Emba Derho deposit; (2) the *Debarwa–Adi Nefas trend* extends at least 25 km south and 5 km north of the capital and includes the Debarwa, Shiketi, Adi Lamza, Adi Nefas deposits, and the Adi Adieto occurrence; and (3) the *Adi Rassi–Kodato trend* to the east. The latter two trends are defined in part by a chert/exhalite unit whereas the Emba Derho trend becomes less-well delineated to the southwest where many of the metal occurrences are hosted within granitoids.***Emba Derho*** ***volcanogenic massive sulfide deposit*** The *Emba Derho* VMS deposit is located ~15 km north-northwest of Asmara (Fig 6.37) within Neoproterozoic metavolcanic and metasedimentary rocks that are cut by granitoid intrusions. The VMS deposit is exposed to the surface by a prominently outcropping gossans cover developed over an area of about 800 × 220 m, which is tightly folded with northwest-oriented fold axial planes and steeply dipping limbs. The gossans have been subjected to at least two phases of folding and has a W-shape, open to the northwest. These gossans have been known since at least the 1970s. They comprise oxidized and supergene acid-leached felsic tuffaceous rocks and flows, weathered massive-to-semimassive sulfides, and orange-brown weathering rhyolite dykes/sills 1–2 m in thickness. The gossans are surrounded by relatively poor exposure of typically well-foliated acid-leached, predominantly fine tuffaceous rocks of both mafic and felsic composition. These lithologies are cut by strongly weathered postdeformation granitic dykes of various compositions. The lithology of the footwall below the massive sulfide ores comprises blue quartz–phyric rhyolite flows, flow breccias, and associated felsic fragmental tuffaceous rocks that are locally altered to sericite–chlorite schists. These are overlain by stacked layers of massive-to-semimassive sulfides ranging in thickness from 5 to 40 m, separated by numerous tuffaceous and volcanic flow partings and one barite layer (e.g., Barrie 2004; Daoud and Greig 2007). All of these rock types are cut by various postdeformation felsic dykes, which are typically 1–5 m in thickness. The hanging-wall sequence is composed of pillow basalt and pillow breccia units that have been subjected to significant epidote–silica alteration. The altered mafic volcanic units just above the massive sulfides contain several manganiferous, siliceous chemical sedimentary units; a thin sill of altered and deformed coarse-grained pyroxenite occurs within the mafic volcanic flows. The entire sequence generally dips steeply to the north.

The Emba Derho VMS deposit has a typical zonation. (1) The *gossans/oxide zone* is a dense, dark red-brown gossans cover composed of hematite, limonite, goethite, and locally magnetite that was largely derived from surface weathering of massive sulfides. It occurs as discontinuous, commonly folded layers that may be up to several meters or more in thickness. Outside of the main gossans zone, there is a local centimeters–to–tens of centimeters scale of layers and veins, predominantly within acid-altered host rocks. It has also been locally remobilized to form so-called “ferricrete” caps with very delicate textures. Oxidation typically extends to the water table, which is ~ 20–30 m below the surface. (2) The *Cu-enriched supergene zone* occurs as fine-to-medium-grained, vuggy, locally sandy, massive pyrite with interstitial secondary Cu minerals such as covellite, digenite, and minor bornite. This zone is found at or below the water table. Zinc is depleted relative to the hypogene mineralization. (3) The *hypogene Cu-rich massive sulfide zone* is well-defined in the northern part of the deposit and comprises medium-to-coarse-grained massive pyrite and pyrrhotite with interstitial chalcopyrite and magnetite, with massive bands, stringers, and blebs of chalcopyrite. (4) The *hypogene Zn-rich massive sulfide zone* is well-developed in the southern and western parts of the deposit and comprises fine-to-medium-grained massive pyrite with sphalerite occurring as interstitial disseminations and as thin bands and laminae within the pyrite. Different types of sphalerite were recognized: Fe-rich, rusty-brown, high-temperature-phase, honey-yellow, and Fe-poor, whitish-grey, lower-temperature-phase sphalerite. (5) The *hypogene pyritic massive sulfide zone* is a massive sulfide ore that occurs immediately below the chert and silica-rich chemical sediments and mafic flows of the hanging-wall sequence, representing the stratigraphic top of the massive sulfide horizon. Sulfide minerals are mostly fine-to-medium-grained massive pyrite with fine-grained disseminated magnetite and very minor chalcopyrite and sphalerite.

The mineralization and host rocks are cut by at least five felsic intrusive phases, the most prominent of which is a suite of fine-to-medium-grained postkinematic leucocratic rocks, ranging from tonalite to granite in composition. These are interpreted to related to a high-level intrusion of similar composition exposed to the north of the deposit. Dykes generally parallel the northwest of the layered host sequence, although north-northeast trends are common in the northeastern part of the deposit. An earlier, much less voluminous suite of postkinematic diorite dykes is also mapped, generally trending to the north.

The premining feasibility study at Emba Derho as of May 2013 (Senior et al 2013) estimated measured + indicated mineral resources of the oxide-Au zone (0.5 g/t Au cutoff grade) at ~1.74 Mt ore, with average grades of 1.06 g/t Au, 4.3 g/t Ag, 0.07 wt% Cu, and 0.04 wt% Zn. The Cu-rich supergene ore (0.5% Cu cutoff grade) is estimated to be ~1.64 Mt ore, grading at 0.17 g/t Au, 12.2 g/t Ag, 0.94 wt% Cu, and 0.38 wt% Zn. The Cu-rich hypogene zone (0.3% Cu cutoff grade) was estimated to be ~49.8 Mt ore grading at 0.17 g/t Au, 7.7 g/t Ag, 0.83 wt% Cu, and 0.93 wt% Zn. The Zn-dominated hypogene zone (<0.3% Cu; >1% Zn cutoff grade) was estimated to be 16.8 Mt ore, with average grades of 0.31 g/t Au, 9.9 g/t Ag, 0.14 wt% Cu, and 2.80 wt% Zn. The total estimated tonnage of the Emba Derho deposit is ~70 Mt ore. The estimated inferred mineral resources of the Cu-rich hypogene zone (0.3% Cu cutoff grade) were ~13.28 Mt ore, with average grades of 0.25 g/t Au, 10 g/t Ag, 0.87 wt% Cu, and 0.89 wt% Zn. The estimated inferred mineral resources of the Zn-rich hypogene zone (<0.3% Cu; >1% Zn cutoff grade) were ~1.77 Mt ore, grading at 0.39 g/t Au, 11 g/t Ag, 0.20 wt% Cu, and 1.94 wt% Zn. The total estimated inferred tonnage of the ore is ~15.05 Mt.

***The Adi Nefas*** ***volcanogenic massive sulfide deposit*** The *Adi Nefas* VMS deposit is located ~10 km north of the center of Asmara and ~8 km southeast of the Emba Derho deposit (Fig 6.37). Similar to the Emba Derho, the Adi Nefas VMS deposit is also hosted by a Neoproterozoic bimodal sequence of mafic and felsic volcanic rocks (Kuroko-type), intruded by later quartz porphyry sills and dykes. Basalts in the footwall, or western side of the deposit, are strongly epidotized and are locally transformed into epidosites. The sequence on the eastern, hanging-wall side of the massive-to-semimassive sulfides, mainly comprise pillow basalts and foliated equivalents, intruded by minor quartz–porphyry dykes and sills. The pillowed basalts and associated mafic metavolcanic rocks overlain by undifferentiated tuffaceous sedimentary rocks and more pillow basalts containing silicate–magnetite chemical sediment lenses. The geological sequence of the Adi Nefas area (Fig 6.38) can be summarized as follows, from bottom to top (Barrie 2004): (1) A >300-m-thick pillowed basalt with pillow breccia and moderate-to-intense quartz–epidote alteration. (2) A 200-m-thick dacite of heterolithic tuff/fragmental and ash lapilli tuff that has been altered to sericite and chlorite schist containing 2%–10% disseminated pyrite. This part of the sequence is intruded by multiple quartz porphyry dykes and sills. (3) Adi Nefas massive-to- semimassive sulfides. (4) An approximately 200-m-thick basaltic tuff with minor dacite lapilli tuff that was altered to chloritic schist with a few quartz porphyry sill/dyke intrusions. (5) A >250-m-thick pillowed basalt with pillow breccia, locally containing amygdules; it has been subjected to quartz–epidote alteration. The interval contains one or more silicate–magnetite chemical sediment lenses and a few thinner quartz porphyry sill/dykes. The gossans cover over the Adi Nefas hypogene deposit averages ~10 m in thickness and is well-exposed over a ~700-m interval but is sporadically mapped over a strike length of ~2 km (Fig 6.38). It comprises a silica, hematite, and goethite-rich assemblage that represent the surface expression of the massive sulfide unit and the immediate semimassive-to-dense disseminated sulfide-rich host rocks. The Adi Nefas deposit has a vertical zonation due to weathering. The underlying deposit is an elongated north-northeast-trending (Fig 6.38), steeply east dipping, massive sulfide lens ranging from 5 to 20 m in thickness and is mostly hosted within a hydrothermally altered felsic quartz–sericite–chlorite–pyrite schist that is, in turn, flanked stratigraphically above and below by altered metabasaltic rocks. The more heavily altered section of the felsic sequence ranges 25–60 m in thickness. The upper oxide and underlying transition zones are leached and strongly depleted in Cu and Zn relative to the hypogene sulfide mineralization and accompanied by a slight enrichment in Au. There is, however, a slight increase in the grade of base metals with depth in these zones. These upper zones are typically developed from surface to the water table, which is generally at a depth of 20–30 m below surface. Below this level, supergene zone typically 20–40 m in thickness is significantly enriched in Cu and Au and slightly enriched in Ag relative to the hypogene sulfide mineralization. Zinc is still depleted relative to the hypogene zone. The mineralization within the hypogene sulfide zone is more Zn-rich than the other deposits of the Asmara district making it a Zn–Cu–Ag–Au VMS deposit. In all other respects, the Adi Nefas deposit is very similar in style to the Debarwa deposit. The premining feasibility study at Adi Nefas as of May 2013 showed (Senior et al 2013)indicated mineral resources of hypogene sulfides (2 wt% Zn cutoff grade) at ~1.841 Mt ore, grading at 3.31 g/t Au, 115 g/, 1.78 wt% Cu, and 10.05 wt% Zn.

***The Debarwa* *volcanogenic massive sulfide deposit*** The Debarwa deposit is located ~30 km south-southwest of the center of Asmara (Figs. 6.30, 6.32, 6.37). It is hosted by an overturned, moderately-to-steeply dipping sequence of variably and intensely altered, bimodal, submarine, low-K tholeiitic basaltic and rhyolitic volcanic rocks together with minor chemical sedimentary rocks. The host rocks of the Debarwa mineralization are altered felsic rocks, underlain by mafic rocks that locally mark the stratigraphic footwall. Mafic rocks predominate within the 6-km-long NNE-trending belt that hosts the Debarwa deposit and Shiketi gossan (Fig 6.39). The massive sulfide mineralization at Debarwa is expressed on the surface by a gossans cover with a strike length of ~1.2 km, which marks the crest of a sharp, west-facing ridge flanking the Gual Mereb river. There are two main zones of massive sulfides (Fig 6.39):(1) The *Debarwa main lens*, ~830 m long, which comprises at least three subparallel mineralized horizons. The western part of the lens is the best developed, thickest, and most continuous. It dips at ~50–60° W, is approximately 8–30 m thick, and has been traced to a depth of ~250 m below the surface. Massive sulfides are confined to this western horizon and vary from <1 to ~22 m in thickness. The overlying supergene and oxide zones are up to 50 m thick. (2) The *Debarwa south lens* is the smaller, is approximately 285 m long, with a massive sulfide zone that steepens from 35° W to 45° W in the north to around 60° W in the south. It is thinner, low in grade, but not as continuous as the Debarwa main zone, and has been traced to ~250 m below the surface. The mineralization at Debarwa is divided into the following parts, from top to bottom (Fig 6.39): (1) The *gossans/oxide zone*, in which the base metals have been mostly leached over a vertical interval of ~80 m below the highest points to between 35 and 50 m below the floor of the Gual Mereb river valley. The Debarwa gossans vary from deep brick-red to black, are largely composed of iron oxides and hydroxides (hematite, limonite, goethite, and minor jarosite), silica, and remnant clay. They may include a variety of lithologies, including siliceous botryoidal limonite–hematite, jasperoid, and greenish impure barite layers beds. The gossans cover above the Debarwa main zone have oxides that typically contain erratic but generally high-Au grades from 0.4 to 14 g/t Au (commonly >4 g/t) over widths between 7 and 17 m. Silver values range from 0.4 and 183 g/t, typically >15 g/t, while Cu and Zn values are relatively insignificant. (2) The *transition zone* marks the gradual change from the oxide to supergene zones and is ~10 to 15 m thick. This transition ore zone is the most enriched in Au and Ag, but most depleted in base metals, particularly Cu and Zn. The intersection with ore zone ranges m 32 to 40 m in depth (8 m), and grades at 39.1 g/t Au, 519.5 g/t Ag, 0.07 wt% Cu, and 0.02 wt% Zn. (3) The *supergene zone*: It is the zone most enriched in Cu, derived from the acid leaching of metals from the oxide zone. Supergene mineral assemblage includes digenite, chalcocite, tenorite, covellite, and bornite. These secondary sulfides replace and form coatings around hypogene sulfides such as chalcopyrite, bornite, and pyrite, and crystallize in the voids left by sphalerite. Supergene grades are higher in the Debarwa main zone with typical supergene intersections ranging between 2 and 26 m, with grades varying from 0.9 to 32 wt% Cu. Precious metals range from 0.5 to 4 g/t Au, and 16 to 144 g/t Ag. Zinc is usually very low, having been almost completely stripped. (4) The *hypogene zone* is located just below the supergene zone, at depths of >65 to 90 m below the valley floor of the Mereb and Gual Mereb rivers. The sulfide assemblages in the hypogene zone are pyrite and chalcopyrite, with common bornite and sphalerite, in massive, semimassive, and stringer vein zones that range to 15 m in thickness. Typical drill intersections of the primary mineralization zone at the Debarwa main zone carry between 2.0 and 9 wt% Cu, 0.5 and 7 g/t Au, 6 and 150 g/t Ag, and 1 to 12 wt% Zn. The premining feasibility study of mineral resources at Debarwa as of May 2013 showed (Senior et al.et al 2013): The measured + indicated mineral resources for the oxide-Au zone (0.5 g/t Au cutoff grade) were ~0.374 Mt ore, with average grades of 1.47 g/t Au, 6 g/t Ag, 0.06 wt% Cu, and 0.04 wt% Zn. The Cu-rich transition zone (0.5 wt% Cu cutoff grade) gave ~0.72 Mt ore, grade at 2.85 g/t Au, 27 g/t Ag, 0.08 wt% Cu, and 0.05 wt% Zn. The Cu-rich supergene zone (0.5% Cu cutoff grade) gave 1.389 Mt ore, 1.40 g/t Au, 33 g/t Ag, 5.15 wt% and 0.07 wt% Zn. The Cu-rich hypogene zone (0.5 wt% Cu cutoff grade) gave 0.774 Mt ore, grading at 1.30 g/t Au, 29 g/t Ag, 2.34 wtu, and 3.92 wt% Zn. The Zn-rich hypogene zone (<0.5 wt% Cu; >2 wt% Zncutoff grade) gave 1.24 Mt ore, grading at 0.31 g/t Au, 22 g/t Ag, 3.05 wt% Cu, and 2.80 wt% Zn. The total measured + inferred metric tonnage of Debarwa is 3.312 Mt ore. The inferred mineral resources at the oxide-Au zone (0.5 g/t Au cutoff grade) are 0.239 Mt ore, grading at 1.1 g/t Au, 5 g/t Ag, 0.10 wt% Cu, and 0.10 wt% Zn. The Cu-rich transition zone (0.5 wt% Cu cutoff grade) gave 0.138 Mt ore, at 1.4 g/t Au, 22 g/t Ag, and 0.10 wt% Cu. The Cu-rich supergene zone (0.5 wt% Cu cutoff) gave 0.144 Mt ore, with average grades of 0.6 g/t Au, 31 g/t Ag, 2.7 wt% Cu, and 0.07 wt% Zn. The Cu-rich hypogene zone (0.5 wt% Cu cutoff grade) gave 0.154 Mt ore, grading at 2.6 g/t Au, 41 g/t Ag, 1.2 wt% Cu, and 3.60 wt% Zn. The Zn-rich hypogene zone (<0.5 wt% Cu; >2 wt% Zn cutoff grade) gave 6 Kt ore, at 1.1 g/t Au, 21 g/t Ag, 0.40 wt% Cu, and 3.30 wt% Zn. The total inferred tonnage was approximately 0.681 Mt ore. **6.7 Volcano–Sedimentary Mineral Deposits in Ethiopia**

Base metal sulfides and gold in Ethiopia are attracting the attention of many exploration companies, including National Mining Company, Ezana Mining Development Plc (EMD), Sheba Mineral Exploration Company, Donia Mineral Exploration Company, and Harvest Mineral Exploration Company, among others. The modern extensive exploration programs in Ethiopia have resulted in delineation of many potential areas in Neoproterozoic basement in different parts of the country for base and precious metals discoveries. These efforts in the Tigray region, northern Ethiopia, have resulted in identifying many potential areas of Au and base-metal mineralization. Base-metal sulfides in the Neoproterozoic basement rocks of Ethiopia are essentially found as polymetallic VMS deposits in the northern part of the country. Exploration activities have been done and some are still running in many areas in Ethiopia, particularly in the Tigray region (including Meli, Terer, and Terakempti), where drilling is being conducted to confirm the deposit and to evaluate and estimate the mineral resources. In addition to the importance of base-metal deposits, these VMS mineralizations are also attracting attention because they are Au-bearing (Ezana 2009; Bheemalingeswara and Araya 2012). EMD (2008) is a pioneer exploration company in this regard, having identified and reported the presence of auriferous polymetallic VMS deposits near Rahwa/Meli in the Adi Ekele belt and Terer in northwestern Tigray, northern Ethiopia. The VMS deposits are mainly identified on the basis of the surface expression of gossans cap rock developed on these sulfide deposits. Among these occurrences, the focus has been made on the Meli deposit, which has ~30 m thick auriferous gossans cover (having ~2 t Au) (Bheemalingeswara and Araya 2012; Samuel et al 2015). Diamond drilling has confirmed the presence of a primary VMS deposit ~20–30 m in thickness beneath gossans cover in the Tigray area (EMD 2008).

Following is detailed information on the Meli VMS occurrence, including host-rock geology, ore geology, petrography, alteration patterns, and metal content. The majority of information here is mainly based on the technical report on the geological evaluation of the Meli Property prepared by Greig and Rowe (2020) for the *Sun Peak Metals Corporation*.

***The Meli volcanogenic massive sulfide deposit***  The Meli VMS Project is located in the northwestern part of Tigray, approximately 570 km (~1,100 km by ground travel) north of the capital city of Addis Ababa, and 24 km southwest from the town of Shire (Fig 6.40). The Meli Project concessions are located within the Asgede–Tsimbila Woreda, centered, approximately, around 13° 58' 12'' N and 8° 2' 26.88'' E, or in the local UTM datum WGS84, zone 37N coordinates of 396,400 E, 1,544,620 N. The exploration license comprises a block measuring ~11 km north/south by 9 km east/west and covering a total area of ~100 km2. The most significant with respect to the Meli project is the nearby deposits of the Asmara and Bisha mineral districts in Eritrea. The Nakfa terrane underlies much of the central part of Eritrea and is made up of mixed volcanic and metasedimentary (siliciclastic and carbonate) rocks. As described earlier, the Nakfa terrane contains the VMS deposits of the Asmara and Bisha greenstone belts. The Nakfa terrane extends southerly into the northern part of Ethiopia and comprises the area covered by the Meli property (Fig 6.41). The Meli area is underlain by the same rock units of volcanic and volcano–sedimentary rocks as the Asmara VMS district, which is located ~160 km to the northeast. The convergence and amalgamation of the four regional belts of north-central Eritrea and northern Ethiopia of oceanic and island arc rocks resulted in deformation, metamorphism, uplift, and a late- to posttectonic granitoid intrusive events.

The Meli VMS project area is found in the southern part of the Nakfa terrane (Fig 6.41), which has been further subdivided into a number of tectonically and stratigraphically distinct blocks, one of which, the Adi Nebrid block, host the majority of mineral occurrences. It consists of a northeasterly striking, steeply dipping, low-grade sequence of mafic-to-intermediate flows, pyroclastics, minor rhyolite, and various epiclastic sedimentary rocks of Neoproterozoic age. A number of granitoid intrusive complexes cut and locally deformed the older layered rocks. This block cuts through the area of the Meli property, which is primarily underlain by Tsaliet group metavolcanic and metavolcaniclastic rocks (Fig 6.42). The diversity of lithologies within the Adi Nebrid block is a function of the collapsed back-arc basin of the area. This setting is postulated due to the presence of cycles of mafic and felsic volcanic and volcanoclastic rocks, synvolcanic intrusions, and the occurrence of deep and shallow water sediments (Archibald et al 2014). The area underwent significant deformation during destruction of the back-arc basin resulting in the development of isoclinal and recumbent folds as well as thrusts and shear faults. The subsequent period of crustal thickening resulted in the emplacement of late orogenic granitic bodies (Greig and Rowe 2020).

The Meli project area is underlain by bimodal mafic-to-felsic metavolcanic rocks, quartzite, ultramafic rocks, and foliated granitoids (Fig 6.43). Regional mapping has shown that there is a repetition in the volcanic stratigraphy from felsic to mafic dominant. Detailed mapping at prospective localities has shown that the packages are a complex sequence of interlayered extrusive and local intrusive rocks that, on some occasions, include minor chert horizons. The extrusive rocks can include tuffaceous and volcaniclastic sequences. The Meli VMS prospects occur more commonly within felsic or intermediate rocks, typically near their contact with mafic rocks, including at the eastern Meli gossan VMS prospect in the south-central part of the property (Fig 6.43). Regionally, at VMS prospects, banded iron formation (BIF) and chert horizons have also been found, and jasperoid alteration is common. Detailed descriptions of the lithologies, structures, metamorphism, alteration assemblages and mineralized zones in the Meli project area can be found in the Technical Report of Meli Prospect, northern Ethiopia (Greig and Rowe 2020).

The oxidized sulfidic-rich gossans cover is localized mainly in felsic crystal tuff or flow that occur mainly as a long narrow belt adjacent to mafic and intermediate metavolcanic units in the central part of the project area. The central and western Meli gossans (Fig 6.44) are closely associated with this rock type, with the most conspicuous feature being that it has unevenly and variably distributed grains of quartz “eyes” that vary from fine to medium and even locally coarse-grained, constituting ~10% of the rock. The rocks typically weathered to an orange-brown color, and are buff, white, or pale grey on fresh surfaces (Fig 6.45). In places, particularly close to the gossans, the felsic tuff is more chloritic and the rock may take on a green hue. The typically strongly foliated parts may locally display a crenulation cleavage and commonly display variegated colors, ranging from reddish brown, to white-grey and locally, dark brown (Fig 6.45). Toward the gossans, the content and size of the quartz eyes appears to decrease, possibly due to intense shearing and comminution of individual crystals. Kaolinization of these rocks may locally be prominent, and the felsic rocks are also commonly cut by abundant quartz veins. The petrographic examination of the felsic tuff revealed the following modal abundances (Greig and Rowe 2020): quartz (65%), calcite (15%), chlorite (10%), and pyrite (10%). The rocks showed well-developed schistosity outlined by fine-grained quartz, calcite, and chlorite in anastomosing bands, which wrapped around the euhedral to subhedral quartz phenocryts (Fig 6.45), which showed wavy extinction, likely resulting from deformation. Mineralization of the Meli property is primarily observed as Au- and minor base-metal-bearing surficial iron oxide minerals (goethite, limonite). Precious and base-metal-rich massive and semimassive sulfide VMS mineralization has been intersected in a number of deeper diamond drill holes beneath the better-developed massive gossans (Greig and Rowe 2020). The surficial gossans material is generally deep brown to red in color, locally varying to yellow. Vuggy and boxwork textures are locally created by leaching of sulfide minerals; disseminated, layered or laminated, wavy, and grooved hydrated silica (chert/jasper) have also been observed within the gossans area. Milky, glassy, iron-stained and brecciated quartz veins and veinlets occur, and are commonly concordant with the gossans. Ghosts of weathered sulfide minerals may also be observed as disseminations and fine stringers in the typically strongly foliated, sericitized, and kaolinized felsic metavolcanic rocks, which commonly occur adjacent to the gossans. Borehole drilling and geophysical surveys have defined the zones of strong oxidation beneath the gossans as occurring up to an average depth of 30 m from the surface in the eastern gossans and, to a depth of possibly up to 75 m in the central and western gossans (Fig 6.44). The sizes and character of the Meli gossans vary considerably. The better-known eastern gossans zone extends for ~650 m along strike; it is ~80 m across in its eastern part, and ~1 m wide near its western end (Fig 6.44). The trend of the mineralization is concordant with the east/west trends in the host rocks; the gossans and underlying sulfide mineralization dip steeply to the south. The central gossans has a strike length of ~100 m and the surface width varies from 1 to 5 m. The trend varies from east/west to north/east along strike and the mineralized zone appears to dip steeply to the south. Layering, quartz, and primary or secondary sulfide minerals are not observed in the central gossans. The western gossans zone has a strike length of ~100 m and the surface width varies from 1 to 6 m. The trend varies from east/west to north/east along strike and like, the other mineralized zones, the western gossans zone appears to dip steeply to the south. Brecciated quartz and banded white chert with concretion-like zones of yellowish and deep-brown hydrated silica/jasper are found within the gossans, but as with the central gossans, primary or secondary sulfide minerals and bedding are not observed.

Malachite and azurite occur very rarely in the surface gossans, which suggests that most of the primaryCu (and Zn) has been leached out from the surficial oxide zones. The Cu and Zn may have been redeposited within the supergene zones at depth. Similar to the nearby Eritrean deposits, where the supergene enrichment zone forms significant grade concentrations, the supergene zones also represents attractive and little-tested targets in the Meli region. The eastern Meli gossans zone has long been known by its presence of Au; the majority of Au-bearing mineralized intercepts of the property come from there. The mining activities have been ongoing at the eastern Meli gossans since 2017, where drilling of the gossans has yielded some excellent intercepts in the gossanous material, such as in drill hole RVH-07, which returned 39.51 g/t Au over 12 m. Most of the drill holes were drilled only in the oxide cap; however, a number of the few deeper holes have intersected primary massive sulfide mineralization, returning very encouraging values, such as 4.2 wt% Cu, 0.7 wt% Zn, 1.5 g/t Au, and 37.1 g/t Ag over 17.4 m (hole RH-DH-01, 28.65–46.05 m) (Greig and Rowe 2020). The identified hypogene sulfide mineral assemblage includes (Samuel et al 2015), in decreasing order of abundance, pyrite, chalcopyrite, sphalerite, and galena, in varying proportions. Pyrite is the most abundant sulfide mineral, where it has well-developed along fractures with other sulfides, particularly chalcopyrite and galena. Chalcopyrite, sphalerite, and gangue minerals are also found intergrown with pyrite crystals and locally as inclusions within pyrite. Chalcopyrite was the only copper mineral observed; bornite, covellite, and chalcocite, which may expected to be found in a supergene-enriched zone, were not found in the samples examined by Samuel et al (2015). Sphalerite was locally found to be replaced by chalcopyrite and later pyrite. Galena occurs as a minor phase, and is found as inclusions within pyrite and chalcopyrite as well as in the fractures within early pyrite. Base metal abundances and types are somewhat similar to those in the primary massive sulfide mineralization at the Bisha VMS deposit in Eritrea, which can be classified here as Cu-Zn (+Au)-rich deposit. The host rocks of the sulfide mineralization at the Meli prospect are also bimodal mafic–felsic volcanic rocks, which are comparable to that of the metavolcanic rocks of the Adi Nebrid block that host Eritrean VMS deposits in the region to the north, which has been interpreted to have been deposited in an island arc setting.

To date, with very limited drilling at the Meli project, only a single VMS lens has yielded intersections suggestive of truly significant thicknesses and, so far, that lens appears to be approximately 20 m thick with a minimum strike length of 200 m (Samuel et al 2015). This larger body appears to lie along stratigraphic contacts, between either mafic metavolcanic rocks and intermediate metavolcanic or meta-volcaniclastic rocks, or between flows of these metavolcaniclastic rocks. It is clear that the sulfide body follows the trend of the host rocks, where the contact is quite sharp, and the alteration is quite conspicuous in the host rocks close to the contact. In contrast to the eastern Meli gossans zone, gossanous surface exposures of the central and western zones suggest that those zones are relatively thin and discontinuous, at least close to the surface. **References**

Abd Allah AG (2012) Two genetic types of volcanic-hosted massive sulfide mineralizations from the Eastern Desert of Egypt. Arabian Journal of Geosciences 5, :217–231.

Abraham S, Bheemalingeswara K, Gebreselassie S (2015) Geology of volcanogenic massive sulfide deposit near Meli, northwestern Tigray, northern Ethiopia. Momona Ethiopian Journal of Science (MEJS), V7(1):85–104 Abu Fatima M (2006) Metallogenic genesis and geotectonic evolution of the Polymetallic massive sulphides and the associated gold deposits at Ariab – Arbaat Belt, Red Sea Hills, Sudan. Dissertation, Université Henri Poincaré

Ahlbrandt TS (2002) Madbi Amran/Qishn Total Petroleum System of the Ma‘Rib-Al Jawf-Shabwah, and Masila-Jeza Basins, Yemen. USGS Bulletin, 2202-G, pp 1–28

Al Ganad I (1991) Etude géologique du gisement Zn-Pb-Ag de Jabali (Bordure sud du bassin du Wadi al Jawf): Unpublished dissertation, Université Orleans, France

Al Ganad I, Lagny, Ph, Lescuyer, JL, Rambo, C, Touray, JC (1994) Jabali, a Zn-Pb-(Ag) carbonate-hosted deposit associated with Late Jurassic rifting in Yemen. Mineralium Deposita 29:44–56

Alexander Nubia Inc (2015) Felsic Dome at Hamama Gold-Rich VMS. Unpublished internal report

Ali-Bik, MW, Hassan SM, Sadek MF (2020) Volcanogenic talc-copper deposits of Darhib-Abu Jurdi area, Egypt: Petrogenesis and remote sensing characterization. Geological Journal 55:5330–5354

Allen CR (2000) Jabali ZnOx Deposit, Yemen. Unpublished report, Cominco American. Archibald SM, Martin C, Thomas DG (2014) NI 43-101 Technical Report on a Mineral Resource Estimate at the Terakimti Prospect, Harvest Property (centred at 38°21'E, 14°19'N), Tigray National Region, Ethiopia. Prepared for Tigray Resources Inc

Ashley PM (2013) Petrographic Report on thirty-six drill core samples from the Bisha Mine, Eritrea. Unpublished Technical Report (#846) for Bisha Mining Share Company by Paul Ashely Petrographic and Geological Services

As-Saruri MA, Sorkhabi R, Baraba R (2010) Sedimentary basins of Yemen: their tectonic development and lithostratigraphic cover. Arabian Journal of Geosciences 3:515–527

Aton Resources Ltd (2017) Hamama West Deposit, Abu Marawat Concession, Arab Republic of Egypt. https://www.atonresources.com/site/assets/files/1215/june152016-1.pdf. Accessed in April 2021.

Barrie CT (2004) Report on the Geology and Geochemistry of the Bisha VMS Deposit and Property, Western Eritrea. Internal Report, Nevsun Resources, August 2004

Barrie CT (2008) Lead isotope analysis of the Ariab and Nuba Mountains areas, Sudan. Internal report for La Mancha Resources

Barrie CT, Abdalla MAF, Hamer D (2016) Volcanogenic massive sulphide–oxide gold deposits of the Nubian Shield in Northeast Africa in Mineral deposits of North Africa, mineral resource reviews, Bouabdellah M, Slack J (eds). Springer Nature, Berlin, pp 417–435. https://doi.org/10.1007/978-3-319-31733-5\_17

Barrie CT, Hannington MD (1999) Volcanic-associated Massive Sulphide Deposits: Processes and Examples in Modern and Ancient Settings: Introduction. In: Barrie CT, Hannington MD (eds) Volcanic-Associated Massive Sulphide Deposits: Processes and Examples in Modern and Ancient Settings. Reviews in Economic Geology, vol 8. pp 1–11

Barrie CT, Kjarsgaard I (2010) Hadal Awatib East petrography and mineral chemistry report—internal report for La Mancha Resources Inc

Barrie CT, Nielsen FW, Aussant C (2007) The Bisha volcanic-associated massive sulphide deposit, Western Eritrea: Economic Geology 102:717–738

Barrie CT, Nielsen FW, Aussant CH (2007) The Bisha volcanic-associated massive sulfide deposit, Western Nafka Terrane, Eritrea. Economic Geology 102:717–738

Bellivier F, Abu Safiyah M, Peyrol L (with the collaboration of Abdulhay G, Al Jadhali N, Artignan D, Felenc J, Genna A, Itard Y, Khali I, Miehé JM, Siddiqui AA) (1999) Mineral exploration in the Baydan area. Saudi Arabian Deputy Ministry for Mineral Resources Technical Report BRGM-TR-97-6

Beydoun ZR, As-Saruri MAL, El-Nakhal H, Al-Ganad IN, Baraba RS, Nani ASO, Al-Aawah MH (1998) International lexicon of stratigraphy, 2nd edn, vol 3. Republic of Yemen. International Union of Geological Sciences and Ministry of Oil and Mineral Resources, Republic of Yemen Publication 34

Bheemalingeswara K, Araya A (2012) Rahwa auriferous gossan, northern Ethiopia: A strong indicator of subsurface massive sulfide mineralization. International Journal of Earth Sciences and Engineering 5:402–408

Bosc, R, Tamlyn N, Kachrillo JJ (2012) The Hassai mine project—VMS resources update. Red Sea State, Sudan. NI 43-101 Technical Rept prepared for La Mancha Resources Inc Bosence DWJ (1997) Mesozoic rift basins of Yemen. In:Bosence DWJ (ed) Special issue on Mesozoic rift basins of Yemen. Marine and Petroleum Geology 14:611–730

Botros NS (2003) On the relationship between auriferous talc deposits hosted in volcanic rocks and massive sulfide deposits in Egypt. Ore Geology Reviews 23:223–257

Bournat G (1972) Completion report on drilling at the Nuqrah Prospects; drill holes NU10, 11, 12, 13, 14, 15, 16, 17, 18 19, 20, and 21: Bureau de Recherches Géologiques et Minières Technical Record BRGM 72-JED 4

Bournat G (1981) Jabal Sayid copper-zinc deposit; synthesis of work and results of 1971-1974: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-01-7

Chisholm R, Delisle PC, Nielsen FW, Daoud D, Ansell S, Davis G (2003) Exploration and Drilling Program on the Bisha Property for Nevsun Resources (Eritrea) Ltd, Bisha Exploration Permit 2003, Work Program: Internal company report, Nevsun Resources, August 2003

Christmann, P, Lagny, P, Lescuyer JL, Sharaf Ad Din A (1989) Discovery of the Jabali deposit (Zn-Pb-Ag) in the Jurassic cover of the Yemen Arab Republic. Chronique de la Recherche Miniere, special issue, 43–52

Cottard F, Abdulhay GJ, Artignan D, Géïot JL, Roubichou P, Trinquard R, Vadala P (1994) The Al Hajar gold deposit (Kingdom of Saudi Arabia): a newly discovered example of supergène enrichment from a massive sulfide deposit of late Proterozoic age: Chronique de la Recherche Miniere/Chronicle of Mineral Research and Exploration 510:13–24

Daoud DK, Greig CJ (2007) Geology and mineralization of the Emba Derho deposit. Internal Sunridge report

Delfour J (1975) Geology and mineral exploration of the Nuqrah quadrangle (25/41A). Bureau de Recherches Geologiques et Minieres Saudi Arabian Mission Technical Record 75-JED-28, 96 pp

Deschamps Y, Lescuyer JL, Guerrot C, Osman AA (2004) Lower Neoproterozoic age of the Ariab volcanogenic massif sulphide mineralization, Red Sea Hills, Sudan. 20th College of African Geology, BRGM, Orleans, p 133 (abstract)

Doebrich JL (1989) Evaluation and geochemical survey of the Farah Garan prospect, Kingdom of Saudi Arabia. Saudi Arabian Directorate General of Mineral Resources Technical Record USGS-TR-09-5

Donzeau M (1980) Geologic study of the Jabal ash Shizm prospect: Bureau de Recherches Géologiques et Minières Technical Record 80 JED 5.

Dubé B, Gosselin P, Mercier-Langevin P, Hannington M, Galley A (2007) Gold rich volcanogenic massive sulphide deposits. In: Goodfellow, WD (2007) Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces and Exploration Methods.Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, pp 75–94

Ellis AC, Kerr HM, Cornwell CP, Williams DO (1996) A tectono stratigraphic framework for Yemen and its implications for hydrocarbon potential. Petroleum Geoscience 2:29–42

Elsass P, Breton JP, Labbe JF, Sabir H, Vaillant FX (1983) The Sha’ib Lamisah prospect fieldwork 1400-1402 A.H**,**  (1980-1982 A.D.). Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-03-11 Evans AM (2009) Ore geology and industrial minerals: An introduction, 3rd edn. Wiley-Blackwell, Hoboken

Ezana Mining Development PLC (2009) Geological Report of Meli Area, private company report

Faisal M, Yang X, Khalifa IH, Amuda AK, Sun C (2020) Geochronology and geochemistry of Neoproterozoic Hamamid metavolcanics hosting largest volcanogenic massive sulfide deposits in Eastern Desert of Egypt: Implications for petrogenesis and tectonic evolution. Precambrian Research 344:105751

Fernette GL (1994) Al Masane polymetallic deposit. In: Collenette P, Grainger DJ (eds) Mineral Resources of Saudi Arabia. Saudi Arabian Directorate General of Mineral Resources Special Publication SP-2, 294–297

Gibson HL, Allen RL, Riverin G, Lane TE (2007) The VMS Model: Advances and application to exploration targeting. In: Milkereit B (ed) Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, pp 713–730

Giroux GH, Barrie CT (2009) Hambok Deposit, Mogoraib Exploration License, Gash-Barka District, Western Eritrea, 43-101 Technical Report and Preliminary Resource Assessment

Greig CJ, Rowe JD (2020) A Geological Evaluation of the Meli Property, Tigray National Regional State, Northern Ethiopia. Unpublished NI 43-101 Technical Report, Prepared for Sun Peak Metals Corp

Hall D, McHugh JJ (1989) Gold Exploration in the Eastern Desert, Egypt: A Case History. Mineral Exploration Programmes 89, Paper 18, 25 pp

Hannington M, Jamieson J, Monecke T, Petersen S, Beaulieu S (2011) The abundance of seafloor massive sulfide deposits. Geology39:1155–1158

Hargrove US (2006) Crustal evolution of the Neoproterozoic Bi'r Umq suture zones, Kingdom of Saudi Arabia: Geochronological, isotopic, and geochemical constraints: Richardson, Texas. Dissertation, University of Texas at Dallas

Helmy HM (1996) Precious metal and base metal sulfide mineralization at Abu Swayel and Um Samiuki, Eastern Desert, Egypt. Dissertation, Minia University, Egypt

Helmy HM (1999) Um Samiuki Precambrian volcanogenic Zn-Cu-Pb deposit, South Eastern Desert, Egypt: a possible new occurrence of cervelleite. Canadian Mineralogist 37:143–154

Johnson PR, Kattan FH (2012) The Geology of the Arabian Shield. Saudi Geological Survey, p 466

Klemm R, Klemm D (2013) Gold and gold mining in ancient Egypt and Nubia. In: Natural Science in Archaeology. Springer Nature, Berlin, p 341

Koch-Mathian JY, Tayeb S, Siddiqui AA (1994) Results of copper-gold exploration in the Rabathan prospect (Wadi Bidah Belt). Technical Report BRGM-TR-14-2, Ministry of Petroleum and Mineral Resources, Directorate General of Mineral Resources, Jiddah, Kingdom of Saudi Arabia

La Mancha Resources Inc (2009) Hadal Awatib East Cu-Au VMS Deposit, Sudan, Resource Estimates. NI 43-101 Technical Report, 106 pp

Large RR, McPhie J, Gemmell JB, Hermann W, Davidson GJ (2001) The Spectrum of Ore Deposit Types, Volcanic Environments, Alteration Halos and Related Exploration Vectors in Submarine Volcanic Successions: Some Examples from Australia. Economic Geology 96:913–938

Lydon JW (1984) Ore deposits models—8. Volcanogenic massive sulfide deposits Part I: A descriptive model. Geoscience Canada 11:195–202

Lydon JW (1988) Volcanogenic massive sulphide deposits; Part 2, Genetic models: Geoscience Canada 15:43–65

Lydon JW (2007) An overview of the economic and geological contexts of Canada’s major mineral deposit types. In: Goodfellow WD (ed) Mineral Resources of Canada: A Synthesis of Major Deposit-types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: St. John's, Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, pp 3–48

Menzies M, Al Kadasi M, et al (1994) Geology of the Republic of Yemen. In: McCombe DA, Fernette GL, Alawi AJ (eds) Geology and Mineral Resources of Yemen. Geological Survey and Mineral Exploration Board, Yemen Mineral Sector Project Technical Report, pp 21–48

Miller NR, Avigad D, Stern RJ, Beyth M (2011) The Tambien Group, Northern Ethiopia (Tigre). Geological Society Memoir 36(1), 263–276

Mondillo N, Boni M, Balassone G, Joachimski M, Mormone A (2014) The Jabali nonsulfide Zn–Pb–Ag deposit, western Yemen. Ore Geology Reviews 61:248–267

Mondillo N, Boni M, Balassone G, Grist B (2011) In search of the lost zinc: a lesson from the Jabali (Yemen) nonsulfide zinc deposit: Journal of Geochemical Exploration 108:209–219

Morad AE, Helmy HM (2021) Convergent-margin polymetallic volcanic-hosted massive sulfide deposits. In: Hamimi Z, Arai S, Fowler A.R, El-Bialy MZ (eds) The Geology of Egyptian Nubian Shield, Regional Geology Reviews, Ch. 16, pp 409–423. <https://doi.org/10.1007/978-3-030-49771-2> Accessed

Nevsun (2004) Exploration Program on the Bisha Property, Gash-Barka District, Eritrea 2004, internal company report, Nevsun Resources (Eritrea) Ltd, September 2004

Noweir AM, Abu El-Ela AM (1991) The Shadli Volcanic province a remnant of a Late Proterozoic island arc. Egyptian Journal of Geology 35:167–183

Parker TWH (1982) Assessment of the mineral potential of the Kutam-Al Halahila district southeast Asir: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-02-22, 149 pp

Payne JG (2013) Report 130086: Petrographic report on samples from holes AHA-015, AHA-019, AHA-020, AHA-021 and AHA-026. Internal Alexander Nubia Inc. internal report, February 2013, 33 pp

Pitre CB, Siddiqui AA, Fauvelet E (1984) Jabal Sayid copper deposit: results of underground exploration, phase 2 (1983-1984): Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-05-7

Ridley J (2013) Ore Deposit Geology. Cambridge University Press, Cambridge

Riofinex (1979) An Assessment of the Mineral Potential of Part of the Wadi Bidah District

Roobol MJ (1989) Stratigraphic control of exhalative mineralization in the Shayban paleovolcanoes (22/39A). Saudi Arabian Directorate General of Mineral Resources Open-File Report DGMR-OF-10-7

Rosa CJP, McPhie J, Relvas JMRS, Pereira Z, Oliveira T, Pacheco N (2008) Facies analyses and volcanic setting of the giant Neves Corvo massive sulfide deposit, Iberian Pyrite Belt, Portugal. Mineralium Deposita 43:449–466

Roubichou P, Artignan D, Beurrier M, Cottard F, Lescuyer JL (1989) Results of gold exploration in the Wadi Bidah district: Gihab and Mulhah gold prospects. Saudi Arabian Directorate General of Mineral Resources Open-File Report BRGM-OF-09-8, 50 pp

Sangster DF, Abdulhay GJS (2005) Base metal (Cu-Pb-Zn) mineralization in the Kingdom of Saudi Arabia: Jeddah, Saudi Geological Survey, 128 pp

Searle DL, Carter GS, Shalaby IM (1978) Mineral exploration at Um Samiuki. U.N. technical report, Egypt, 72–008/3

Selim AQ (1994) Mineralization and wall rock alteration in Al-Derhib mine, south Eastern Desert, Egypt. M.Sc. thesis, Cairo University, Cairo, p 218

Senior N, Finch A, Ross AF, Rees SD, Martin CJ (2013) Asmara Project Feasibility Study, An NI 43-101 Technical Report prepared by SENET Pty Ltd. for Sunridge Gold Corp 264 pp

Shalaby IM, Stumpfl EF, Helmy HM, El Mahallawi OA, Kamel OA (2004) Silver and silver-bearing minerals at the Um Samiuki volcanogenic massive sulfide deposit, Eastern Desert, Egypt. Minerlium Deposita 39:608–629

Shukri NM, Mansour MS (1980) Lithostratigraphy of Sheikh Shadli metavolcanics and the older metasediments in Um Samiuki district, eastern desert, Egypt. Precambrian Research 6, A36–A37

Sillitoe RH, Hannington MD, Thompson JFH (1996) High Sulfidation deposits in the volcanogenic massive sulphide environment. Economic Geology 91:204–212

SRK Consulting (2005) Jabali Feasibility Study, Geology and Resources. Unpublished report, ZincOx Resources plc, 45 pp

SRK (2017) Structural Study and Geotechnical Review of Bisha Mine, Eritrea, March 2017

Stacey JS, Hedge CE (1984) Geochronologic and isotopic evidence for Early Proterozoic crust in the East Arabian Shield. Geology 12:310–313

Stern RJ, Kröner A, Rashwan AA (1991) A late Precambrian (710 Ma) high volcanicity rift in the southern Eastern Desert of Egypt. Geologische Rundschau 80:155–170

Takla MA, Sakran ShM, Awad NT, Abd El Rahim AH (1999) Geological and structural evolution of Um Samiuki area, southeastern Desert, Egypt. In: Proceeding of 4th International Conference of Geology of the Arab World, Cairo University, pp 168–184

Tornos F, Peter JM, Allen R, Conde C (2015) Controls on the siting and style of volcanogenic massive sulphide deposits. Ore Geology Reviews 68:142–163

Viland J (1986) Assessment for gold in the Zalim area, Central Arabian Shield, Review of BRGM work. Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-06-11, 110 pp

Volesky JC (2002) Massive sulfide deposits of the Wadi Bidah mineral district, Saudi Arabia; geologic control of mineralization, remote sensing and mineral exploration, geochemical exploration and petrogenesis. Dissertation, University of Texas at Dallas, 129 pp

Volesky JC, Leybourne MI, Stern RJ, Peter JM, Layton-Matthews D, Rice S, Johnson PR (2017) Metavolcanic host rocks, mineralization, and gossans of the Shaib al Tair and Rabathan volcanogenic massive sulphide deposits of the Wadi Bidah Mineral District, Saudi Arabia. International Geology Review 59:1975–2002

Volesky JC, Stern RJ, Johnson PR (2003) Geological control of massive sulfide mineralization in the Neoproterozoic Wadi Bidah shear zone, southwestern Saudi Arabia, inferences from orbital remote sensing and field studies: Precambrian Research 123:235–247

Voormeij D (2015) Geological Model for Hamama. Unpublished Alexander Nubia Inc. internal report, 3 pp **Figure captions**

**Fig 6.1** Empirical relations between aquifer rock type and metal content of sediment-hosted hydrothermal ore deposits and examples of each deposit type (modified from Ridley 2013). The ore composition indicates the relative economic value of the metals rather than the concentrations

**Fig 6.2** Distribution of major significant base-metal sulfide occurrences in the Arabian–Nubian shield, including the typical VMS as well as Cu–Zn sulfide occurrences of uncertain deposit type (after Volesky et al 2017)

**Fig 6.3** Simplified geological map of the Mahd Adh Dhahab, Gebel Sayid, and Umm ad Damar areas (from Johnson and Kattan 2012)

**Fig 6.4** Geologic map of the Gebel Sayid VMS deposit (after Johnson and Kattan 2012)

**Fig 6.5** Simplified geological map of the Gebel Samran–Gebel Shayban mineral district (after Johnson and Kattan 2012)

**Fig 6.6** **a** Landsat ETM+ (7–5–4) color composite image using the convention (R–G–B) of the WBMD indicating the locations of the Shaib al Tair and Rabathan prospects. **b** Geological map with major structures of the WBMD (after Volesky et al 2003 2017)

**Fig 6.7** Simplified geological map of the Wassat–Al Masane–Kutam mineral district (after Johnson and Kattan 2012)

**Fig 6.8** Schematic plan (above) and cross section (below) of Al Masane VMS deposit, Asir terrane (after Johnson and Kattan 2012)

**Fig 6.9** Schematic plan (above) and cross section (below) of the Farah Garan VMS deposit, Asir terrane (after Johnson and Kattan 2012)

**Fig 6.10** Simplified cross section through the Nuqrah south deposit (MODS 0013) (after Johnson and Kattan 2012)

**Fig 6.11** Geological map of Yemen, showing the Jabali position (from the Yemen Geological Survey and Mineral Resources Board 2009). 1 = Sab'atayn basin; 2 = Say'un-Masilah basin. Blue = hydrocarbon-producing Mesozoic basins; yellow = other Mesozoic basins (from Mondillo et al 2014)

**Fig 6.12** Distribution of base-metal occurrences in Yemen (from Yemen Geological Survey and Mineral Resources Board 1994, 2009)

**Fig 6.13** Simplified geological map of the Jabali mining site showing the location of drill cores and an open-pit area (from SRK Consulting 2005)

**Fig 6.14** Stratigraphic sequence of the Jabali area (Al Ganad et al 1994)

**Fig 6.15** Nonsulfide Zn-Pb mineralization of Jabali area (from Mondillo et al 2014). **a** Smithsonite in outcrop, with a vuggy–highly porous texture. **b** Hydrozincite coating smithsonite and host rock. **c** Partly oxidized ore, with remnants of sphalerite and galena. **d** Massive smithsonite, replacing Zn-dolomite, and smithsonite crusts in cavities. (e) Gypsum veins, cutting both dolomite and smithsonite.

**Fig 6.16** Exposed Proterozoic ANS rocks in the Eastern Desert of Egypt showing the distribution of VMS deposits and occurrences in the SED and CED of Egypt.

**Fig 6.17** Simplified geological map of the Abu Marwat concession of Aton Resources, showing the distribution of possible VMS deposits in Hamama West and surroundings ([Aton Resources Technical Report, March 15 2020](https://www.northernminer.com/news/egypt-approves-aton-resources-mining-licence-for-hamama/1003814034/)).

**Fig 6.18** Simplified geological map of the Hamama West VMS deposit showing the different zones of mineralization and their host rock lithology ([Aton Resources Technical Report, March 15 2020](https://www.northernminer.com/news/egypt-approves-aton-resources-mining-licence-for-hamama/1003814034/)).

**Fig 6.19** **a** Simplified geological map of the northern part of the SED of Egypt, showing the Umm Samiuki mineral district and surroundings. 1 = Derhib, 2 = Abu Gurdi, 3 = Genina Gharbia, 4 = Um Samiuki, 5 = Abu Hamamid intrusion, 6 = Wadi Ranga, 7 = Gebel Hamata, 8 = Wadi Atshan, 9 = Wadi Kharit, 10 = Wadi Natash, 11 = Migif–Hafafit gneiss dome, 12 = Wadi El Gemal, 13 = Wadi Ghadir. **b** Geological map of the Um Samiuki mineral district (including the Um Samiuki, Helgate, and Maaqal prospects) (after Faisal et al 2020).

**Fig 6.20** Schematic diagram of stratigraphic column of Gebel Abu Hamamid area, South Eastern Desert, Egypt (from Faisal et al 2020).

**Fig 6.21** Detailed geological map of Darhib–Abu Gurdi area, Baranis Quadrangle Map, scale 1:250,000 (EGSMA 1992). The inset shows the location area and the extent of SMB within the domain of the basement rocks of the Eastern Desert of Egypt (after Ali-Bik et al 2020).

**Fig 6.22** Field photographs showing **a** the location of Derhib talc mine at the contact between Shadli metavolcanic and metasedimentary rocks. **b** Malachite (green) staining in the surface oxidized zone of Gebel derhib. **c** Abu Gurdi talc mine along shear zones between lower metasedimentary rocks and overlying metagabbros. **d** Malachite staining in the surface oxidized sulfide-rich zone of Gebel Abu Gurdi (from Ali-Bik et al 2020).

**Fig 6.23** ASTER density slice image of the Gebel Drhib and Gebel Abu Gurdi area. Red pixels represent talc-rich alteration zones, and green pixels represent the malachite-bearing alteration zones (from Ali-Bik et al 2020).

**Fig 6.24** Location map showing the distribution of VMS occurrences in the Ariab Mineral District, northeastern Sudan.

**Fig 6.25** General geological map of the Ariab–Arbaat greenstone belt. The Hassai South and Hadal Awatib deposits are also shown along with selected other deposits (La Mancha Resources Inc. Technical Report 2009).

**Fig 6.26** Schematic section showing the relationship between the surface iron oxide gossans Au ore, silica barite rock “SBR” Au ore, and the beneath Cu-Zn-Au VMS mineralization (from La Mancha Resources Inc. Technical Report 2009).

**Fig 6.27** Simplified geology of the Ariab VMS–oxide gold district, northeastern Sudan, and representative deposits. **a** Geology of the Hassai South and Hassai North area. **b** Geology of the Hadal Awatib area. Note the continuous strike length of Hadal Awatib massive sulfide lens, which is among the most extensive VMS deposits known globally (from Barrie et al 2016).

**Fig 6.28** **a** The western end of Hassai South open-pit mine, outline the outcropping silica-barite-rock (SBR) and/or massive sulfide (red dotted line). **b** Hadal Awatib East open-pit mine AB, and CD **c** outline the outcropping SBR and/or massive sulfide (red dotted line). **d** Hadal Awatib West open-pit mine outlining the outcropping SBR and/or massive sulfide deposit (red dotted line). (from La Mancha Resources Inc. Technical Report 2009).

**Fig 6.29** **a** Hadayamet open-pit outline the outcropping SBR and/or massive sulfide (red dotted line). **b** Taladeirut open-pit outline the outcropping SBR and/or massive sulfide (red dotted line). **c** Oderuk open-pit outline the outcropping SBR and/or massive sulfide deposit (red dotted line). **d** Adassedakh open-pit outline the outcropping SBR and/or massive sulfide deposit (red dotted line) (from La Mancha Resources Inc. Technical Report 2009).

**Fig 6.30** Map of Eritrea showing the exploration licenses and companies working in base- and precious-metals exploration (Andiamo Exploration Ltd, Gold, Copper and Zinc in Eritrea 2017).

**Fig 6.31** Simplified geologic map of Neoproterozoic Terranes of Eritrea with selected VMS deposits in the western and eastern Nakfa terrane (modified from Barrie et al 2007).

**Fig 6.32** Simplified geological map of northern Eritrea showing some selected VMS deposits in the Bisha and Asmara mineral districts (from Giroux and Barrie 2009).

**Fig 6.33** Simplified geologic map of the Mogoraib license area, west central Eritrea, showing the VMS mineralization at Bisha (main, N, NW), Hambok and selected other occurrences in the Bisha mineral district (from Giroux and Barrie 2009).

**Fig 6.34** General view of the Bisha Main massive sulfide deposit below the open-pit mine below the oxide-Au surface zone (NI 43-101 Technical Report Bisha Mine, SRK Consulting 2017).

**Fig 6.35** Schematic lithological diagram showing the weathering profile of Bisha Main VMS deposit (NI 43-101 Technical Report Bisha Mine, SRK Consulting 2017).

**Fig 6.36** **a** Field location of the Bisha Northwest (NW) deposit project area, to the northwest of Bisha Main site. **b** Simplified geologic map of the Bisha NW deposit. (from NI 43-101 Technical Report Bisha Mine, SRK Consulting 2017).

**Fig 6.37** Simplified Geologic map of the Asmara mineral district showing the main VMS occurrences (from Senior et al 2013).

**Fig 6.38** Simplified geologic map of the Adi Nefas VMS deposit area, showing the main lithology and distribution of the gossans and hypogene mineralization (from Senior et al 2013).

**Fig 6.39** Simplified geologic map of the Debarwa VMS deposit area, showing the main lithology and distribution of the gossans and hypogene mineralization (from Senior et al 2013).

**Fig 6.40** Satellite image showing the location of Meli project, northern Ethiopia.

**Fig 6.41** Simplified geological map of the Meli project with relation to the Asmara mineral district and Bisha mine (from Greig and Rowe 2020).

**Fig 6.42** Simplified geologic map of the Meli region, showing the Adi Nebrid Block and associated VMS occurrences (from Miller et al 2011).

**Fig 6.43** Local geology of the Meli property (from Greig and Rowe 2020).

**Fig 6.44** Simplified geologic map of the Meli gossans area showing the different mineralization zones in Meli prospect (from Ezana private company Technical Report 2009). **Fig 6.45** Foliated oxidized sulfide-rich felsic tuff cut by quartz veins (boudinaged quartz eyes) (from Greig and Rowe 2020).