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Epithermal Gold Discoveries in the Emerging Khundii Metallogenic Province, Southwest Mongolia

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Abstract

Mineral exploration since 2005 in a previously underexplored region of southwestern Mongolia resulted in the definition of the Zuun Mod porphyry Mo-Cu deposit, followed by discovery of the Altan Nar and Bayan Khundii epithermal gold deposits along with several prospects and advanced exploration projects. These discoveries form the core of the emerging Khundii ("Valley") metallogenic province, ~50 × 100 km in size, located within a single island arc terrane of Middle Carboniferous to early Permian age and predominantly within an individual mapped subterrane. The province is situated ~700 km west-northwest of the late Devonian Oyu Tolgoi porphyry Cu-Au deposit in a belt of mid-Paleozoic island arcs that are part of the Central Asian orogenic belt, host to world-class porphyry Cu-Au and epithermal gold deposits that stretch from southern Mongolia to the west, into China, Kazakhstan, and beyond.

The Zuun Mod porphyry Mo-Cu deposit (297 ± 4.8 Ma) is hosted by a granodiorite intrusion cut by B-type quartz-molybdenite-chalcopyrite veins with K-feldspar alteration selvages plus disseminated biotite and magnetite. After definition of this deposit, a regional exploration program was initiated in 2009 over 110,000 km^2, based on the underexplored nature of the region. Exploration included compilation of existing geologic, geochemical, and geophysical data and interpretation of satellite imagery followed by ground exploration that included stream, soil, and rock-chip sampling and geologic and alteration mapping. The Nomin Tal Cu-Au prospect was discovered in early 2011, and based on the indications from initial soil sampling, a 400- × 400-m soil survey was conducted over the southern part of the exploration license, which identified a Pb-, Zn-, and Au-in-soil anomaly over an area of ~1.5 × ~5.5 km. The first drill hole within the soil anomaly in late 2011 resulted in the discovery of the Altan Nar Au-polymetallic epithermal deposit with veins of coarsely crystalline quartz-adularia (309.7 ± 0.5 Ma) and Ca-, Mg-, Mn-, and Fe-carbonate gangue that host the base metal sulfides.

The Bayan Khundii gold deposit was discovered in 2015 as the result of prospecting, ~16 km southeast of Altan Nar. Subsequent discovery of the Khar Mori gold project was announced in early 2021, ~3 km north of Bayan Khundii along a structural trend, and later in 2021 drilling discovered wide zones of disseminated gold at Ulaan Southeast, ~800 m west of Bayan Khundii. The epithermal quartz-adularia-gold veins (336.8 ± 0.5 Ma) at Bayan Khundii have colloform bands with minor pyrite and are enveloped by proximal illite alteration. The epithermal veins and alteration overprint an earlier, unrelated alteration style of residual quartz and pyrophyllite ± dickite ± diaspore-kaolinite. Similarly, residual quartz and pyrophyllite-dickite at Khar Mori are overprinted by epithermal mineralization, including arsenopyrite. At the central Ulaan project, ~3 km northwest of Bayan Khundii, intense quartz-white mica-pyrite alteration is widespread at surface, including tourmaline bodies and local copper anomalies, associated with nearby residual quartz and related aluminosilicate alteration. These alteration styles indicate erosion of a lithocap to its base, exposing K-feldspar and magnetite plus quartz-white mica-pyrite related to the top of a porphyry deposit, as yet only tested by a few scout drill holes. The undated porphyry-related alteration was subsequently overprinted by the gold-bearing epithermal veins after significant erosion.

Introduction

The emerging Khundii metallogenic province is located ~700 km west-northwest of the well-known Oyu Tolgoi district, all part of the Devonian to Permian-age Central Asian orogenic belt, which hosts world-class porphyry Cu-Au and epithermal gold deposits (Fig. 1; Yakubchuk et al., 2012). This report provides an overview of the geology of the newly defined metallogenic province, along with first descriptions of the epithermal discoveries and our understanding of the geologic parameters that contributed to their formation.

All hydrothermal deposits and prospects are located within a single island arc terrane, and predominantly within an indi-

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vidual mapped subterrane, thus constituting a metallogenic province (Petrascheck, 1965). There are a variety of known hydrothermal deposits, with the most notable discovery being a gold-rich, sulfide-poor epithermal deposit, now in development, which overprints porphyry-related alteration at the base of a lithocap. In addition, other discoveries in the ~100- × 50-km province include an Au-Ag-base metal epithermal vein deposit as well as an Mo-Cu porphyry deposit, styles associated with porphyry copper systems (Sillitoe, 2010) that are common across the Central Asian orogenic belt.

Exploration History

Prior to 2005, there were only a few gold and base metal showings in the entire Trans-Altai terrane (Fig. 1), which includes the Khundii metallogenic province. Previous work in the area consisted of regional 1:200,000-scale geologic mapping and related geologic studies (Zabotkin et al., 1988; Bukhbat and Naraanbaatar, 1998; Cerny et al., 2003; Gansukh et al., 2003). Their mapping identified minor gold and base metal anomalies, although no exploration work is known to have taken place on Erdene's exploration license areas.

In 2005, Erdene (Erdene Resource Development Corporation) began work in the area after acquiring the assets of Gallant Minerals, which had intersected porphyry-related mineralization at Zuun Mod in a scout drill hole in 2002. Erdene subsequently defined a mineral resource at Zuun Mod, from the surface with a cutoff grade of 0.04% Mo, consisting of 218 million metric tonnes (Mt; measured and indicated) at 0.057% Mo and 0.069% Cu and 168 Mt (inferred) at 0.052% Mo and 0.065% Cu (Clark and Baudry, 2011). The Khuvyn Khar porphyry Cu-Ag prospect is located 3 km northwest of Zuun Mod, within the same porphyry intrusive complex, and as yet has only been tested by initial scout drilling.

A regional exploration program initiated by Erdene in 2009 examined ~110,000 km^2, including the entire Trans-Altai terrane, based on the success at Zuun Mod and the underexplored nature of the region. Exploration methodology included compilation of existing geologic, geochemical, and geophysical data and reprocessing and interpretation of satellite imagery. Alteration anomalies noted from ASTER (Advanced Spaceborne Thermal Emission Reflection Radiometer) satellite imagery were instrumental in identifying prospective areas for follow-up targeting. Desktop compilation was followed by a comprehensive regional ground exploration program. Detailed follow-up activities in prospective areas included grid soil and rock-chip sampling; geologic and alteration mapping including shortwave infrared (SWIR) analysis of minerals in alteration zones; ground magnetic surveys which assisted in detailed geologic mapping of hydrothermally altered areas, with associated magnetite destruction causing low magnetic response; induced polarization (IP) gradient array and dipole-dipole surveys to outline silicified zones with high resistivity response and zones of high chargeability response due to disseminated sulfide mineralization; and detailed ground gravity surveys to identify potential granitoid intrusions at depth that may be related to porphyry mineralization. A regional granite sampling program, starting in 2012, used the methodology of Loucks (2014) to identify potentially fertile intrusions and intrusive complexes. A regional (dry) stream sediment survey consisting mostly of fourth- or fifth-order streams (N = 1,317) was completed over the entire Trans-Altai terrane in 2016. Stream data and alteration anomalies from satellite imagery identified prospective catchments for follow-up exploration. The results of this work indicated that the strongest mineral potential in the 110,000-km^2 area of interest was in the southeastern portion of the Trans-Altai terrane, eventually defined as the Khundii metallogenic province (Fig. 1).

The Nomin Tal Cu-Au prospect (Fig. 2) on the Tsenkher Nomin exploration license was first identified in 2011 by the discovery of historic pits containing copper carbonate minerals, which led to a tight soil grid plus IP and ground magnetic surveys followed by drilling of eight shallow scout holes (Erdene, 2011a [1]). Following this drilling, a soil survey on a 400- × 400-m grid was completed over much of the southern part of the exploration license, which defined Pb-, Zn-, and Au-in-soil anomalies over an area of ~1.5 × ~5.5 km (see below), followed by more widespread IP and magnetic surveys. The central part of the soil anomaly, in an area with some epithermal-textured quartz pebbles at surface and a coincident IP chargeability anomaly, was tested by drilling later in the year, leading to discovery of the Altan Nar Au-polymetallic deposit by the initial drill hole (TND-09), which intersected a 55-m interval from 20 m depth with 1.02 g/t Au, 12 g/t Ag, 0.26 wt % Pb, and 0.47 wt % Zn (Erdene, 2011b[1]). Subsequently, an NI 43-101-compliant mineral resource for the Altan Nar deposit (Clark et al., 2018) was defined, with 5.0 Mt of resource (measured and indicated) at 2.0 g/t Au, 14.8 g/t Ag, 0.6 wt % Zn, and 0.6 wt % Pb, and 3.4 Mt of inferred resource at 1.7 g/t Au, 7.9 g/t Ag, 0.7 wt % Zn, and 0.7 wt % Pb.

At about the same time in 2011, Australia-based Voyager Resources Ltd. announced the discovery of porphyry-style Cu-Ag-(Au-Mo) mineralization at the Khul Morit project, ~40 km southwest of Altan Nar (Fig. 2). Niislelkhuu et al. (2013) summarized exploration results at Khul Morit from 2004 to 2012, describing mineralization as associated with a series of quartz-tourmaline veins and breccia pipes over a 6.4- × 4.3-km area, containing a Cu-Ag-Au resource.

In 2015, prospecting led Erdene to identify anomalous gold at the Bayan Khundii project, ~16 km southeast of Altan Nar, with surface rock chip samples returning up to >4,000 g/t Au (Erdene, 2015a[1]). Drill targeting was assisted by an IP survey despite the low sulfide content in most of the deposit, with high resistivity outlining zones of strong silicification. Results from the initial drill program at Bayan Khundii included a 7-m interval of 27.5 g/t Au from 14-m depth (Erdene, 2015b[1]). Subsequent exploration in the area led Erdene to discover

1. Erdene press releases, all accessed on 15 February 2022:
Erdene Resource Development Corporation, 2011a, https://erdene.com/site/assets/files/3905/2011-07-06_nr.pdf
Erdene Resource Development Corporation, 2011b, https://erdene.com/site/assets/files/3900/2011-10-12_nr.pdf
Erdene Resource Development Corporation, 2015a, https://erdene.com/site/assets/files/3747/2015-10-05_nr.pdf
Erdene Resource Development Corporation, 2015b, https://erdene.com/site/assets/files/3740/2015-12-09_nr.pdf
Erdene Resource Development Corporation, 2021a, https://erdene.com/site/assets/files/4237/erd_pr.pdf
Erdene Resource Development Corporation, 2021b, https://erdene.com/site/assets/files/4286/epr_en.pdf
Erdene Resource Development Corporation, 2022, https://erdene.com/site/assets/files/4328/epr_en.pdf

gold mineralization at the Khar Mori ("Dark Horse") project in early 2021, ~3 km north of the Bayan Khundii gold deposit (Erdene, 2021a[1]). One drill hole (AAD-58) intersected a 45-m interval of 5.97 g/t Au, beginning at 10-m depth. Later in 2021, gold mineralization was discovered in the southeastern corner of the Ulaan exploration license, called Ulaan Southeast, located approximately 800 m west of the Bayan Khundii gold deposit (Erdene 2021[1]). One hole (UDH-10) from the maiden drill program intersected a 258-m interval which averaged 0.98 g/t Au from 92 m downhole. Subsequent drilling intersected the widest auriferous zones to date in the Khundii metallogenic province, with one 364-m interval averaging 0.79 g/t Au (including 91 m at 1.98 g/t Au).

An updated feasibility study was completed in 2023 for the Bayan Khundii gold deposit (Lawrence, 2023) based on 375 drill holes spaced at 10 to 25 m for a total of 56,249 m. The measured and indicated resource of 613,000 ounces of gold has an average grade of 2.58 g/t Au. Included within this are proven and probable reserves of 464,900 ounces gold at an average grade of 3.8 g/t Au; development has commenced.

Recent exploration in the Khundii metallogenic province by Mongolia Minerals Corporation and Steppe Gold has included geochemical and geophysical surveys, with several precious and base metal prospects announced in the Khongor and Uudam Khundii exploration licenses, respectively. Interest is increasing in this province, which is still underexplored.

Regional Geologic Setting

The Khundii metallogenic province is located within the southeast part of the Trans-Altai terrane (previously referred to as the Edren terrane; Badarch et al., 2002), as defined by recent 1:50,000-scale geologic mapping and associated reports sponsored by the Mongolian government (Lhundev et al., 2019). The Trans-Altai is an island arc terrane within the Central Asian orogenic belt, which extends more than 3,000 km from the Urals to the Pacific, and from the northern Siberian

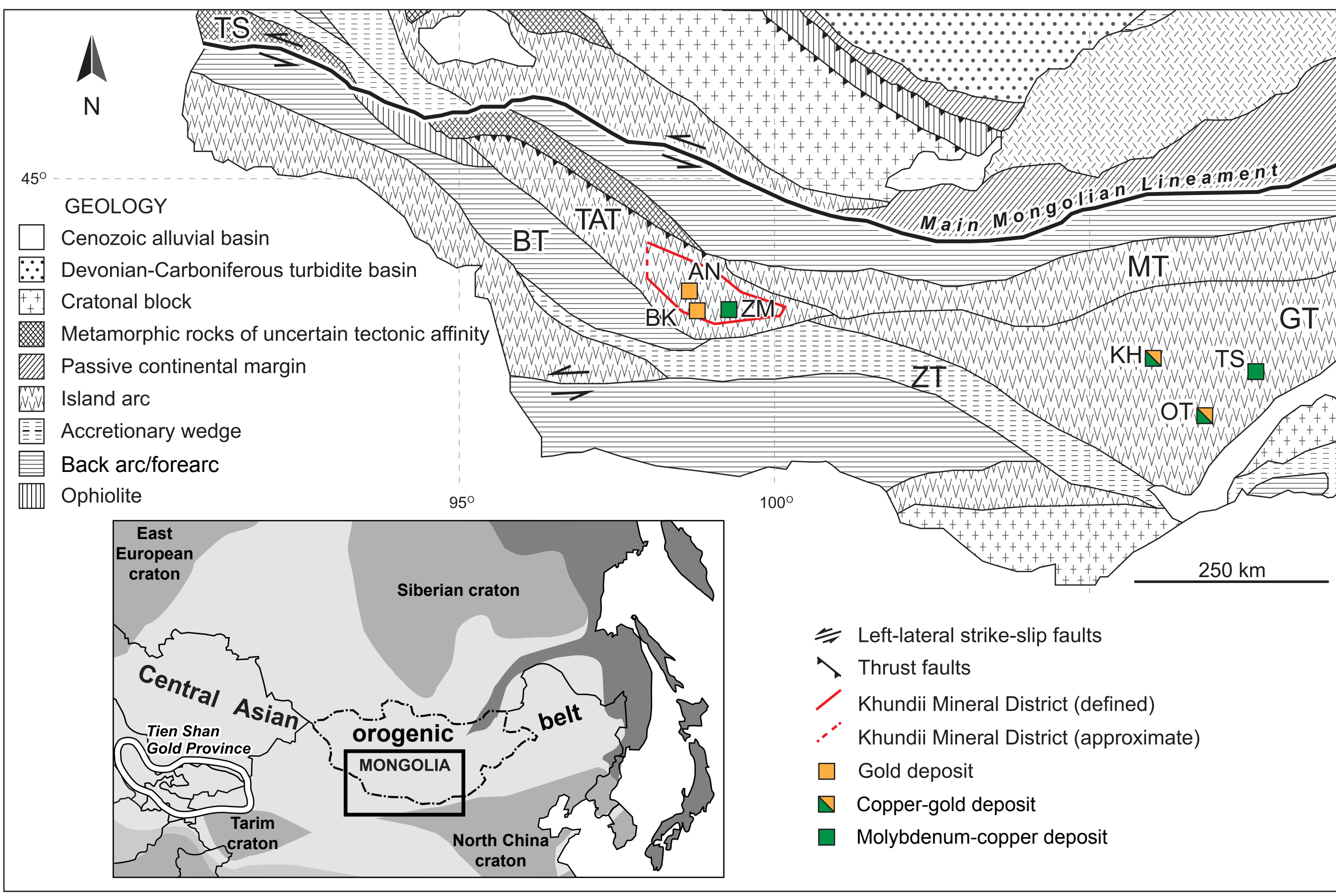

Fig. 1. Tectonostratigraphic terrane map of southwestern Mongolia (modified after Badarch et al., 2002) showing the location of the Trans-Altai terrane (TAT) and adjacent terranes, including the Mandalovoo island arc (MT), Baraan back arc/fore arc (BT), Tseel metamorphic (TS), Gurvansaikhan island arc (GT), and Zoolen accretionary wedge (ZT) terranes. Locations of the main discoveries within the southeastern part of the Trans-Altai terrane include the Zuun Mod porphyry Mo-Cu deposit (ZM), the Bayan Khundii-Ulaan-Khar Mori Au-Ag deposit (BK), and the Altan Nar polymetallic deposit (AN). The northern, southern, and eastern boundaries of the proposed Khundii metallogenic province correspond to subterrane boundaries (Fig. 2), whereas the western boundary provisionally marks the extent of the exploration coverage. The Oyu Tolgoi (OT), Kharmagtai (KH), and Tsagaan Suvarga (TS) porphyry deposits form the Oyu Tolgoi cluster in the Gurvansaikhan terrane (GT), east of the Khundii region. The inset shows the location of the map within the Central Asian orogenic belt (black box); the Tien Shan gold province is indicated by the solid white line.

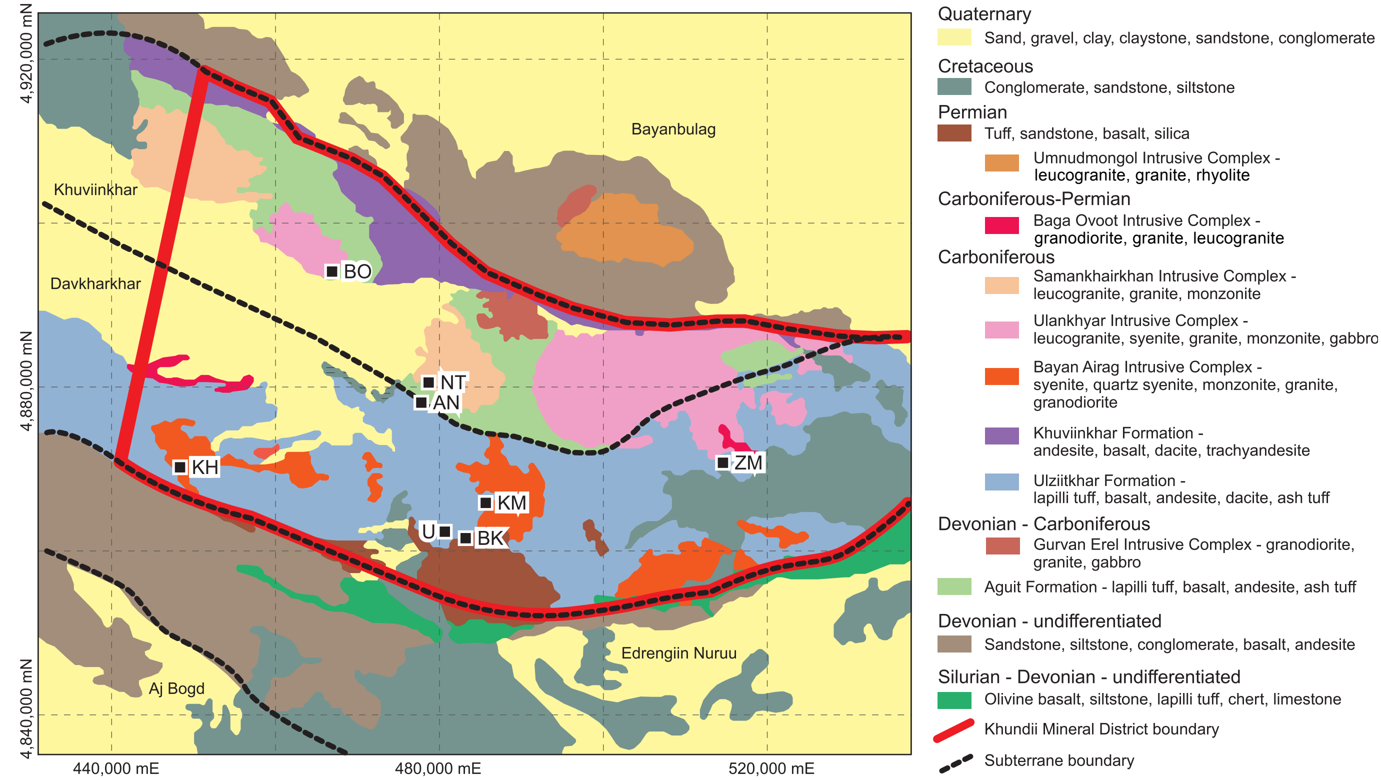

Fig. 2. Geologic map of the proposed Khundii metallogenic province from recent 1:50,000-scale geologic mapping (Lhundev et al., 2019; Togtogkh et al., 2019; Tumurchudur et al., 2020). The limits of the province are indicated by the solid red lines. Locations noted for the Bayan Khundii (BK), Ulaan southeast (U), Khar Mori (KM), Altan Nar (AN), and Zuun Mod (ZM) deposits and the Nomin Tal (NT), Khul Morit (KH), and Bor Khairkhan (BO) prospects. The five subterranes within the Trans-Altai terrane include (from north to south) the Bayanbulag accretionary wedge, Khuviinkhar island arc, Davkharkhar island arc, Edrengiin Nuruu island arc, and Aj-Bogd accretionary wedge.

and East European cratons to the southern North China and Tarim cratons (Windley et al., 2007; Fig. 1). This orogenic belt formed by the accretion of island arcs, ophiolites, ocean islands, seamounts, accretionary wedges, and microcontinents. Windley et al. (2007) suggested a similarity to the Mesozoic-Cenozoic accretionary orogens of the circum-Pacific. The belt began its growth in the Proterozoic at ~1.0 Ga (Khain et al., 2002) and continued until the late Permian at ~250 Ma (Xiao et al., 2003), when the Paleo-Asian Ocean closed.

The Central Asian orogenic belt (Fig. 1) is host to numerous porphyry copper and epithermal gold deposits of largely Devonian to Permian age (intrusions and/or ore; Yakubchuk et al., 2012; Wang et al., 2021). The closest known deposits in Mongolia are those of the Oyu Tolgoi cluster (370 Ma), located ~700 km east-southeast of Khundii (Fig. 1). They contain >36 Mt Cu and >1,400 t Au; smaller nearby deposits contain ~1 Mt Cu (Tsagaan Suvraga and Kharmagtai; Fig. 1). The Tuwu porphyry Cu deposit in the Tian Shen of China (280 Mt at 0.75% Cu, 0.16 g/t Au; Singer et al., 2008) is the closest known orebody, located ~500 km west-southwest on the southern margin of the Central Asian orogenic belt. Re-Os dating of molybdenite yielded an isochron age of 335.6 ± 4.1 Ma (Wang et al., 2021), with the adjacent Yandong porphyry deposit reporting a weighted average Re-Os age of 331.8 ± 2.1 Ma. Further west in Kazakhstan, the Nurkazghan (410 Ma), Koksai (330 Ma), Aktogai and Aidarly (320 Ma), and Kounrad (323 Ma) porphyry deposits contain 3 to 6 Mt Cu each, with variable gold (70 to >600 t; Yakubchuk et al., 2012). The Central Asian orogenic belt continues southwest into Uzbekistan along the middle Tien Shan range; Kalmakyr (11 Mt Cu, 2,650 t Au) and Dalnee (11 Mt Cu, 990 t Au) of the Almalyk cluster of porphyry deposits formed at ~320 to 314 Ma (Yakubchuk et al., 2012). Many smaller porphyry deposits of similar age are present in Kazakhstan and Uzbekistan, as well as epithermal gold deposits, some of notable size (Kochbulak, 120 t Au, formed at >280 Ma; Singer et al., 2008).

Geochronological data indicate that the porphyry and epithermal deposits of the Central Asian orogenic belt (including those indicated in Fig. 1) are temporally similar (Yakubchuk et al., 2012), with their isotope signatures suggesting the incorporation of a moderate mantle component (Chiaradia et al., 2006). Yakubchuk et al. (2012) concluded that the greatest metal endowment and largest number of individual deposits in the Central Asian orogenic belt were formed during the period from 340 to ~320 Ma (e.g., Almalyk and Aktogai), with the second most important period at 385 to 370 Ma (e.g., Oyu Tolgoi). Preliminary geochronological data for deposits from the Khundii metallogenic province, as documented below, are coeval with metallogenic ages from the Tien Shan belt, over 1,000 km to the west (Fig. 1), but somewhat younger than the Late Devonian activity that formed Oyu Tolgoi.

A tectonostratigraphic terrane map of Mongolia, modified after Badarch et al. (2002; Fig. 1), shows that the region north of the Main Mongolian Lineament is dominantly Precambrian and lower Paleozoic rocks. The region south of the lineament is dominantly upper Paleozoic rocks and is composed of a collage of island arc terranes, including the Gurvansaikhan terrane, which hosts the Oyu Tolgoi Au-Cu deposit, and the Trans-Altai terrane, which hosts the Khundii metallogenic province. Other terranes in the collage include ophiolites, accretionary wedges, back-arc/fore-arc basins, and metamorphic complexes typical of global accretionary orogenic belts (Windley et al., 2007).

The Trans-Altai terrane is elongate (~100 × ~450 km) and trends northwest (Fig. 1). The Trans-Altai terrane was subdivided into five subterranes (Fig. 2) by Lhundev et al. (2019), Togtogkh et al. (2019), and Tumurchudur et al. (2020), as follows from north to south: (1) Bayanbulag accretionary wedge; (2) Khuviinkhar island arc; (3) Davkharkhar island arc; (4) Edrengiin Nuruu island arc; and (5) Aj-Bogd accretionary wedge. The Khundii metallogenic province is entirely underlain by rocks of the Khuviinkhar and Davkharkhar island-arc subterranes, with recent discoveries hosted by the Davkharkhar subterrane (Fig. 2). The E-W-trending southern margin of the Trans-Altai terrane is parallel to an adjacent crustal-scale sinistral fault (Badarch et al., 2002; Fig. 1) and is the dominant structural orientation of the Central Asian orogenic belt.

Geology of the Khundii Metallogenic Province

Geologic setting

The Mineral Resource and Petroleum Authority of Mongolia (MRPAM), a ministry of the Government of Mongolia, contracted the completion of six 1:50,000-scale bedrock geologic maps covering the southeast portion of the Trans-Altai terrane, including the area of the Khundii metallogenic province. Geologic mapping was completed between 2014 and 2018. Lhundev et al. (2019), Togtogkh et al. (2019), and Tumurchudur et al. (2020) presented reports and maps of their survey results in Mongolian (Fig. 2).

The province is bounded to the north by the Bayanbulag accretionary wedge subterrane, comprising Devonian siliciclastic sedimentary rocks and mafic to intermediate volcanic flows and tuffs. These rocks were intruded by Late Devonian intrusions of the Gurvan Erel intrusive complex, which range in composition from gabbro to leucogranite and rhyolite porphyry. The Devonian siliciclastic and volcanogenic rocks were subsequently cut by Permian intrusions of the Umnudmongol intrusive complex, ranging in composition mostly from granite to leucogranite. The contact between rocks in the province and the Bayanbulag subterrane is a thrust fault, with district rocks thrust over Devonian rocks to the north (Lhundev et al., 2019). These recent observations are consistent with the tectonostratigraphic terrane work by Badarch et al. (2002), where the Trans-Altai (Edren) terrane was interpreted as being thrust over rocks of the metamorphic Tseel terrane and the island arc Mandalovoo terrane to the north (Fig. 1).

The province is bounded to the south by a series of Devonian siliciclastic sedimentary rocks and mafic and intermediate volcanic flows and tuffs, thus resembling the rocks to the north of the province, with areas locally underlain by Silurian to Devonian mafic to intermediate volcanic flows and tuffaceous rocks. These rocks all make up part of the Edregiin Nuruu subterrane of the Trans-Altai terrane (Togtogkh et al., 2019; Tumurchudur et al., 2020) and form a narrow zone (<1–5 km wide; Fig. 2) along most of the southern margin of the province. The northwest structural trend of Devonian rocks along the southwest margin of the province changes to a mostly east-west orientation directly south of the Bayan Khundii deposit and forms an arcuate shape with east-northeast structural trends in the southeast part of the province (Fig. 2). The presence of an E-W–trending crustal-scale sinistral fault near and subparallel to the southern margin of the province (Badarch et al., 2002; Fig. 2), coupled with the folding of the Devonian strata, suggests that the southern margin of the province may be a fault contact. Silurian and Devonian rocks are unconformably overlain by a large Permian to Jurassic sedimentary basin comprising mostly siliciclastic rocks, with minor volcanogenic flows extending to the south (Lhundev et al., 2019), and unconformably overlain by Quaternary sand, gravel, and clay deposits (Fig. 2).

The western margin of the province has provisionally been placed just west of the Khul Morit and Bor Khairkhan prospects (Fig. 2); however, this margin is poorly constrained and may subsequently be extended to the northwest, should additional discoveries be made.

General geology

Davkharkhar subterrane: The southern portion of the province is underlain by the Davkharkhar subterrane of the Trans-Altai terrane (Fig. 2), which comprises volcanogenic units of the Middle Mississippian Ulziitkhar Formation. Figure 3 is a stratigraphic column showing the main volcanic, sedimentary, and intrusive units in the Davkharkhar and Khuviinkhar subterranes and the host units for the known mineral deposits, including geochronological data (Table 1). Most of the deposits and advanced projects discovered to date in the province are located in the Davkharkhar subterrane, including Altan Nar, Bayan Khundii, and Zuun Mod.

The Ulziitkhar Formation (Lhundev et al., 2019) has been subdivided into three conformable members as follows:

1. A 1,200-m-thick lower member comprising tuffaceous rocks (ash, lapilli, block and ash tuffs) and volcanoclastic sedimentary rocks. This member hosts the Bayan Khundii gold deposit and a large area (~2 × 3 km) of intense quartz-white mica-pyrite alteration of the central Ulaan project (see below).
2. An 800-m-thick middle member, comprising mostly basalt and andesite flows and tuffaceous rocks, hosts the Khar Mori gold and Altan Arrow Au-Ag prospects (Figs. 2, 3), north of Bayan Khundii. A U-Pb zircon age from an andesite unit returned an early Carboniferous (Visean) age of 337 ± 7 Ma (Lhundev et al., 2019; Table 1).
3. A 1,150-m-thick upper member of mostly andesite and dacite flows and volcanic breccia hosts the Altan Nar Au-polymetallic deposit. A U-Pb zircon age from a rhyolite flow yielded a Middle to Late Mississippian age of 331 ± 2 Ma (Javkhlan et al., 2022).

Outcrop patterns for the three members of the Ulziitkhar Formation (Lhundev et al., 2019; Togtogkh et al., 2019; Tumurchudur et al., 2020) show a complex pattern of local folding and widespread block faulting, which has juxtaposed rocks

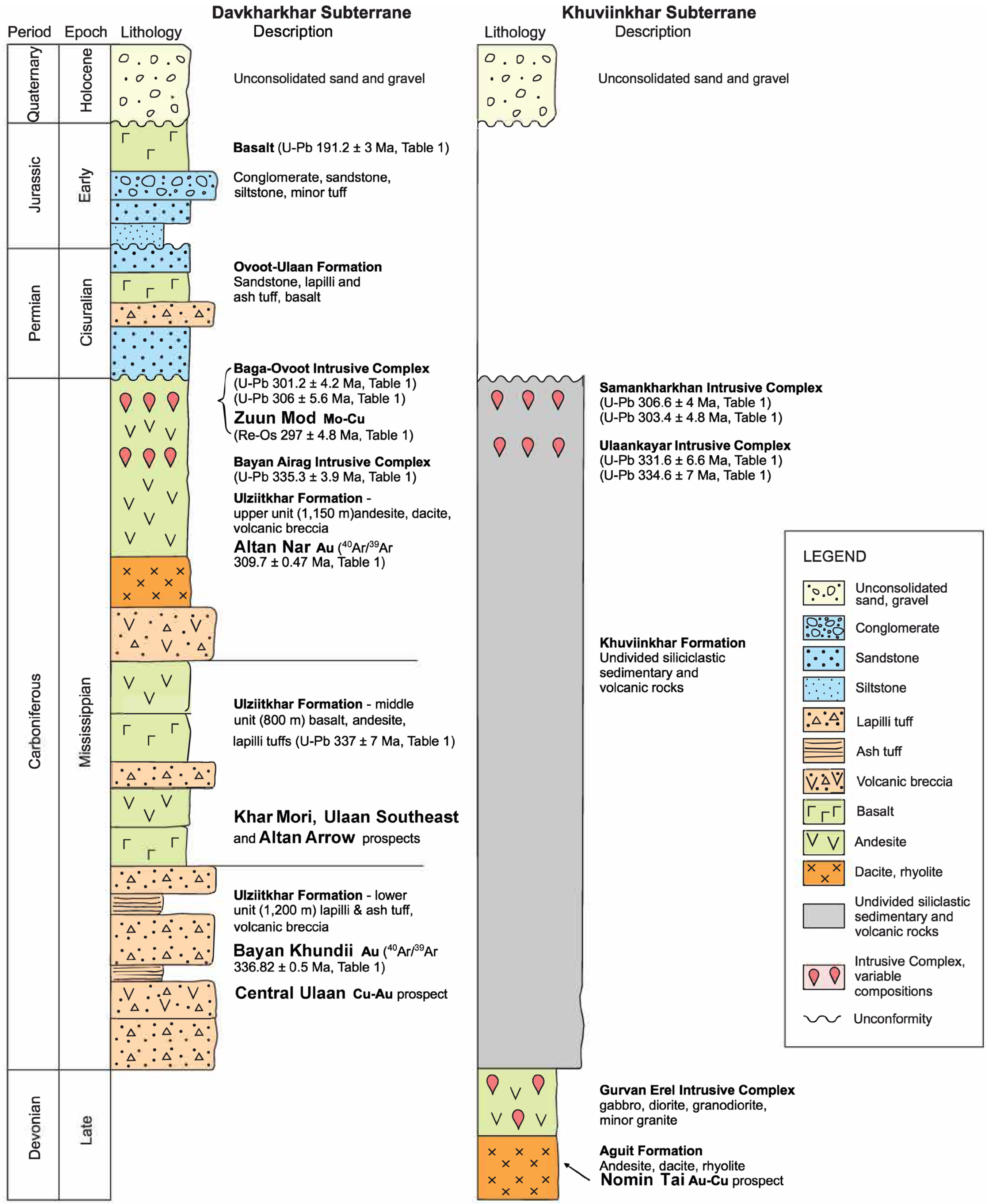

Fig. 3. Stratigraphic column for the Davkharkhar and Khuviinkhar subterranes of the Trans-Altai terrane, with host units for the major deposits in the Khundii metallogenic province and geochronological data for major units and mineral deposits from Table 1.

Table 1. Compilation of Geochronological Data for the Khundii Metallogenic Province

Unit/deposit	Method	Age	Period	Reference/source	Sample description
Cover rocks	U/Pb	191.2 ± 3 Ma	Early Jurassic	Lhundev et al., 2019	Zircon from basalt
Zuun Mod Mo-Cu deposit	Re-Os	297 ± 4.8 Ma	Permian (Cisuralian)	Altankhuyag et al., 2023	Molybdenite from B-type mineralized quartz veins
Baga Ovoot Intrusive Complex	U/Pb	301.2 ± 4.2 Ma	Carboniferous (Late Pennsylvanian)	Altankhuyag et al., 2012	Zircon from granodiorite which hosts the Zuun Mod Mo-Cu deposit
Baga Ovoot Intrusive Complex	U/Pb	301.8 ± 2.7 Ma	Carboniferous (Late Pennsylvanian)	Altankhuyag et al., 2023	Zircon from granodiorite which hosts the Zuun Mod Mo-Cu deposit
Baga Ovoot Intrusive Complex	U/Pb	306 ± 5.6 Ma	Carboniferous (Late Pennsylvanian)	Altankhuyag et al., 2012	Zircon from quartz monzonite near the Zuun Mod Mo-Cu deposit
Baga Ovoot Intrusive Complex	U/Pb	305.3 ± 3.6 Ma	Carboniferous (Late Pennsylvanian)	Altankhuyag et al., 2023	Zircon from quartz monzonite near the Zuun Mod Mo-Cu deposit
Samankharkhan Intrusive Complex	U/Pb	306.6 ± 4 Ma	Carboniferous (Late Pennsylvanian)	Togtogkh et al., 2019	Zircon from gabbro
Samankharkhan Intrusive Complex	U/Pb	303.4 ± 4.8	Carboniferous (Late Pennsylvanian)	Tumurkhuu and Otgonbaatar, 2013	Zircon from alkali leucogranite
Altan Nar Deposit	$^{40}Ar/^{39}Ar$	309.7 ± 0.5 Ma	Carboniferous (Middle Pennsylvanian)	This report	Adularia from mineralized quartz vein - Discovery Zone, Altan Nar gold-polymetallic deposit
Ulaankayar Intrusive Complex	U/Pb	331.6 ± 6.6 Ma	Carboniferous (Middle Mississipian)	Lhundev et al., 2019	Zircon from syenite
Ulaankayar Intrusive Complex	U/Pb	334.6 ± 7 Ma	Carboniferous (Middle Mississipian)	Lhundev et al., 2019	Zircon from quartz syenite
Bayan Airag Intrusive Complex	U/Pb	335.3 ± 3.9 Ma	Carboniferous (Middle Mississipian)	Lhundev et al., 2019	Zircon from monzonite
Bayan Airag Intrusive Complex	U/Pb	330 ± 12 Ma	Carboniferous (Middle Mississipian)	Hanzl et al., 2008	Zircon from granodiorite at the Khul Morit prospect
Bayan Airag Intrusive Complex	U/Pb	333 ± 2 Ma	Carboniferous (Middle Mississipian)	Javkhlan et al., 2022	Zircon from granite
Bayan Khundii Deposit	$^{40}Ar/^{39}Ar$	336.8 ± 0.5 Ma	Carboniferous (Middle Mississipian)	This report	Adularia from mineralized quartz vein - Bayan Khundii gold deposit
Ulziitkhar Formation	U/Pb	337 ± 7 Ma	Carboniferous (Middle Mississipian)	Lhundev et al., 2019	Zircon from andesite - Middle Member of the Ulziithar Formation

from each of the three members. The resulting map patterns are too complex to show at the scale of Figure 2. Despite the local folding of the Ulziitkhar Formation, the strike of the units in all three members is mostly northwest trending in the west, east to west trending in the south-central part of the district, and east-northeast to west-southwest trending to the east. This feature is similar to the arcuate shape of the adjacent Devonian volcanic and sedimentary rocks of the Edregiin Nuruu subterrane (Fig. 2), which we interpret as folding adjacent to a large crustal-scale sinistral fault.

Rocks of the Ulziitkhar Formation were intruded by multiple plutons and stocks of the Middle Mississippian Bayan Airag intrusive complex (Figs. 2, 3), ranging in composition from diorite, granodiorite, and monzonite to granite, quartz syenite, syenite, and alkali leucogranite. A U-Pb zircon age determination from monzonite returned a Middle Mississippian (Visean) age of 335.3 ± 3.9 Ma (Lhundev et al., 2019; Table 1), interpreted to be the crystallization age. Hanzl et al. (2008) reported a similar U-Pb zircon age of 330 ± 12 Ma for granodiorite of the Bayan Airag intrusive complex, collected from the Khul Morit Cu-Ag prospect (Fig. 2). Javkhlan et al. (2022) also reported a similar U-Pb zircon age of 333 ± 2 Ma for a granite from the Bayan Airag intrusive complex. Sinuous contacts between many small intrusive plugs and the host Ulziitkhar Formation (Fig. 2) suggest that the level of erosion is near the roof zones of the Bayan Airag intrusions.

The Ulziitkhar Formation was also intruded by the Late Pennsylvanian to early Permian Baga Ovoot intrusive complex (Lhundev et al., 2019), ranging from an early phase of quartz monzonite with U-Pb zircon ages of 305.3 ± 3.6 Ma (Altankhuyag et al., 2023; Table 1) and 306 ± 5.6 Ma (Altankhuyag et al., 2012; Table 1), a main phase of leucogranite, granite, and minor quartz syenite, and a late phase of leucogranite porphyry. A granodiorite phase of the Baga Ovoot complex that hosts the Zuun Mod Mo-Cu deposit returned U-Pb zircon ages of 301.8 ± 2.7 Ma (Altankhuyag et al., 2023; Table 1) and 301.2 ± 4.2 Ma (Altankhuyag et al., 2012; Table 1).

The area south of the Bayan Khundii gold deposit mostly consists of Permian to Jurassic siliciclastic sedimentary rocks, flood basalt units, and minor tuffaceous rocks, which unconformably overlie the Carboniferous volcanogenic and intrusive rocks (Figs. 2, 3). A U-Pb zircon age for a flood basalt in the upper member returned an Early Jurassic age (191.2 ± 3 Ma; Lhundev et al., 2019; Table 1).

Khuviinkhar subterrane: The northern portion of the Khundii metallogenic province is underlain by the Khuviinkhar subterrane, comprising andesite, dacite, and rhyolite of the Devonian to Carboniferous Aguit Formation (Lhundev et al., 2019) and overlying Early Carboniferous Khuviinkhar Formation of mixed siliciclastic and volcanic rocks in a large basin. The Nomin Tal Cu-Au prospect (Figs. 2, 3) is the only notable mineral occurrence known in this subterrane, albeit close to the terrane boundary with the Davkharkhar subterrane and the Altan Nar deposit. Despite lacking in notable discoveries, the Khuviinkhar subterrane reports several Au-in-soil anomalies, Au-, Pb-, and Mo-in-stream sediment anomalies, and precious and base metal showings identified during early exploration.

The Aguit Formation and overlying Khuviinkhar Formation were intruded by three separate granitoid complexes (Lhundev et al., 2019; Fig. 3), including the following: (1) a Devonian-Carboniferous Gurvan Erel intrusive complex comprising mainly gabbro, diorite, granodiorite, and a late granite phase; (2) a Middle Mississippian Ulaankayar intrusive complex, consisting of an early phase of quartz monzonite and quartz monzodiorite and a monzonite porphyry phase, followed by quartz syenite and syenite with a U-Pb zircon age of 331.6 ± 6.6 Ma (Lhundev et al., 2019; Table 1); (3) a late phase of quartz syenite and syenite with a U-Pb zircon age of 334.6 ± 7 Ma (Lhundev et al., 2019; Table 1); and (4) the Late Pennsylvanian Samankharkhan intrusive complex that consists of an early phase of monzonite, monzodiorite, and gabbro with a U-Pb zircon age of 306.6 ± 4 Ma (Togtogkh et al., 2019; Table 1); a main phase of alkali leucogranite, granite porphyry, and rhyolite porphyry with a U-Pb zircon age of 303.4 ± 4.8 Ma (Tumurkhuu and Otgonbaatar, 2013; Table 1); and a late phase of alkali leucogranite.

Structural kinematic framework

The Trans-Altai terrane has a dominant regional WNW-trending accretionary tectonic trend of compressional foliations, folds, and thrusts, which reflects a prolonged history of Devonian-Carboniferous and Permian-Jurassic plate convergence, crustal shortening, and development of the broader Central Asian orogenic belt (e.g., Kroner et al., 2010). The degree of deformation, however, was reported to be heterogeneous, with structural disruption being most intense and continuous along terrane and subterrane boundaries, and with less-deformed areas such as within the Khundii metallogenic province preserved in between (Lehmann et al., 2010).

The results from a regional gravity survey commissioned by the Mongolian government over a portion of the Trans-Altai terrane, including the Khundii metallogenic province (Fig. 4), outline a series of ENE-trending structures which are interpreted to reflect sinistral movement along basement structures that offset the gravity patterns. Gravity data indicate the rocks of the northern Khuviinkhar subterrane have a lower density than those of the Davkharkhar subterrane to the south. The Altan Nar and Bayan Khundii gold deposits are located along or near two of the major east-northeast structures (Fig. 4). For the Khundii metallogenic province, our analysis of topographic relief, ASTER satellite imagery, and geophysical maps, with spot checks in the field, distinguished three sets of structures on the basis of their orientation and length, relationship to granitoid intrusions, and crosscutting relationships.

The largest and oldest set comprises first-order ENE-trending lithospheric scale lineaments that can be traced across Mongolia for over 2,000 km (Dolgopolova et al., 2013). Despite the great length of these lineaments, most have limited offsets, suggesting that they are deep-seated, inherited basement structures. In the Khundii province, their surface expression is somewhat cryptic; however, at least two such structures coincide with local gravity anomalies (Fig. 4), and as noted, the Altan Nar and Bayan Khundii deposits are located along two separate east-northeast structures. The general geologic map pattern as well as the gravity breaks indicate a sinistral horizontal component of offset.

A second set comprises structures that trend northeast and individually are 10- to 20-km-long en echelon fault segments (Fig. 4) that collectively define the east-northeast lithospheric trend. These structures follow lithological contacts, contacts with intrusions, and topographic lows, without an obvious horizontal component of offset. This set of NE-trending faults, including those at the Bayan Khundii deposit, are interpreted as a series of normal faults with dip-slip displacement. These extensional faults are interpreted to have formed the controlling structures at Bayan Khundii based on surface maps and drilling data, including the orientation of volcanic layering, faults, veins, and granitoid dikes. Model integration of structural data in three dimensions indicates a set of tilted extensional fault blocks in which gold was deposited in a fractured relay-ramp structure (Fossen and Rotevatn, 2016) between the fault tips of two soft-linked normal faults (Fig. 5). The overall en echelon asymmetry and distribution of the faults is consistent with a sinistral horizontal component of movement along the first-order east-northeast trend, indicating NNE-SSW–directed crustal shortening. En echelon normal fault arrays are expected as second-order structures in zones with a horizontal component, as demonstrated by the sandbox models of Dooley and Schreurs (2012).

A third set of smaller, N-S–trending, 10- to 15-km-long lineaments are present throughout the area of detailed structural analysis (blue lines in Fig. 4). These lineaments are commonly bounded by the NE-trending extensional faults and have an orientation of dextral, conjugate Riedel shears within the sinistral ENE-trending slip system (see Dooley and Schreurs, 2012, for examples). One of these north-south structures hosts the Khar Mori gold project (details below) and can be traced for ~3 km to the south where it connects to the extensional faults of the Bayan Khundii deposit.

All three sets are interpreted to have been active coevally and formed a complex connected network at the time of mineralization (336.8 ± 0.5 Ma at Bayan Khundii), each contributing to the focusing of gold-bearing fluids.

Known mineralization styles in the province

Three distinct styles of hydrothermal mineralization have been identified within the Khundii metallogenic province, with details provided in the following sections. These include the following:

1. Epithermal vein and disseminated gold mineralization are present in a ~2- by 7-km belt at Bayan Khundii (336.8 ± 0.50 Ma), Ulaan Southeast, Khar Mori, and Altan Arrow. Gold mineralization occurs in adularia-bearing, comb-textured quartz veins and disseminations, poor in sulfides and hosted by lapilli and ash andesite tuffs. The epithermal quartz veins and illite-adularia alteration clearly overprint earlier lithocap-related alteration, the latter typical of the tops of porphyry deposits (Sillitoe, 2010).
2. Epithermal polymetallic (Au-Ag-Pb-Zn ± Cu) vein mineralization at the Altan Nar deposit (309.7 ± 0.5 Ma), 16 km northwest of Bayan Khundii, has multiple occurrences within a 1.5- by 5.5-km Pb-Zn-Au soil anomaly. Mineralization is associated with northeast-southwest and lesser

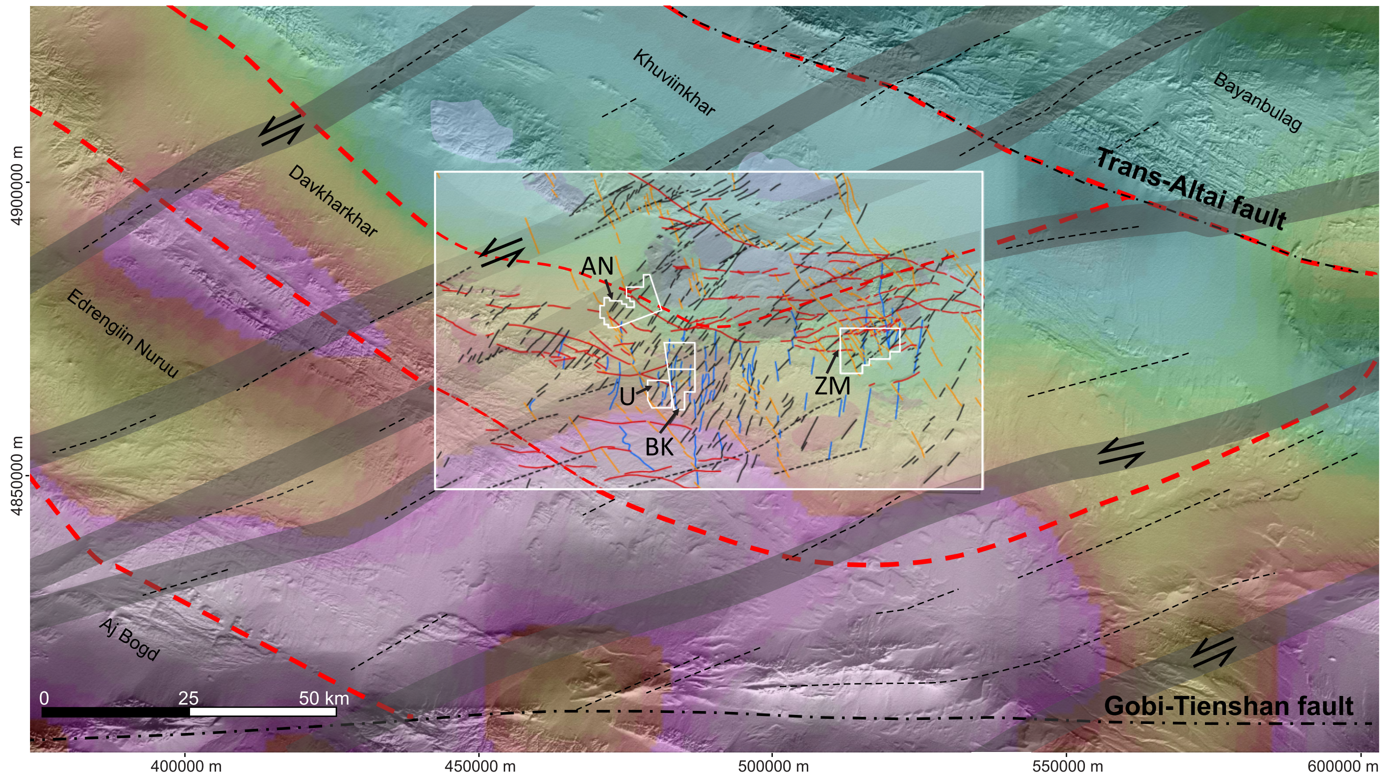

Fig. 4. Gravity map (courtesy of Getech; warm colors for gravity high, cold colors for gravity low) superimposed on topographic relief for the Khundii metallogenic province. Red dashed lines indicate the boundaries of five subterranes. The general location and trend of six first-order, ENE-trending, inherited basement lineaments (gray shaded bands) were interpreted based on topographic lows and geologic breaks. South of the Khundii province, these lineaments coincide with steps in the regional gravity pattern. The gravity breaks and the general geologic map patterns indicate a sinistral horizontal component of offset. The detailed structural map (white box) of the Khundii metallogenic province shows fault sets, including an east-northeast cryptic trend (set 1, gray shading), northeast extensional faults (set 2, in black), and N-S–trending dextral steep set (set 3, in blue). The solid red lines are contractional fabrics, foliations, folds, and thrusts. Erdene's tenement boundaries are shown in thin white lines, with locations of the Altan Nar (AN), Bayan Khundii (BK), and Zuun Mod (ZM) deposits and the Ulaan exploration license (U).

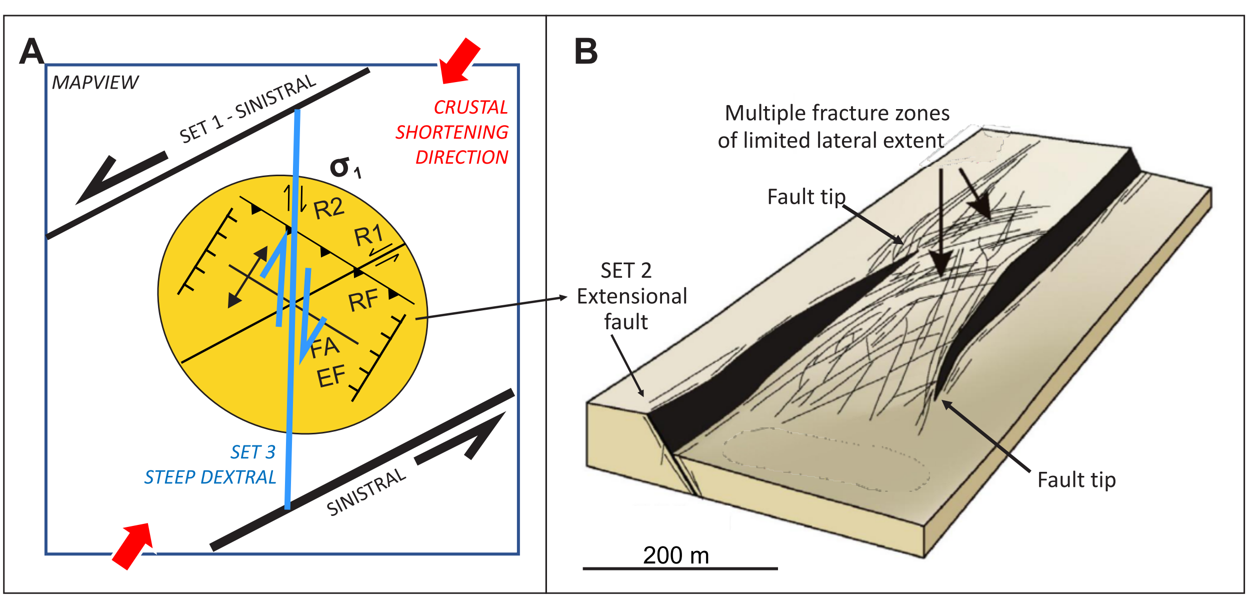

Fig. 5. A) Kinematic interpretation of the sinistral slip on the ENE-trending fault system (set 1) that developed second-order extensional faults (set 2) and N-trending shears (set 3). This structural interpretation explains how extensional faults were developed at Bayan Khundii, with the potential for dilation along both the NE-trending segments and N-trending structures at the time of crustal shortening. B) Block model of an extensional relay ramp, illustrating how multiple fracture zones of limited length at Bayan Khundii trend at high angles to the extensional faults.

north-south faults and shears, especially within dilational jogs in these structures, with galena and sphalerite (± chalcopyrite) plus Fe-, Mn-, and Mg-carbonate gangue minerals. Alteration includes Fe- and Mg-chlorite, tremolite, actinolite, and epidote, with zones of intense white mica alteration.

3. Porphyry Mo-Cu mineralization is present at the Zuun Mod deposit (297 ± 4.8 Ma; Re-Os for molybdenite; Table 1), plus several Cu-Ag ± Mo porphyry-style occurrences within the ~4-km-diameter Zuun Mod-Khuvyn Khar porphyry complex. Molybdenite and chalcopyrite occur with B-type quartz veins in a granodiorite intrusion with potassic alteration, as well as pervasive quartz-white mica ± pyrite on the margins. Zuun Mod has recently been studied by Altankhuyag et al. (2023).

A few kilometers northwest of Bayan Khundii, in the central Ulaan project (~35 km west-southwest of Zuun Mod), low-level Cu anomalies in soils (≤235 ppm) and scout drilling (to ~300 m depth; ≤308 ppm) are associated with widespread quartz-white mica-pyrite alteration, interpreted as representing the upper level of a porphyry system (Sillitoe, 2010), likely associated with the lithocap-related alteration to the east and southeast, where it is overprinted by epithermal veins including those at Bayan Khundii.

Bayan Khundii-Ulaan Southeast-Khar Mori

The geology of the Bayan Khundii-Ulaan Southeast-Khar Mori area is presented in Figure 6, with geochronological data for both mineralization and main rock types (Table 1) noted in the stratigraphic column (Fig. 3). Interpretation of ASTER

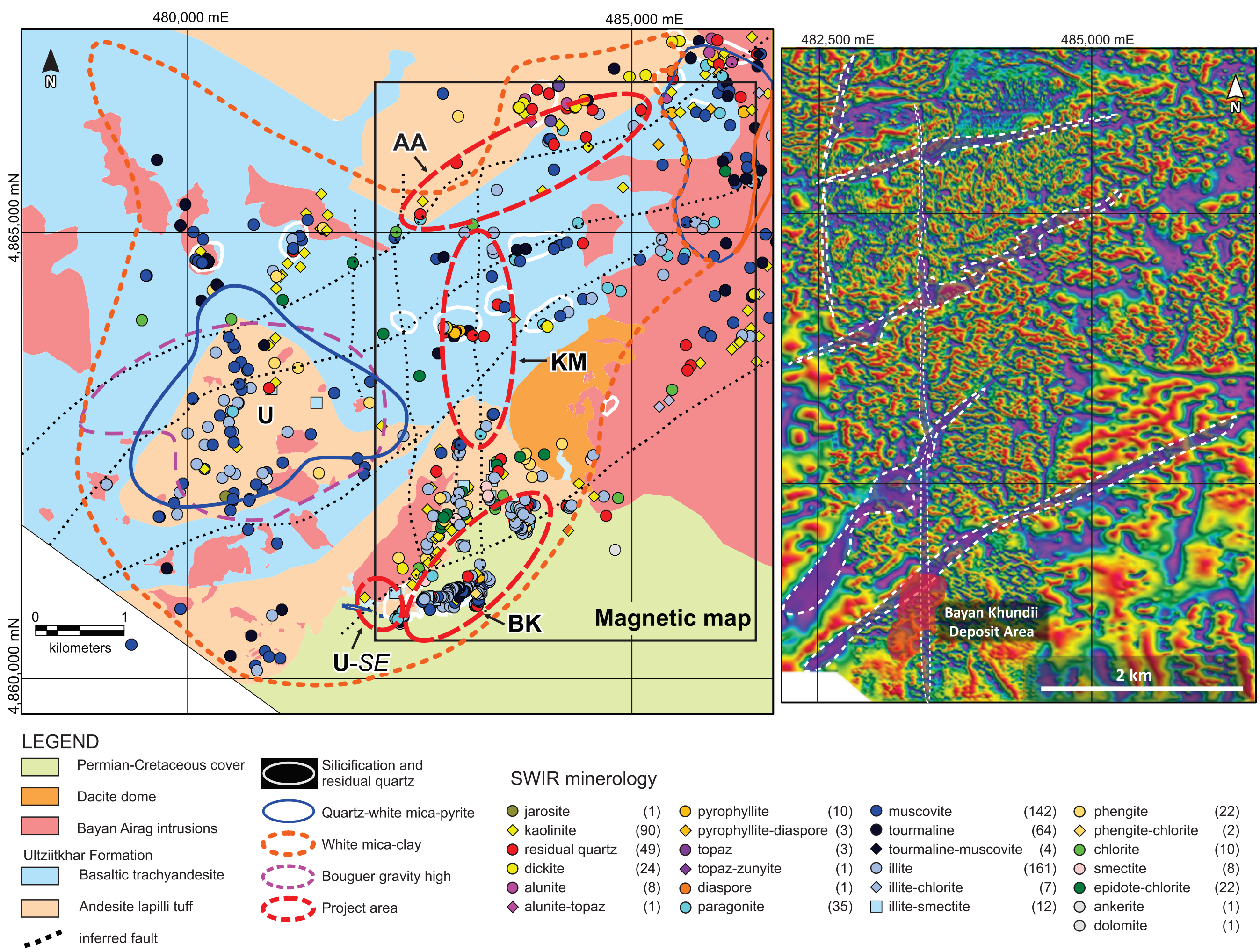

Fig. 6. Geology of the Bayan Khundii area from Erdene mapping and the locations of the Bayan Khundii (BK), Ulaan (U), Ulaan Southeast (U-SE), Khar Mori (KM), and Altan Arrow (AA) project areas. The extent of the white mica-clay alteration over most of the area was determined from reprocessed ASTER satellite data, indicated by a dashed orange line. The dashed purple line over the Ulaan project indicates the extent of a positive Bouguer gravity anomaly and the overlapping solid blue line indicates the area of intense quartz-white mica-pyrite alteration. Results from shortwave infrared (SWIR) analysis of surface samples and drill core are indicated by colored symbols (legend; residual quartz from hand lens identification). Inset image: Detailed ground magnetic surveys (tilt derivative) of the area noted by black box on the geology map. A series of N-S– and NE-SW–trending zones with low magnetic response on the magnetic map (purple-blue linear areas with white dashed outlines) are interpreted as zones of magnetite destruction in the host felsic tuffs and intermediate volcanic host rocks, correlating with intense white mica alteration.

satellite imagery outlined a broad, elliptical-shaped zone of white mica alteration over the central part of the map area (~6 × ~7 km in size). A program of detailed geologic mapping coupled with SWIR analyses of surface rock chip samples from this zone indicates a complex alteration history. Several alteration types include the following: (1) a widespread zone of weak to moderate white mica and clay alteration; (2) zones of more intense alteration, including quartz-white mica-pyrite alteration over the central part of the Ulaan prospect (2 × 3 km in size), that correspond with a positive gravity anomaly (Fig. 6); (3) several areas (100–500 m diameter) of strong silicification (Fig. 6), locally of residual quartz (Hedenquist and Arribas, 2022) origin, with spatially associated aluminosilicate alteration; this is interpreted as part of a now largely eroded lithocap of advanced argillic (pyrophyllite-dickite-kaolinite-alunite) alteration; and (4) illite-adularia alteration related to Bayan Khundii vein structures, which overprints these earlier alteration styles.

Bayan Khundii epithermal Au-Ag deposit

The Bayan Khundii gold discovery was made during prospecting and reconnaissance geologic mapping by Erdene (subsequently defined as the Striker Zone) following identification of an outcrop of intensely altered (K-feldspar and biotite plus quartz and adularia) and gold-mineralized tuffs of the lower Ulziitkhar Formation (Figs. 3, 7). These Middle Mississippian tuffs represent an erosional window, surrounded and unconformably overlain by Permian to Jurassic red-bed sedimentary strata and flood basalts. Assays of surface rock chips with comb-textured quartz veins from initial prospecting returned up to 4,380 g/t Au and were the guide to initial drill targeting. As noted above, an updated feasibility study was completed in 2023 based on 375 drill holes (total 56,249 m).

Unpublished but publicly available technical reports described the geology and mineralization of the Bayan Khundii gold deposit (MacDonald, 2017, 2018). The geologic map of the Khundii deposit and surrounding area (Fig. 7) shows that gold mineralization is hosted by andesite lapilli tuffs, with minor ash tuffs and block and ash tuffs of the lower member of the Ulziitkhar Formation (Fig. 3), all intensely altered. The presence of erosional features on the upper contact of the ore zone and the nature of alteration zones, coupled with the occurrence of unconformably overlying unaltered Permian red-bed strata and Jurassic flood basalts (Fig. 8), indicates that the mineralized tuffs were variably eroded prior to the deposition of the postmineral cover rocks. The lower portion of some of the deposit was intruded by postmineral alkaline granitoids (syenite, quartz syenite) of the Middle Mississippian Bayan Airag intrusive complex (Fig. 8). Thus, the original Bayan Khundii gold deposit was partially eroded, and part may also have been removed by intrusion.

Structural control: Gold mineralization is mostly hosted in parallel northwest-southeast, moderately dipping (~45° SW) zones that range in width from ~5 to ~150 m (Fig. 8). Within these zones gold mineralization consists of a series of high-grade intervals with good continuity within broad low-grade halos (mostly <0.1 g/t Au). Quartz veins within these zones have three main orientations, including the dominant northwest-southeast vein set with a moderate southwest dip, a conjugate and subordinate northeast-southwest set with a moderate southeast dip, and a minor N-S–trending vein set, steeply dipping to vertical. The presence of gold mineralization in sheeted SW-dipping zones (Fig. 8) indicates that structures were critical in formation of the deposit. The NW-SE–trending, SW-dipping ore zones contain numerous small individual veins and have a limited strike length (generally 100–200 m); however, the strike width is several hundred meters. Collectively, the mineralized zones define a volume with a NE-trending envelope interpreted as a relay-ramp structure (Fig. 5) between the fault tips of two parallel but stepping NE-trending normal faults, within an extensional structural domain. Several NE-trending fault sets and a north-south structure have a corresponding low magnetic response (Fig. 6) and are adjacent to and intersect the relay ramp, which may have provided permeability for mineralizing fluids.

Mineralization: Visible gold is common in drill holes at Bayan Khundii but is not always a good indicator of gold grade, as numerous samples have returned moderate to high gold values where no visible gold was noted during logging. Most gold is present as electrum, with 10.2 to 30.1 wt % Ag (mostly 24–30 wt % Ag), as indicated from a scanning electron microscope (SEM) study. In addition, gold grains of high fineness (97.5–100 wt% Au) are present as fracture infillings, as individual grains, and rarely as rims on individual electrum grains. Electrum is hypogene in origin, whereas the high fineness gold is supergene in origin, consistent with its association with goethite.

Visible gold is present in several modes, including the following:

1. Veins: Various textures are associated with gold:
   a. Massive-saccharoidal, laminar, and comb-textured quartz ± hematite (specularite) veins (Fig. 9A), which are mostly <1 to 2 cm wide and commonly have specularite and/or open space in vein centers and may have narrow colloform bands along vein margins. Within these veins gold is present (1) along prismatic quartz grain boundaries; (2) within the vein centers ± specularite; and (3) along vein margins.
   b. Multistage composite quartz-chalcedony-adularia ± specularite veins, commonly with a mottled texture (mostly <1–10 cm wide; Fig. 9B) and breccia zones with subrounded fragments of milky quartz-adularia or dark chalcedony, some with disseminated gold, rimmed by euhedral adularia crystals. Vein margins may have colloform bands, commonly with abundant fine-grained gold.
   c. Multistage quartz-adularia-chalcedony veins with bladed calcite, now pseudomorphed by lattice quartz, and dark gray, gold-rich chalcedony along vein margins.
   d. Large composite veins (up to ≥1 m wide) composed of a, b, and c-type veins, described above, which commonly are brecciated with a hematite matrix.
2. Breccias: Quartz-hematite breccias (from ~5 to 40 cm wide; Fig. 9C) contain subangular to subrounded fragments of quartz or tuffaceous rocks in a hematite matrix with fine-grained gold.
3. Disseminated: In intensely illite-quartz altered lapilli tuffs (Fig. 9D), where gold is commonly associated with hematite that partially or completely replaced early-stage pyrite.

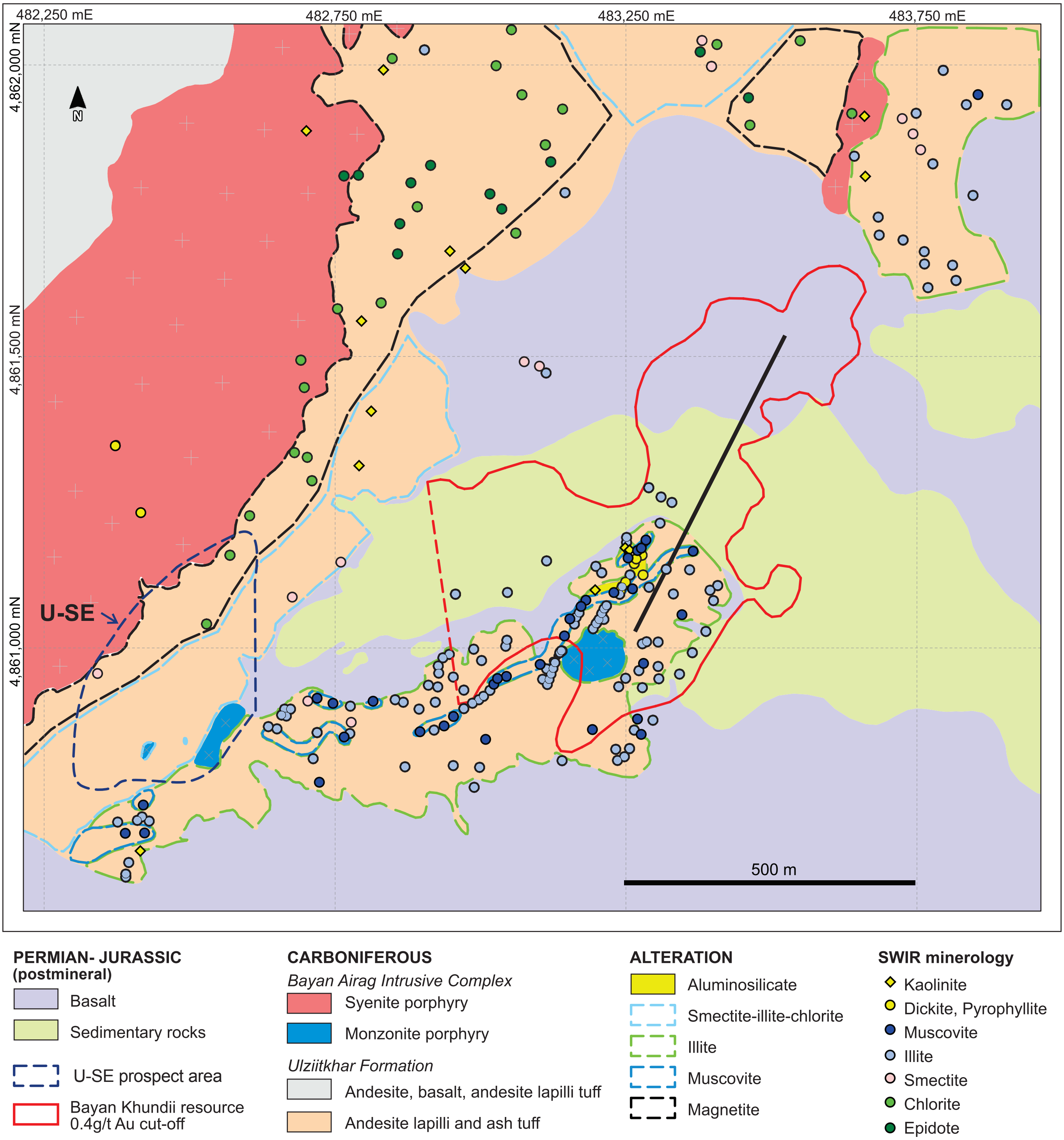

Fig. 7. Detailed geology map of the Bayan Khundii gold deposit, showing the distribution of intensely altered (quartz-illite and quartz-muscovite) Carboniferous andesite lapilli and ash tuffs of the lower Ulziitkhar Formation, which host epithermal gold mineralization. The 0.4 g/t Au cutoff grade for the Bayan Khundii resource (red line) indicates the mineralized tuffs extend beneath the unmineralized cover rocks. The location of the Ulaan Southeast (U-SE) project is outlined by blue dashed line. Solid black line indicates the location of the northeast-to-southwest cross section in Figure 8. Altered tuffs are unconformably overlain by Permian-Jurassic postmineral sedimentary and volcanic rocks. Dominant alteration minerals in surface samples and drill core, as determined by shortwave infrared (SWIR) analysis, are indicated by colored symbols (legend).

4. Fractures: High-fineness gold is present along late fractures, microfractures, and joints, commonly associated with supergene hematite, goethite, or jarosite.

Some zones in the northwest part of the Bayan Khundii deposit contain 1 to 2% pyrite, which is present both as disseminated grains and as sulfide veins. Most pyrite-bearing zones have low gold concentrations. The variably replaced disseminated pyrite is thought to have formed during earlier alteration, prior to epithermal gold deposition. This inverse relationship is interpreted as being due to the replacement of pyrite by hypogene hematite (Fig. 9D) as part of the gold mineralizing event.

Hematite, commonly as specularite, is a ubiquitous feature at Bayan Khundii and was observed in surface outcrop, trenches, and in drill core, where it is present (1) commonly within angular fractures that may contain wall rock fragments; (2) as central vein infilling and vein margins in comb-textured quartz veins; (3) as matrix in quartz-hematite breccias, commonly with angular clasts of illite-quartz–altered wall rock; (4) as disseminated grains that are interpreted as pseudomorphs that replaced early pyrite; and (5) as alteration selvages along the margins of fine-grained, dark gray quartz or chalcedony veins.

Some narrow specularite veinlets (<1–2 mm wide), observed in drill core, have medium gray alteration selvages (≤2 cm) of intense silicification and illite alteration, indicating a primary hydrothermal origin. The presence of visible gold in some hematite (specularite) veinlets (Fig. 9D) establishes a genetic relationship between the gold, quartz-illite alteration, and hematite-forming fluids. Similarily, the association of specularite and gold in the central parts or within the margins of comb-textured quartz veins also supports a primary hydrothermal origin for specularite at Bayan Khundii.

Most of the Bayan Khundii deposit contains only trace amounts of sulfide minerals, including pyrite, arsenopyrite plus an As-rich sulfide (likely arsenian pyrite), and minor sphalerite, galena, chalcopyrite, and tennantite-tetrahedrite. This is reflected in the geochemistry of the deposit, with relatively low concentrations of Pb (16 ppm avg.; <2–249 ppm range), Zn (77 ppm avg.; <2–2,749 ppm range; only three samples > 1,000 ppm), and Cu (20 ppm avg.; <1–3,107 ppm range; only two samples > 1,000 ppm) in 20,739 samples of analyzed drill core (MacDonald, 2018). Despite these low concentrations, there are locally elevated levels of Mo, S, and As in drill core. The average Mo concentration is 3 ppm, but Mo attains a maximum concentration of 551 ppm, with 11 samples containing more than 100 ppm, due to molybdenite. The average concentration of As is low (70 ppm), but the maximum value is 10,800 ppm; 45 samples returned more than 1,000 ppm As, reflecting the presence of either arsenopyrite or arsenian pyrite. The average S concentration is 0.12%, but the maximum is 5.0%, with 414 samples (2%) containing more than 1.0% S and 1,368 samples (6.6%) containing more than 0.5% S. Based on analyses, there are sulfide-bearing zones at Bayan Khundii that contain As-, Mo-, Cu-, Zn-, and to a lesser extent P-bearing mineral species. Petrographic examination indicates some of the disseminated Fe sulfides in the host tuffs were altered to supergene goethite or jarosite.

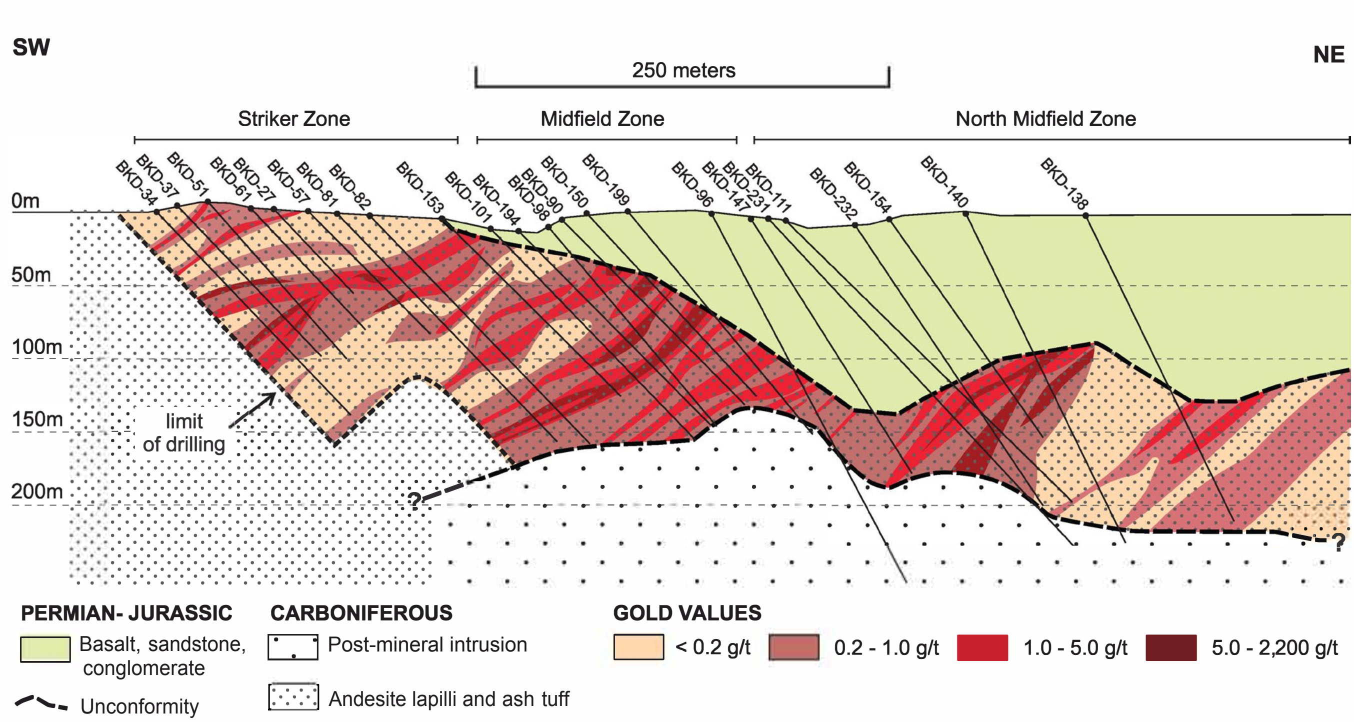

Fig. 8. NE-SW–trending cross section through the Striker, Midfield, and North Midfield zones of the Bayan Khundii gold deposit, based on information from drilling in 2015 to 2017 (cross section location on Fig. 7). Mineralized zones are hosted by andesite lapilli and ash tuffs (fine stippled pattern) and have a consistent northwest trend and dip to the southwest at approximately 45°. A postmineral syenite intrusion (coarse stippled pattern) intruded the lower parts of the deposit; the upper part of the deposit shows erosional features and is unconformably overlain by Permian to Jurassic sedimentary and volcanic cover rocks (green). Average Au assay results (<0.2, 0.2–1.0, >1.0–5.0, and >5–2,200 g/t Au) are indicated by variations of red shading.

There are no veins or breccias, mineralized or otherwise, in the Permian-Jurassic–age sedimentary and basaltic rocks that unconformably overlie the Ulziitkhar Formation, indicating that these units represent a postmineral cover sequence. Some gold ± silver enrichment has been noted in the basal conglomerate, which contains angular, altered, and possibly mineralized Carboniferous tuff clasts directly above the unconformity. A strongly mineralized 1-m interval (51.2 g/t Au) of basal conglomerate was intersected directly above altered and mineralized tuff in the Midfield Zone (Fig. 8). Petrographic analysis identified several gold grains associated with acicular tourmaline within Fe-Mg-Ca carbonate facies that replaced the matrix of the basal conglomerate. The origin of this gold mineralization is unclear; however, the petrographic evidence suggests the gold associated with hydrothermally altered conglomerate is restricted to the Paleozoic-Jurassic contact zone, and may reflect post-Permian hydrothermal activity along the contact.

Alteration: Some gold-bearing quartz veins have narrow (<1–2 mm wide) illite-quartz alteration selvages, but most quartz veins at Bayan Khundii do not have visible alteration selvages, as the tuffaceous host rocks are altered to an assemblage of illite (Al-OH SWIR values ranging from 2,206 to 2,208 nm) or illite-smectite, plus adularia with pervasive silicification, as well as local chlorite, rutile, hematite, and Fe/Mg/Ca-carbonate minerals. The illite with adularia overprints local occurrences of earlier-formed lithocap-style alteration, with residual quartz plus pyrophyllite, dickite, and kaolinite, and rare occurrences of alunite, topaz, and diaspore (Fig. 6); illite alteration is best developed in finely laminated tuffs (Fig. 7).

Adularia from a mineralized quartz vein from the Bayan Khundii deposit was analyzed at the Western Australian Argon Isotope Facility (WAAIF) at Curtin University in Australia and returned a $^{40}Ar/^{39}Ar$ age of 336.8 ± 0.5 Ma (Table 1; Fig. 3; App. 1, Fig. A-1). The 337 ± 7 Ma U-Pb zircon age for

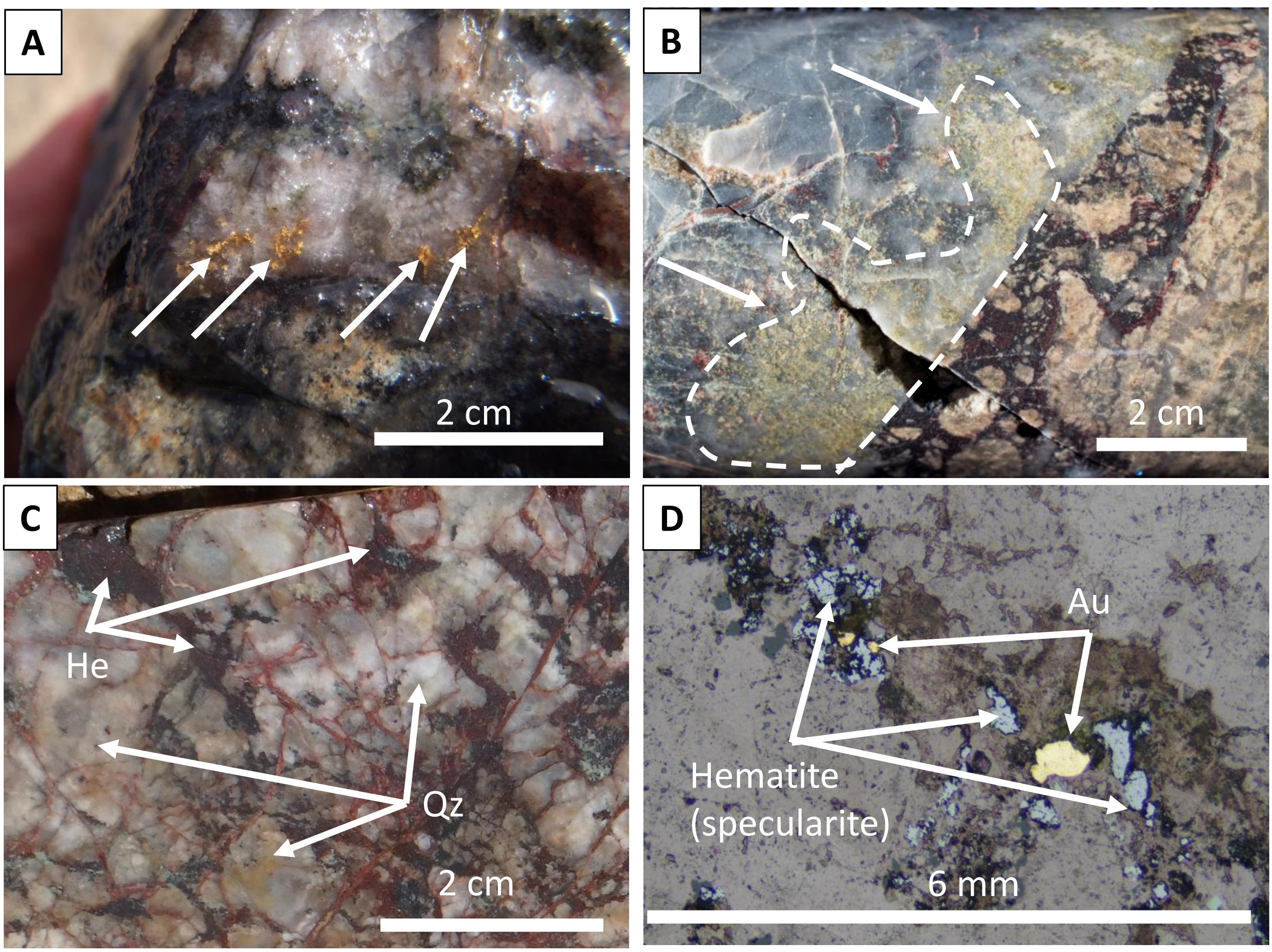

Fig. 9. Gold-bearing quartz veins from the Bayan Khundii Gold deposit. A) Recrystallized quartz-hematite (specularite) vein with remnant comb textures and specularite along vein margins and in vein core. Visible gold (VG) indicated by white arrows. B) Composite multistage quartz-chalcedony-adularia vein (abundant finely disseminated visible gold within white dashed line). Multistage hydrothermal brecciation and quartz veining is evident, including the dark reddish-brown hematite breccia with subangular fragments and quartz veins that cut altered tuff along the right side of the sample. C) Hydrothermal quartz (Qz)-hematite (He) breccia with mottled quartz (variably recrystallized) and hematite patches and veinlets. D) Photomicrograph of electrum (Au) intergrown with hematite (specularite) which has replaced early-stage pyrite.

the middle unit of the Ulziitkhar Formation (Table 1; Fig. 3; Lhundev et al., 2019), which overlies the lower member that hosts the Bayan Khundii deposit, indicates gold mineralization formed soon after tuff deposition.

Petrographic examination indicates that matrix quartz in the altered host lapilli tuffs (quartz, K-feldspar, tremolite/actinolite) has polygonal textures, commonly with 120° triple points, typical of high-temperature porphyry quartz (e.g., Tsuruoka et al., 2021). Fluid inclusions in early-stage quartz veins contain translucent daughter minerals, locally cubic (halite), accompanied by opaque daughter minerals in some samples. This observation indicates a high-salinity liquid (>23 wt % NaCl equiv) during formation of the granular quartz, typical of hypersaline liquids associated with porphyry-related intrusions (Roedder, 1984), which supports the high-temperature nature of early alteration (K-feldspar and local biotite, plus an overprint of advanced argillic assemblages of pyrophyllite, etc.; Fig. 6). By contrast, the later epithermal veins with mosaic quartz textures contain only two-phase liquid-vapor fluid inclusions.

Some tourmaline breccias and tourmaline alteration zones to the west of the Striker Zone (Fig. 6) contain brecciated fragments of quartz veins and also comb-textured quartz overgrowths on tourmaline-altered fragments, suggesting that quartz veining and the tourmaline event, west of Bayan Khundii, locally may have overlapped. The relationship between gold mineralization and tourmaline is unclear, although limited gold mineralization has been encountered to date west of the Striker zone where the tourmaline is located; there is only rare to trace tourmaline in the Striker and Midfield zones of gold mineralization, suggesting the tourmaline and comb quartz overgrowths were separate events.

Paragenesis: The results of geologic and petrographic studies of the Bayan Khundii deposit indicate two distinctly different events of alteration and mineralization followed by supergene weathering (Figs. 10, 11):

1. Porphyry event: Lapilli and minor ash tuffs, which host the Bayan Khundii deposit, were initially altered to K-feldspar, actinolite/tremolite, equigranular and polygonal quartz (Fig. 10A), and minor biotite, magnetite, and apatite; trace amounts of chalcopyrite (altered to supergene Cu oxides; Fig. 10B) and disseminated pyrite and minor sphalerite are locally intergrown with this early alteration assemblage (Fig. 10C). The areas of residual quartz plus pyrophyllite, dickite, and/or kaolinite (Fig. 6) are typical of the margins and roots of porphyry-related lithocaps (Sillitoe, 2010; Hedenquist and Arribas, 2022).
2. Epithermal event: After significant erosion, distinctly different alteration and mineralization was superimposed on the early assemblage, consisting of mosaic-drusy quartz veins plus adularia and illite (Fig. 10D). Where not oxidized, sulfide minerals include pyrite and arsenopyrite plus an As-rich sulfide, locally encapsulated in vein quartz. Crystalline hematite (specularite) of hypogene origin is intergrown with mosaic quartz in veins. As noted above, the gold occurs as electrum in several types of quartz ± specularite ± chalcedony ± adularia veins, hematite fractures and veinlets, and hematite breccias, although disseminated electrum in the host tuffs (Fig. 10E) is associated with some low-grade ore zones.
3. Supergene event: Weathering subsequent to the porphyry and epithermal events caused the formation of supergene alteration minerals; Fe sulfide minerals (pyrite, arsenopyrite, possibly arsenian pyrite), initially of low concentration, were altered to supergene goethite and jarosite, and chalcopyrite was altered to covellite, cuprite, and chalcocite. High-fineness gold (97.5–100% Au) of supergene origin occurs intergrown with goethite and along late-stage microfractures (Fig. 10F).

Ulaan Southeast epithermal gold satellite project

The Ulaan Southeast project is located ~800 m west of the Bayan Khundii gold deposit, in a previously (prior to 2020) underexplored portion of the Ulaan prospect area (Fig. 6). The area is underlain by silicified and illite-altered lapilli andesite tuffs which are similar in composition and have the same alteration assemblage as the host rocks for the adjacent Bayan Khundii gold deposit. Initial exploration results indicate the mineralized and altered zone(s) at Ulaan Southeast extend to the west and north beneath weakly altered andesite units.

Rock-chip samples of quartz-hematite ± adularia veins collected in the southern part of the Ulaan exploration license returned anomalous gold concentrations, up to 13 g/t Au. This led to soil sampling, with several areas of Au-in-soil anomalies identified in the southeast portion of the Ulaan prospect, which were followed up with a scout drilling program in 2021. One initial drill hole included an intersection of 258 m interval that averaged 0.98 g/t Au, and subsequent drilling cut higher-grade zones, including 8.1 g/t Au over 41 m from 187 m downhole (UDH-35). Field evidence suggests the Ulaan Southeast project is a continuation of the Bayan Khundii gold deposit; mapping indicates that quartz-illite alteration is continuous from Ulaan Southeast to Bayan Khundii (Figs. 6, 7). Gold mineralization encountered in drill core is associated with quartz-hematite ± adularia veins within wide zones of illite-altered and silicified lapilli tuffs with little to no sulfide minerals, thus resembling the adjacent Bayan Khundii deposit.

Khar Mori Au-Ag epithermal satellite project

The Khar Mori (Dark Horse) project is located ~3 km north of the Bayan Khundii gold deposit along a north-south structure that connects the two areas, as confirmed by linear trends in magnetic data (Fig. 6, inset). A geologic map of the Khar Mori prospect area (Fig. 12) shows mineralization focused along the north-south structure, which extends southward to the Bayan Khundii gold deposit. Gold-in-soil anomalies and local exposures of epithermal breccia and quartz stockwork veins have been traced from Bayan Khundii along this north-south structure.

The prospect was discovered in 2021 when multiple rock chip samples collected approximately 3 km north of the Bayan Khundii deposit returned >5 g/t Au values, including a 32.9 g/t Au sample of comb quartz-adularia veins. Stockwork veins crosscut an epithermal breccia zone developed in a silicified and illite-adularia altered quartz syenite intrusion of the Bayan Airag intrusive complex (Fig. 2). Several vein types are present, including comb-textured quartz-adularia veins, sugary crustiform-textured quartz veins, and multistage

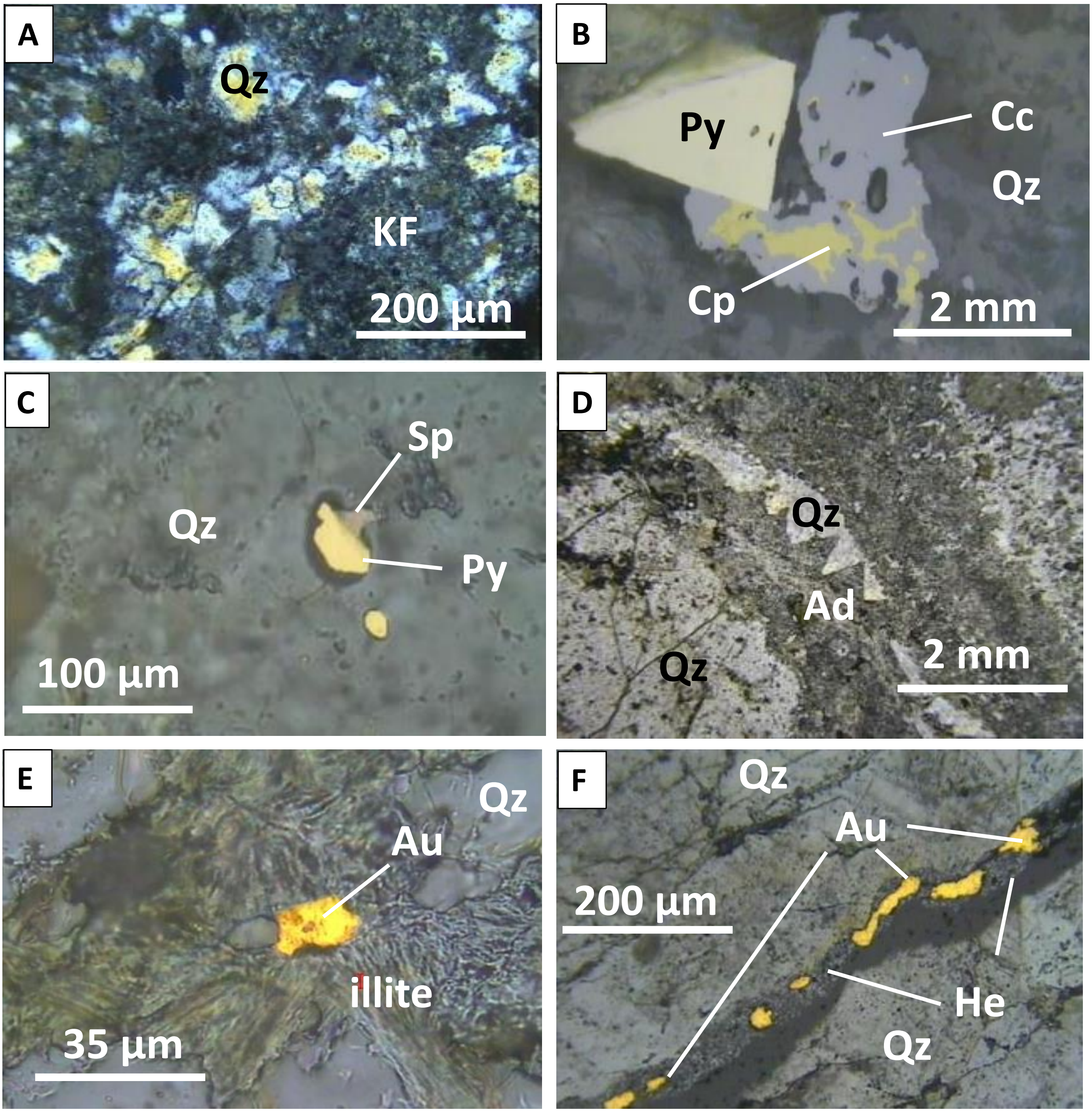

Fig. 10. Photomicrographs of samples from the Bayan Khundii gold deposit (cross-polarized light, CPL; plane-polarized light, PPL; reflected light, RL). Early porphyry event, A-C: A) alteration of host lapilli tuff to a mineral assemblage of polygonal-textured granular quartz (Qz), alkali feldspar (KF), and actinolite/tremolite (CPL); B) chalcopyrite (Cp) altered to supergene chalcocite (Cc) with euhedral pyrite (Py) in a quartz host (CPL); C) disseminated pyrite and minor sphalerite (Sp), locally intergrown with the early alteration assemblage of quartz (PPL/RL). Epithermal gold event, D-E: D) mosaic quartz central to euhedral adularia (Ad) (PPL/RL); E) Au/electrum (Au) intergrown with mosaic quartz and illite of epithermal replacement assemblage (PPL/RL). Supergene event: F) gold-hematite (He) veining in mosaic quartz (PPL/RL).

quartz-chalcedony veins. Recent drilling at Khar Mori (Erdene, 2022[1]) intersected a shallow (<60-m depth) oxide zone with high-grade gold mineralization (including a 5-m interval averaging 123.5 g/t Au) that lies above a deeper sulfide-rich zone (of pyrite, arsenopyrite, and arsenian pyrite) hosted by silicified and illite-altered lapilli andesite tuffs and volcanoclastic units.

Khar Mori shares many features with the Bayan Khundii gold deposit, including field and petrographic evidence for an early high-temperature event of K-feldspar-biotite-quartz alteration, and chalcopyrite encapsulated in quartz, as well as areas of lithocap-style alteration of residual quartz and pyrophyllite (Fig. 6). The early porphyry-like assemblages were overprinted by quartz-illite alteration associated with epithermal gold mineralization. A plot of gold versus silver (App. 2, Fig. B-1A) shows similar ranges to those at Bayan Khundii and Ulaan Southeast, with a wide range of Ag:Au ratios, from <1 to >10. Despite these similarities, Khar Mori has several features which differ from Bayan Khundii, including the following:

1. At Khar Mori there are 1 to 2 vol % Fe sulfide minerals (pyrite and arsenopyrite), locally up to 20 vol % combined sulfide minerals. By contrast, sulfide minerals are present in low concentrations (mostly trace, <1 vol %) in most of the Bayan Khundii deposit; hypogene Fe sulfide minerals (pyrite, arsenopyrite) have largely been replaced by goethite and jarosite at Bayan Khundii.
2. Gold is associated with, and possibly within the mineral structure of, arsenopyrite (possibly as elemental lattice-bound Au^{1+}, or nanoparticles of Au^0; Gopon et al., 2019) at Khar Mori, whereas at Bayan Khundii, gold occurs as electrum, plus some high-fineness supergene gold.
3. Average concentrations of As, Cu, Sb, and Mo from drill core samples (with >0.3 g/t Au) are higher at Khar Mori; average As concentration is 30 times higher (i.e., 1,700 ppm for Khar Mori vs. 65 ppm for Bayan Khundii; App. 2, Fig. B1-B), and Cu is five times higher (89 vs. 16 ppm); Sb (38 vs. 16 ppm) and Mo (12 vs. 5 ppm) are both twice as high at Khar Mori.
4. Khar Mori has well-developed structurally controlled supergene oxide zones, as defined by the presence of abundant Fe oxyhydroxide minerals (up to 15 wt % Fe_2O_3), which exceeds the Fe content of tuffs and andesite from the Ulziitkhar Formation (generally 5.5 to 7.5 wt % Fe_2O_3); gold of high fineness is encased by supergene oxidation products of arsenopyrite within the supergene zone, which may support the presence of nanoparticles of Au^0 in arsenopyrite. By contrast, Bayan Khundii lacks abundant Fe oxyhydroxide minerals, presumably reflecting the relatively low original sulfide content of the deposit, although at least some of the Fe sulfide minerals at Bayan Khundii have been altered to supergene goethite and jarosite.

Altan Nar Epithermal Polymetallic Deposit

The Altan Nar epithermal polymetallic deposit (Fig. 13), a greenfield discovery made in 2011 on the Tsenkher Nomin exploration license, is located ~16 km north-northwest of the Bayan Khundii gold deposit (Fig. 2). The host rocks are a series of andesite, andesite porphyry, and tuffaceous units of the up-

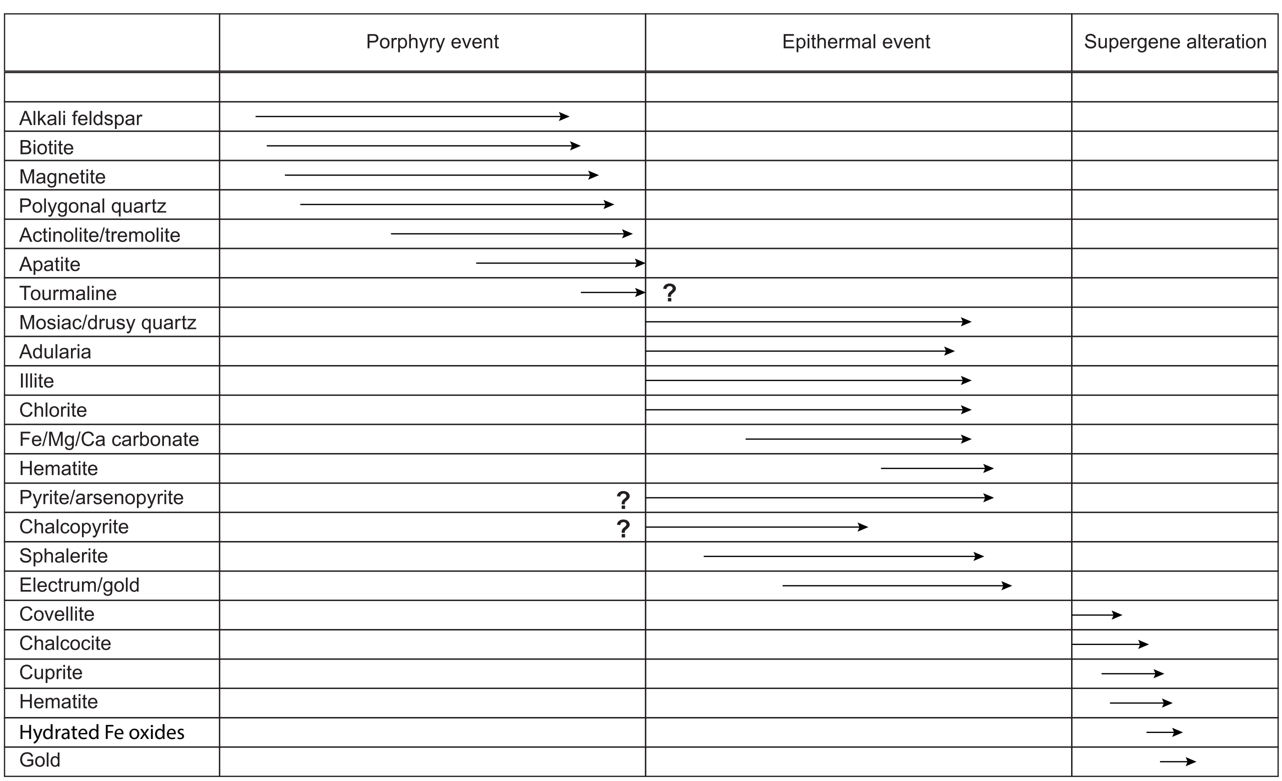

Fig. 11. Paragenetic sequence for the Bayan Khundii gold deposit outlining the mineralogy of (1) the early, intrusion-related porphyry alteration; (2) after erosion, the quartz-illite-adularia alteration overprint associated with formation of the Bayan Khundii epithermal deposit; and (3) late supergene alteration.

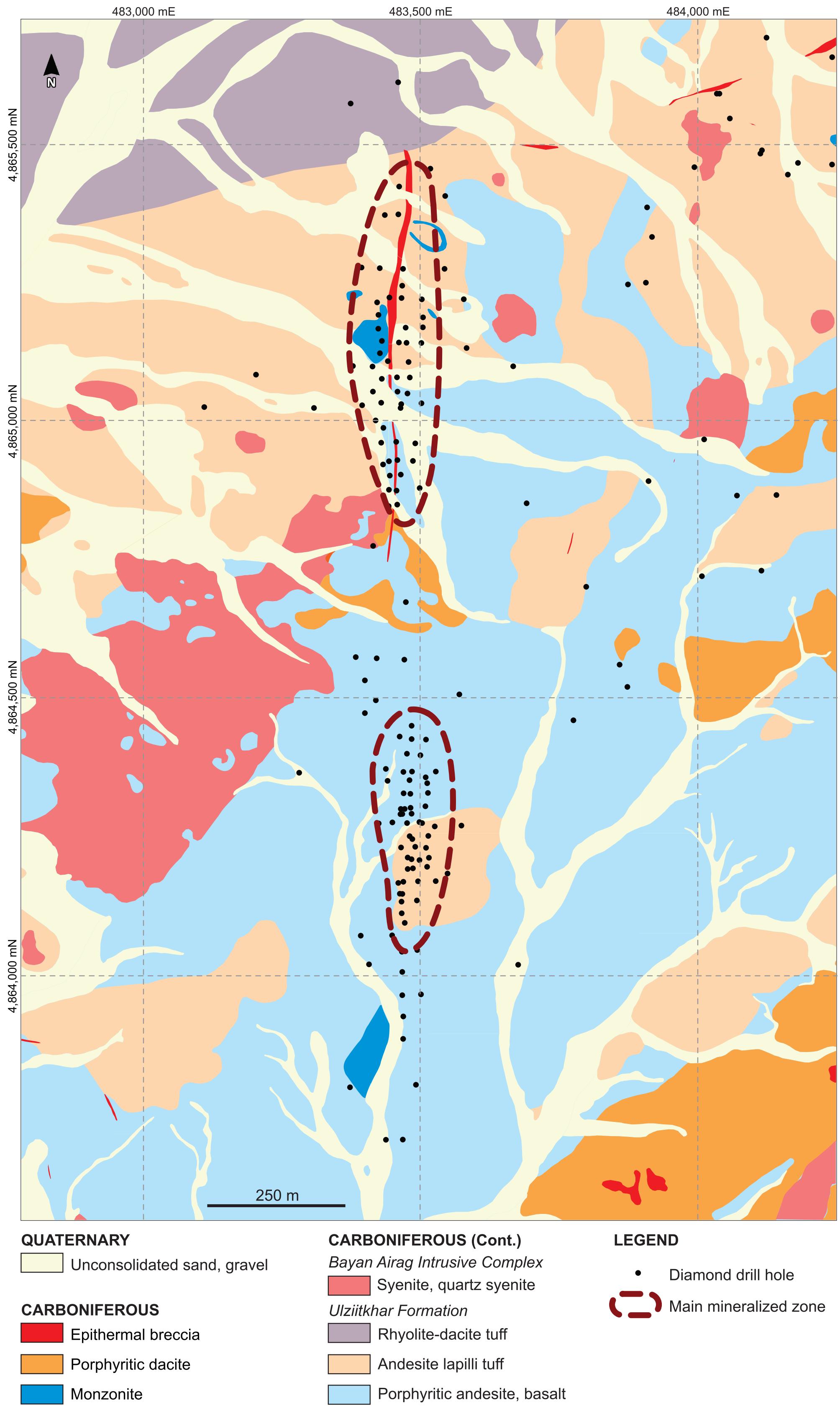

Fig. 12. Geologic map of the Khar Mori project area showing the mineralized zones, which are focused along and adjacent to a N-S–trending structure.

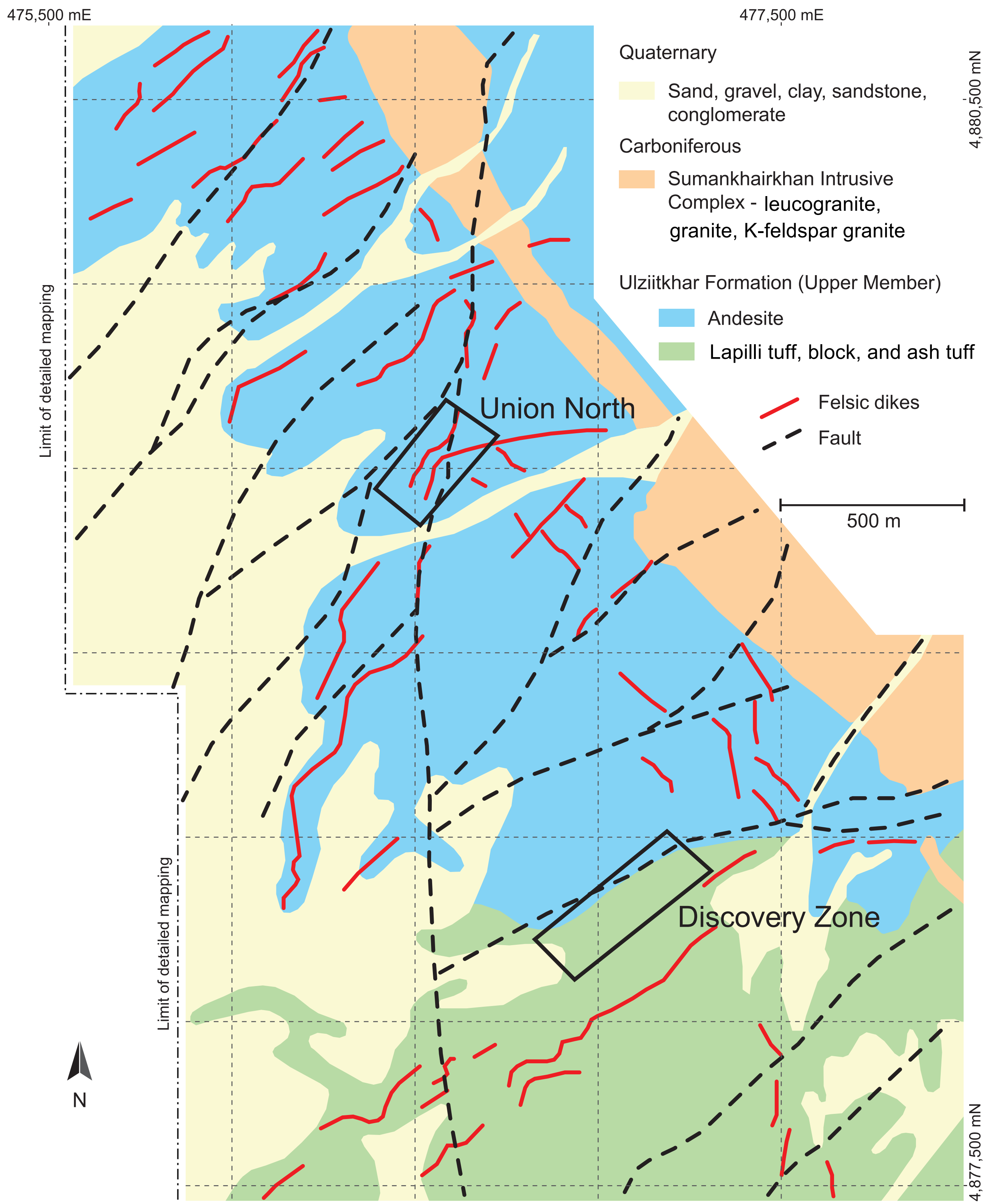

Fig. 13. Geologic map of the Altan Nar deposit showing the location of the Discovery Zone and Union North deposits. The Discovery Zone is located along an NNE-SSW–trending fault, which forms the contact between andesite porphyry (blue) to the north and tuffaceous rocks (green) to the south.

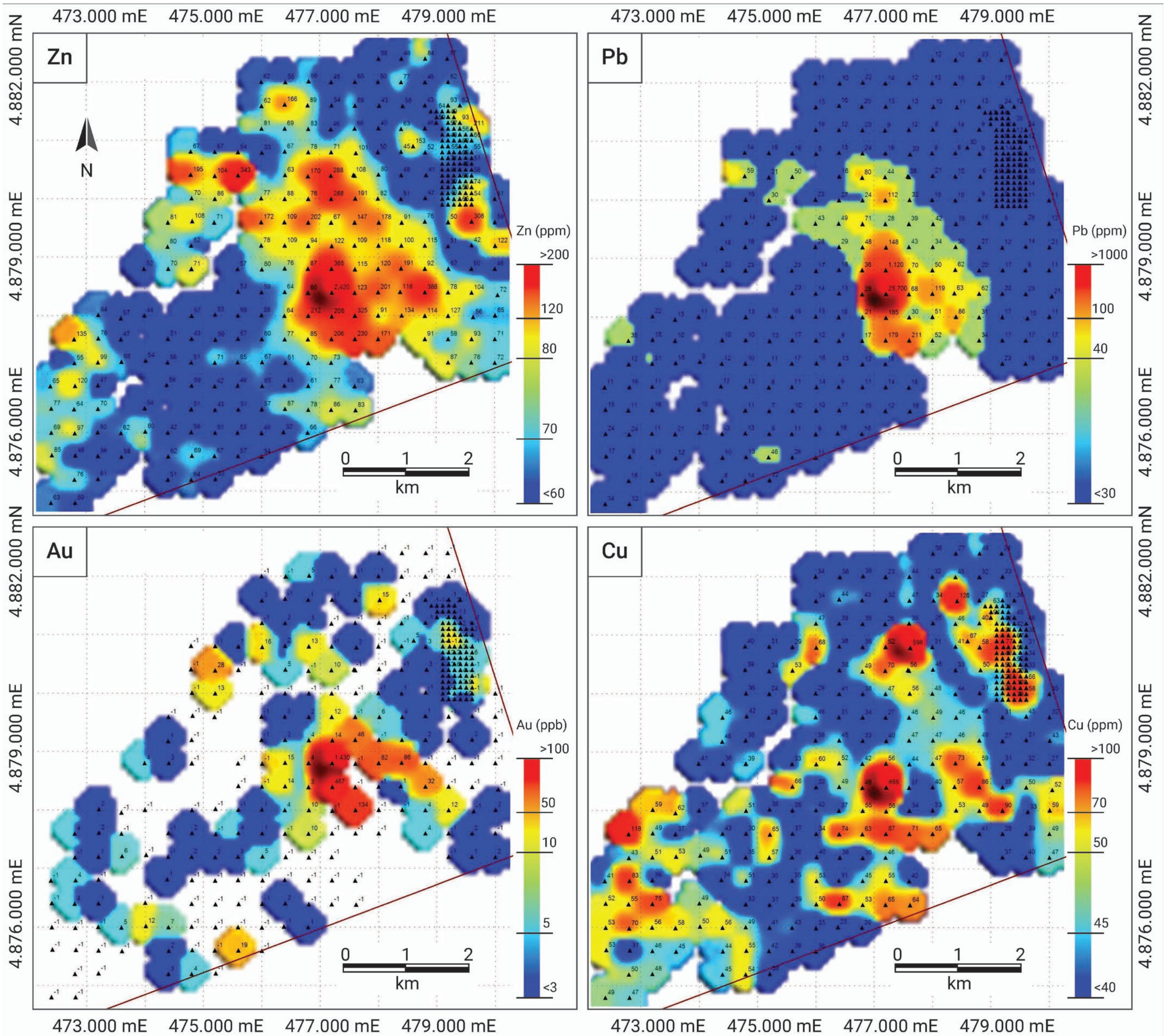

Fig. 14. Soil geochemical plots for the Altan Nar project area showing the distribution of Zn, Pb, Au, and Cu over the south-eastern part of the Tsenkher Nomin exploration license. Soil samples were collected on a 400- × 400-m grid as a follow up to the discovery of Cu-Au mineralization at Nomin Tal, where a detailed (50-m) grid was first surveyed along the eastern margin of the license area. The strongest gold anomalies, in the center of the sample grid, correspond to the Discovery Zone.

per member of the Ulziitkhar Formation, which strike northwest and dip gently (20°–30°) to the northeast, interpreted to have formed a series of tilted extensional fault blocks. Altan Nar is located near one of the strong regional ENE-trending lineaments, as interpreted from gravity data (Fig. 4), which may reflect an underlying deep crustal structure.

The deposit is dominated by fault zones that focused mineralization and were also intruded by a series of postmineral dike swarms. Mineralized zones are mostly present within dilational jogs along NE-SW– and lesser N-S–oriented structures, accompanied by granitoid dikes of similar orientation, such as at the Union North deposit (Fig. 13).

Survey results

A soil survey was conducted over ~48 km² on a 400-m grid (Zn, Pb, Au, and Cu results in Fig. 14). A broad Zn-in-soil anomaly (~4 × ~6 km) and a narrower, NW-trending Pb-in-soil anomaly (~1.5 × ~5 km) were defined in the central part of the grid. A cluster of Au-in-soil anomalies and some high Cu-in-soil values overlap the central lead anomaly. Several anomalous soil samples returned values of up to 1.5 g/t Au and 2.6 wt % Pb. Follow-up mapping and prospecting confirmed the presence of multiple areas containing gold-bearing epithermal-style quartz veins.

The deposit was discovered by the first drill hole of a scout drilling program (Erdene, 2011b[1]), focused on an area with epithermal-textured quartz float and Au-, Pb-, and Zn-in-soil anomalies. The main Discovery Zone is located in the central part of the soil anomaly (Fig. 14), along an ENE-WSW fault, which forms the lithologic boundary between andesite porphyry to the north and coarse lapilli and block and ash tuffs to the south (Fig. 13). Based on these results, Erdene undertook detailed geologic and alteration mapping, trenching, soil and rock-chip sampling, geophysical surveying (gradient array IP, dipole-dipole IP, gravity and ground magnetics), structural analysis, and a grid-drilling program. An NI 43-101–compliant mineral resource for the Altan Nar deposit (Clark et al., 2018) was subsequently defined (see above).

The IP gradient array survey was completed in 2012 over a 16-km^2 area (Fig. 15), with 100-m spacing on E-W–oriented lines, over the central part of the Pb-in-soil anomaly (Fig. 14). This survey identified a series of high-chargeability anomalies, up to 190 m wide, which were interpreted as reflecting both N-S– and NE-SW–trending zones of sulfide mineralization (Fig. 15). A series of 31 E-W–oriented, IP dipole-dipole lines, spaced from 100 to 400 m apart with a 50-m dipole spacing, were completed over the area previously covered by the gradient array survey, for a total of 55 line-km. The dipole-dipole survey results identified multiple high-chargeability anomalies, starting near the surface, and typically continuing to below the survey detection limit of approximately 150 m depth. Several high-chargeability and associated high-resistivity anomalies are proximal to Au-in-soil anomalies (Fig. 14) and outcropping polymetallic veins, and correspond to zones with sulfide mineralization and associated silicification at depth.

Ground magnetic surveys using 100-m line spacing were completed in 2011 and 2012 over a 41-km^2 area, covering most of the Altan Nar project. In addition, a ground magnetic survey using a 25-m line spacing was completed in 2011 over a 14.5-km^2 area, covering the central portion of the broad Pb-in-soil anomaly. Results from these surveys indicated a low-magnetic response over mineralized zones, accompanied by broader zones of magnetite destruction (i.e., martitization). In 2017, a high-resolution ground magnetic survey was completed over the central Altan Nar area (1.5 × 5 km), using 10-m line spacing, with a total of 1,000 survey-line km. The results from this survey (Fig. 15, inset) outlined known mineralized zones and their white mica halos (characterized by magnetic lows) in much greater detail than previously available using either 100- or 25-m data. The distribution of mineralized zones (>2 g/t Au equivalent) from drilling strongly correlate with areas of low magnetic response (Fig. 15, inset).

Mineralization

Polymetallic mineralization is hosted by the upper member of the Ulziitkhar Formation (Figs. 2, 3) and consists of quartz-carbonate veins and multi-stage epithermal breccias, including open-spaced infillings of zoned quartz, sphalerite, and galena with minor vugs partially infilled by finely laminated chalcedony with geopetal structures, which indicate way-up directions at the time of formation. High-grade mineralization in the Discovery Zone is hosted by dark-colored epithermal breccias cemented by black manganese silicate and oxide minerals, with Au, Pb, and Zn at higher grades than in quartz-only veins; light-colored sphalerite has a low Fe content (<2.5 wt %; M. Kirchner, pers. commun., 2012). Locally, arsenic concentration is high due to early arsenopyrite, mainly focused in the southwest portion of the Discovery Zone, where gold recoveries are the lowest due to its association with sulfides.

The Ag:Au values for both the Discovery Zone and Union North range from ~ 1 to >10 (App. 2, Figs. B-2A, B). The highest gold concentrations in the Discovery Zone (>20 g/t Au, capped at 50 g/t Au) are for samples with >1 wt % combined Pb and Zn (App. 2, Fig. B-2A), whereas samples with 0.3 to 20 g/t Au contain variable Pb and Zn values. The Pb- and Zn-rich samples at Union North (>1 wt % Pb + Zn) are more abundant than in the Discovery Zone, and all samples with >5 g/t Au have >1 wt % Pb + Zn (App. 2, Fig. B-2B). The Ag:Au ratio for the combined Discovery Zone and Union North, based on the resource calculations, is ~7.5:1, with 1.2 to 1.4 wt % Pb + Zn, although some high-grade intervals have an Ag:Au ratio close to 1:1, with Pb + Zn up to several percent.

There are variations in the mineralization style within the central Discovery Zone. For example, the following styles were observed within a single drill hole (TND-90; 140 m total depth; Fig. 16):

1. A white quartz vein (1.9 m wide; Fig. 16A) near the top of drill hole TND-90 contains 90 ppb Au and 139 ppm As, plus low base metals (Pb = 222 ppm, Zn = 688 ppm, Cu = 14 ppm).
2. Below this is a gold-rich quartz vein (8 g/t Au) with 40 ppm As (Fig. 16B) at 37 m, and moderate base metal concentrations (Pb = 7,410 ppm, Zn = 11,500 ppm, Cu = 795 ppm).
3. At 124 m, a brecciated interval (Fig. 16C) has moderate gold (3.27 ppm) and Ag (26 ppm), with Pb (4,980 ppm) and Zn (12,600 ppm), plus high As (25,500 ppm) and Mn (25,700 ppm), with siderite.
4. At 134 m, a fragmental zone (Fig. 16D) low in Au (85 ppb), As (257 ppm), Pb (932 ppm), and Zn (1,560 ppm) contains chalcopyrite (9,410 ppm Cu).

Alteration

The alteration associated with polymetallic mineralization includes widespread chlorite (both Mg- and Fe-Mg-rich varieties), tremolite, actinolite and epidote, with zones of intense white mica alteration (muscovite and paragonite plus illite, based on SWIR analysis). Additional gangue and alteration minerals include adularia, rhodonite (as crosscutting veins), rhodochrosite, Mn calcite, and chalcedony, plus dolomite, ankerite, siderite, and calcite, as well as smectite, kaolinite, and nontronite clays. The presence of actinolite and tremolite plus muscovite is consistent with temperatures ≥260° to 280°C at some time in the evolution of the system, whereas the illite indicates temperatures as low as ~200° to 220°C (Reyes, 1990).

Adularia from a mineralized quartz vein in the deposit was analyzed by $^{40}Ar/^{39}Ar$ at the Western Australian Argon Isotope Facility (WAAIF) at Curtin University in Australia and returned an age of 309.7 ± 0.5 Ma (Table 1; App. 1, Fig. A-2). This is younger than the 337 ± 7 Ma U-Pb zircon age of the middle unit of Ulziitkhar Formation that underlies the upper-member host to the Altan Nar deposit (Lhundev et al., 2019) and is approximately 27 m.y. younger than the Bayan Khundii gold deposit (336.8 ± 0.5 Ma).

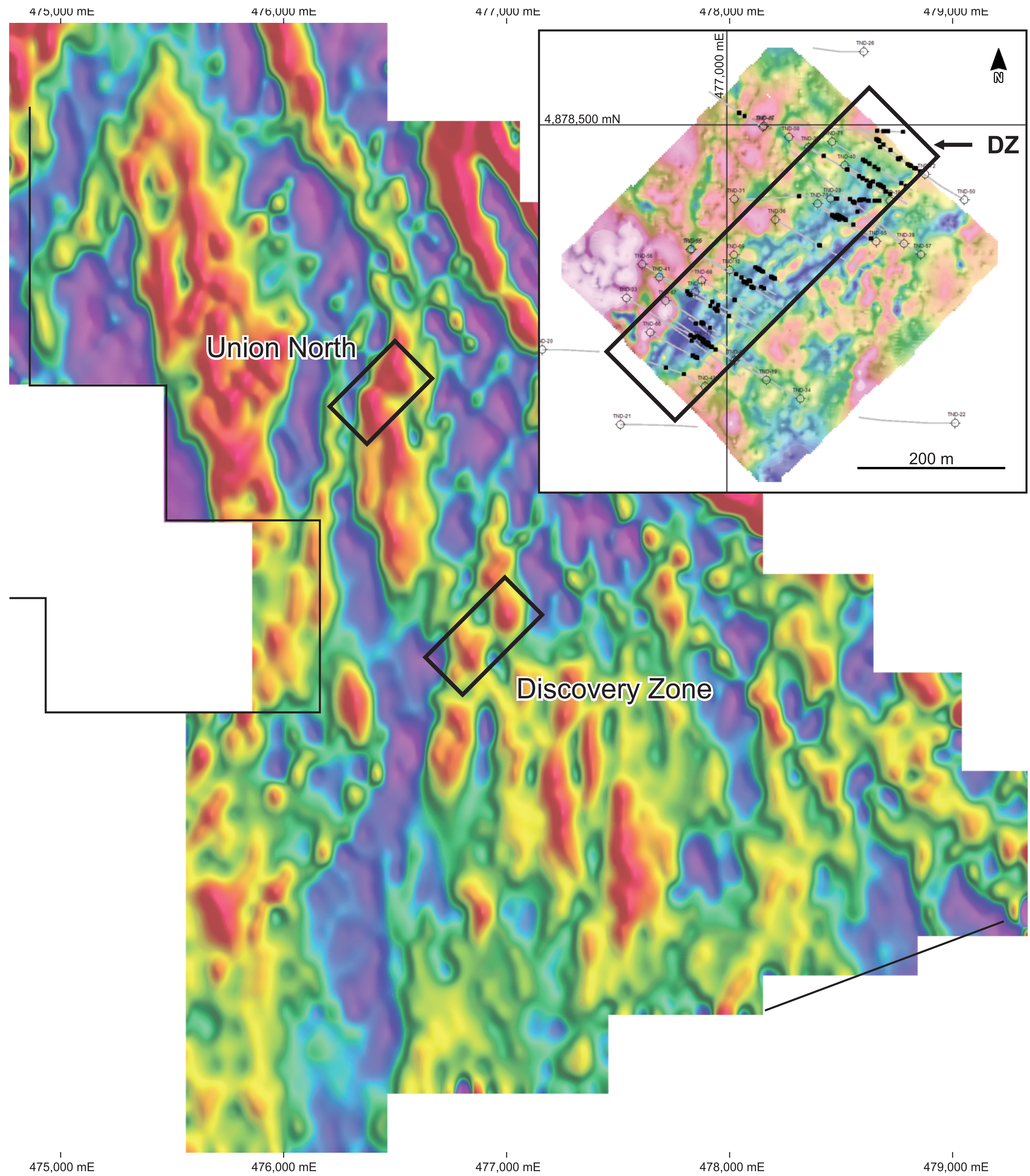

Fig. 15. Results from a gradient array induced polarization (IP) survey over the Altan Nar project area with a series of N-S– and minor NE-trending chargeability anomalies, interpreted to reflect concentrations of sulfide minerals. Locations of the Discovery Zone and Union North deposits are shown. Inset: High-resolution ground magnetic survey, using a 10-m line spacing, over the Discovery Zone (DZ). Areas of low magnetic response (blue colors) correlate with mineralized veins and associated white mica alteration halos and contrast with areas of high magnetic response over weakly- to unaltered andesite (pink color). Black squares indicate intervals from drilling where assay results returned >2 g/t Au equivalent (Au + Au-weighted Ag + Pb + Zn).

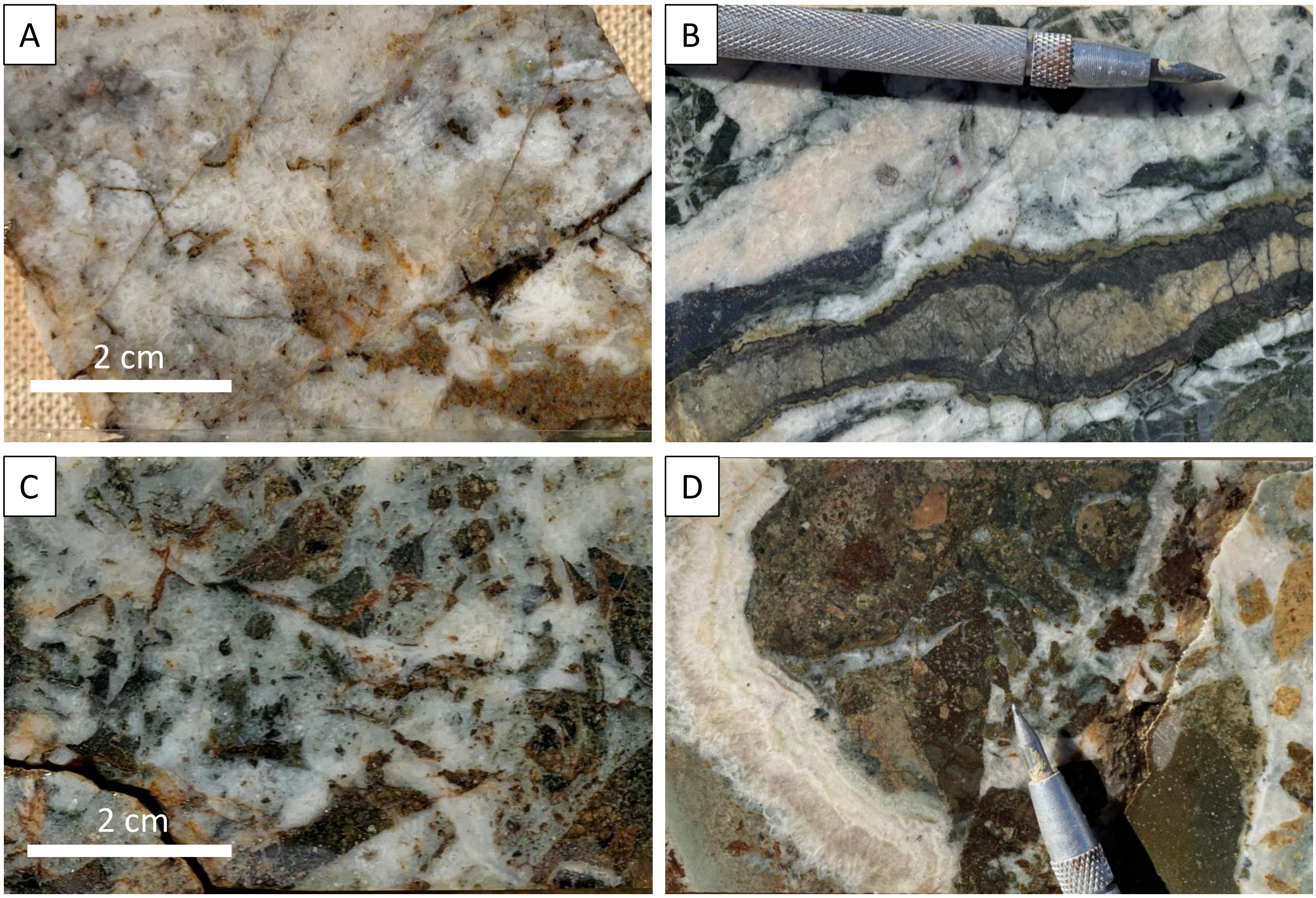

Fig. 16. Drill core from drill hole TND-90 (140 m total depth) at Altan Nar, illustrating four distinct styles of mineralization, including (A) thick (1.9 m) quartz vein with low Au (90 ppb) and low Pb + Zn; (B) quartz vein with up to 8 g/t Au, low As (40 ppm); (C) brecciated interval with Au (3.6 g/t), Ag (8 g/t), Pb (0.17%), Zn (0.30%), and Mn (1.02%); (D) fragmental zone with complex textures including colloform quartz bands, which grade to comb quartz textures and two stages of brecciation, including an early dark-colored, fine-grained hematite-quartz breccia cut by a later breccia with white colloform quartz matrix. This mineralized zone has high Cu (0.94 wt %) and relatively low Au, Ag, Pb, and Zn. Pencil for scale in (B) and (D).

Discussion

Several features of the Bayan Khundii gold deposit indicate similarity to extension-related epithermal deposits (John, 2001), including the presence of auriferous quartz-adularia-illite veins and widespread illite-adularia alteration; low Ag:Au ratios (mostly <1), particularly for the highest-grade gold mineralization; development of colloform bands of quartz (originally colloidal silica gel) within comb-textured quartz veins and chalcedony; sulfide-poor mineralization (typically <1–2%); the occurrence of bladed or lattice quartz textures (after calcite); a low base metal content (at most 100s of ppm base metals); and hematite of likely hypogene origin as infillings of veins and breccias (Sillitoe and Hedenquist, 2003).

Epithermal alteration and veining at Bayan Khundii overprint an early alteration assemblage that includes granular-textured quartz, K-feldspar, biotite, and actinolite/tremolite, the latter with quartz veins containing hypersaline fluid inclusions (characteristic of porphyry deposits). The areas of strong silicification, with local development of residual quartz and advanced argillic alteration (primarily pyrophyllite, dickite, and kaolinite; Figs. 6, 7) at Bayan Khundii are characteristic of the base of lithocap alteration that occurs over porphyry deposits (Sillitoe, 2010; Hedenquist and Arribas, 2022). The extensive quartz-white mica-pyrite alteration at central Ulaan, a few kilometers northwest of Bayan Khundii and west of Khar Mori, is typical of alteration in the transition to the deeper porphyry environment (Sillitoe, 2010). Thus, our preliminary interpretation is that sulfide-poor but gold rich epithermal quartz veins at Bayan Khundii and satellite deposits, with illite-adularia alteration halos, overprinted the upper portion of an older porphyry system after significant erosion (as much as ~1 km); the porphyry deposit likely formed in a distinctly different tectonic setting than Bayan Khundii.

The Bayan Khundii deposit and the Ulaan Southeast and Khar Mori occurrences have separate names, as they were discovered at different times. However, all three may be part of a single epithermal system based on their proximity and generally similar mineralization features, being gold-rich but mostly sulfide poor; they all lie within a contiguous white mica alteration zone (much of which may be related to the earlier porphyry event) and are related to the same structural trends. The ~2- × 7-km size of the Bayan Khundii-Ulaan Southeast-Khar Mori epithermal system (Fig. 6) is typical of the area encompassed by many other epithermal deposits worldwide (Simmons et al., 2005; Simmons, 2017). The higher As and Sb contents in the Khar Mori area suggest that it may represent a shallower erosion level than at Bayan Khundii. The abundance of illite associated with Bayan Khundii veins indicates a minimum of 150 to 200 m (Simmons et al., 2005; Simmons, 2017) of erosion prior to the deposit being covered by post-mineral rocks.

In contrast to Bayan Khundii, the Altan Nar polymetallic epithermal deposit has a moderate Ag:Au ratio of 7.4:1 (based on resource estimate) and relatively high concentrations of base metals (1.3 wt % combined Pb and Zn); epithermal quartz vein textures are coarsely crystalline, and Ca-, Mg-, Mn-, and Fe-carbonate gangue minerals are abundant, with lattice-bladed quartz (replaced bladed calcite) and adularia in mineralized quartz veins. Mineralization at Altan Nar is confined to steeply dipping NE-trending and, to a lesser degree, N-S–trending structures. Such base metal-bearing deposits are typically affiliated with a magmatic center (Sillitoe and Hedenquist, 2003).

The northern part of the Altan Nar deposit is hosted by andesite and andesite porphyry, whereas the southern part of the deposit is hosted by volcanic breccia. In contrast, Bayan Khundii, Ulaan Southeast, and Khar Mori are hosted by a package of lapilli tuff with minor ash, and block and ash tuffs. However, the host rock at both deposits is the Ulziitkhar Formation, the lower member at Bayan Khundii, and the upper member at Altan Nar.

Geochronological data for the Khundii metallogenic province is limited, with only three dates of mineralization and few data for intrusive and host rock types (Table 1). Despite the limited data, several observations can be made. Altankhuyag et al. (2023) noted that the sparse geochemical data of Devonian arc rocks in the Trans-Altai (Edren) terrane have tholeiitic to calc-alkaline affinities, indicative of an immature island arc setting. By contrast, Carboniferous arc rocks have calc-alkaline to high-K calc-alkaline affinities that resemble those of continental arcs. Javkhlan et al. (2022) proposed three distinct pulses of magmatism from Late Devonian to Late Pennsylvanian at 360, 330, and 300 Ma on the basis of isotopic chemistry and four U-Pb zircon dates. The $^{40}Ar/^{39}Ar$ ages of adularia from the Bayan Khundii and Altan Nar deposits (336.8 ± 0.5 and 309.7 ± 0.7 Ma, respectively; Table 1) indicate episodic epithermal activity over a period of at least ~27 m.y., of distinctly different style. Bayan Khundii may have been related to a period of (back-arc?) extension, typical of this style of epithermal deposit (Sillitoe and Hedenquist, 2003), early in the history of the island arc. Altan Nar was likely related to a putative ~310 Ma intrusion, possibly part of the Late Pennsylvanian-early Permian Baga Ovoot intrusive complex (305.3 ± 3.6 to 301.8 ± 2.7 Ma; Altankhuyag et al., 2023; Table 1). The as-yet undated porphyry-style alteration at Bayan Khundii, which was overprinted by later illite alteration and quartz-adularia-gold veins at 336.8 ± 0.5 Ma, indicates that there was (arc-related; Sillitoe, 2010) magmatic-hydrothermal activity prior to the formation of Bayan Khundii and adjacent satellite deposits.

On the basis of the oldest and youngest ages of mineralization in the Khundii metallogenic province (336.8 ± 0.5 and 297 ± 4.8 Ma, respectively; Table 1), we propose a ~40-m.y. period of intermittent intrusive and magmatic-hydrothermal activity.

The Khundii metallogenic province is mostly underlain by Middle Mississippian and, to a lesser degree, Late Pennsylvanian-early Permian intrusive granitoid rocks. The Middle Mississippian to early Permian ages of epithermal and porphyry-related mineralization within the province are similar to the ages of host rocks and mineralization elsewhere within the Central Asian orogenic belt, including the prolific Tien Shan belt (Fig. 1). Yakubchuk et al. (2012) noted that the greatest metal endowment and largest number of individual deposits formed in the Middle Mississippian to Early Pennsylvanian period, at 340 to 320 Ma; the second most important period was 385 to 370 Ma (i.e., Oyu Tolgoi); and the third most important event was in the early Permian, at 295 Ma.

The province experienced little net erosion since formation in the late Carboniferous period, based on the preservation of epithermal deposits. The lack of appreciable smectite alteration and abundance of illite indicates erosion of at least 150 to 200 m below the paleo-water table (Simmons et al., 2005; Simmons, 2017) in the area of the Bayan Khundii deposit, following ~1 km of erosion (Sillitoe, 2010) after formation of the earlier (overprinted) porphyry system, with roots of a lithocap (residual quartz and pyrophyllite) and white mica alteration preserved. The postmineral history in this region of the Central Asian orogenic belt was conducive to preservation of the epithermal (Bayan Khundii and Altan Nar) to top of porphyry (Zuun Mod and central Ulaan) environments.

Exploration to date has focused on near-surface targets, with most drilling less than 250 m deep. Polymetallic epithermal deposits such as that at Altan Nar can have considerable vertical intervals of ore, >500 m in some deposits, with tops of the ore zone locally hundreds of meters below the paleosurface (Simmons, 2017). This indicates the potential for additional epithermal mineralization at depth in the vicinity of Altan Nar and potentially in other parts of the province. Extensive postmineral faulting over the province has juxtaposed blocks of lower, middle, and upper members of the Ulziitkhar Formation (Lhundev et al., 2019), allowing the preservation of shallow epithermal mineralization in downfaulted and/or tilted blocks as well as exposure of the shallow portions of porphyry deposits elsewhere.

Conclusions

Systematic regional mineral exploration activities by Erdene over a large area of southwest Mongolia (110,000 km^2) since 2009 has identified the southeastern part of the Trans-Altai terrane as having the highest mineral potential in the region. Reprocessing and interpretation of ASTER satellite imagery successfully outlined areas of hydrothermal alteration, which were then examined on the ground. Subsequent regional sampling of 4th- or 5th-order (dry) stream sediments, integrated with ASTER anomalies, identified prospective catchment basins. Follow-up work on the company's exploration and mining licenses included soil surveys (400 m spacing) followed by detailed grid soil sampling, some with 12.5-m spacing on grid lines, which outlined numerous precious and base metal anomalies. Induced polarization (IP) gradient array and dipole-dipole surveys were successful in identifying zones of sulfide mineralization, whereas ground magnetic surveys outlined zones of low magnetic response of alteration halos to veins, prior to initial drill testing of prospects. Shortwave infrared (SWIR) analysis of rock chip and drill core assisted in detailed alteration mapping. Ground gravity surveys identified several circular or ovoid gravity high anomalies on Erdene's exploration and mining licenses, which are thought to represent intrusions at depth.

Following the definition of the Zuun Mod porphyry Mo-Cu deposit, exploration led to the discovery of the sulfide-rich Altan Nar Au-polymetallic epithermal deposit and the sulfide-poor Bayan Khundii epithermal gold deposit, 16 km to the south-southeast of Altan Nar, as well as several epithermal and porphyry prospects and projects at various stages of assessment. These discoveries and those by other companies—including porphyry-style tourmaline breccia pipes at Khul Morit and advanced argillic alteration of the Bor Khairkhan prospect—define the Khundii metallogenic province in southwest Mongolia, mainly hosted by the Davkharkhar subterrane of the Trans-Altai terrane.

Geochronological data indicate a ~27-m.y. period between formation of the Bayan Khundii epithermal deposit (336.8 ± 0.5 Ma), which overprinted white mica plus lithocap alteration associated with an older (as yet undated), partly eroded porphyry system, and the younger Altan Nar epithermal deposit (309.7 ± 0.7 Ma). Coupled with the ~297 Ma age of the Zuun Mod porphyry Mo-Cu deposit, the youngest dated deposit in the area, there is evidence for episodic porphyry and epithermal mineralization within the Khundii metallogenic province over a period of more than 40 m.y., from the Middle Carboniferous to the earliest Permian, with additional work needed to refine this long period of activity. The existing epithermal and porphyry deposits were preserved from erosion by Late Mississippian (?) block rotation and faulting, possibly related to back-arc extension, followed by early Permian erosion and deposition of Permian-Jurassic sedimentary and basaltic rocks which partially cover the Bayan Khundii deposit. The epithermal deposits of the Khundii province may indicate a shallower level of erosion overall than that of the Devonian-age Gurvansaikhan island arc terrane, further east in the vicinity of the Oyu Tolgoi porphyry deposit (Crane and Kavalieris, 2012), where epithermal deposits have yet to be reported. The Khundii province, ~50 × 100 km in size and part of the Devonian to Permian-age Central Asian orogenic belt, remains underexplored.

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