Geoscience Frontiers 7 (2016) 375–407

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Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

The geology, structure and mineralisation of the Oyu Tolgoi porphyry copper-gold-molybdenum deposits, Mongolia: A review

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A R T I C L E I N F O

Article history:
Received 25 June 2015
Received in revised form
21 August 2015
Accepted 26 August 2015
Available online 14 September 2015

Keywords:
Tectonic setting
Porphyry copper-gold-molybdenum deposit
High sulphidation
Geology
Alteration
Structure

A B S T R A C T

The Oyu Tolgoi cluster of seven porphyry Cu-Au-Mo deposits in southern Mongolia, define a narrow, linear, 12 km long, almost continuously mineralised trend, which contains in excess of 42 Mt of Cu and 1850 t of Au, and is among the largest high grade porphyry Cu-Au deposits in the world. These deposits lie within the Gurvansayhan island-arc terrane, a fault bounded segment of the broader Silurian to Carboniferous Kazakh-Mongol arc, located towards the southern margin of the Central Asian Orogenic Belt, a collage of magmatic arcs that were periodically active from the late Neoproterozoic to Permo-Triassic, extending from the Urals Mountains to the Pacific Ocean. Mineralisation at Oyu Tolgoi is associated with multiple, overlapping, intrusions of late Devonian (~372 to 370 Ma) quartz-monzodiorite intruding Devonian (or older) juvenile, probably intra-oceanic arc-related, basaltic lavas and lesser volcaniclastic rocks, unconformably overlain by late Devonian (~370 Ma) basaltic to dacitic pyroclastic and volcano sedimentary rocks. These quartz-monzodiorite intrusions range from early-mineral porphyritic dykes, to larger, linear, syn-, late- and post-mineral dykes and stocks. Ore was deposited within syn-mineral quartz-monzodiorites, but is dominantly hosted by augite basalts and to a lesser degree by overlying dacitic pyroclastic rocks. Following ore deposition, an allochthonous plate of older Devonian (or pre-Devonian) rocks was overthrust and a post-ore biotite granodiorite intruded at ~365 Ma.

Mineralisation is characterised by varying, telescoped stages of intrusion and alteration. Early A-type quartz veined dykes were followed by Cu-Au mineralisation associated with potassic alteration, mainly K-feldspar in quartz-monzodiorite and biotite-magnetite in basaltic hosts. Downward reflux of cooled, late-magmatic hydrothermal fluid resulted in intense quartz-sericite retrograde alteration in the upper parts of the main syn-mineral intrusions, and an equivalent chlorite-muscovite/illite-hematite assemblage in basaltic host rocks. Uplift, facilitated by syn-mineral longitudinal faulting, brought sections of the porphyry deposit to shallower depths, to be overprinted and upgraded by late stage, shallower, advanced argillic alteration and high sulphidation mineralisation. Key controls on the location, size and grade of the deposit cluster include (i) a long-lived, narrow faulted corridor; (ii) multiple pulses of overlapping intrusion within the same structure; and (iii) enclosing reactive, mafic dominated wall rocks, focussing ore.

1. Introduction

The Oyu Tolgoi porphyry copper-gold-molybdenum deposits are located in the South Gobi Desert of Mongolia (43°01′40″N, 106°51′34″E), approximately 550 km due south of the capital, Ulaanbaatar, and 80 km north of the Chinese border. They represent the largest high-grade group of Palaeozoic porphyry deposits currently known in the world.

The main Oyu Tolgoi deposits for which resources have been estimated, are distributed over a 12 km interval of a 25 km corridor of mineralisation that defines the NNE aligned Oyu Tolgoi trend. From north to south, the deposits comprise Hugo Dummett, divided into a north and a south deposit, the southern Oyu Tolgoi cluster, including the Central, South and Southwest Oyu deposits and smaller intervening satellite zones, and Heruga and Heruga North.

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Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2015.08.003
1674-9871/

Total reported JORC compliant measured + indicated + inferred resources + reserves (which are reported separately) for all of the deposits, as at 31 December 2014 (Rio Tinto Annual Report, 2015) amounted to 6.382 Gt @ 0.67% Cu, 0.29 g/t Au, of which 1.494 Gt @ 0.85% Cu, 0.31 g/t Au, 1.23 g/t Ag were proven + probable reserves. This resource amounts to 42.76 Mt (million tonnes) of contained copper and 1850 t (tonnes) of gold. The richest part of the deposit is North Hugo, with proven + probable reserves of 499 Mt @ 1.65% Cu, 0.35 g/t Au, 3.39 g/t Ag at the northern end of the string of deposits, whilst Heruga at the opposite end of the trend, which includes a molybdenum zone, has total resources (reserves not yet announced) of 1.817 Gt @ 0.39% Cu, 0.36 g/t Au, 1.40 g/t Au, 113 ppm Mo (=0.64% $Cu_{equivalent}$).

Small historic workings, dating from the Bronze age, are found over the exposed South Oyu deposit, although no serious modern exploration was conducted over the area until the 1980's, when a joint Russian-Mongolian survey conducted a regional geochemical soil sampling survey and reported a single anomalous molybdenum value over the Central Oyu area. One of the geologists involved in the survey, visited the site in 1983 and noted evidence of alteration and copper mineralisation at South Oyu, and in 1996 guided a Magma Copper team to the site. The outcrops with stockwork veining at Central Oyu were identified as a leached capping over a porphyry deposit. During 1997, geochemical and geophysical investigations were undertaken by BHP Limited, which has acquired Magma Copper in late 1996. This was followed by drilling, principally to test the potential for supergene chalcocite mineralisation, with intersections of up to 70 m @ 1.65% Cu, 0.15 g/t Au from a depth of 56 m. By 1999, testing of the supergene and hypogene mineralisation at what was then described as the North, Central, and South mineralised zones, had outlined a preliminary resource of 438 Mt @ 0.52% Cu, 0.25 g/t Au (Perelló et al., 2001).

In 1999, BHP decided not to proceed further and offered the tenements for joint venture, resulting in an agreement with Ivanhoe Mines that allowed for acquisition of up to 100% of the project. Ivanhoe Mines Mongolia Inc. commenced exploration in May 2000, and achieved 100% of the project in 2002. Key moments in that program were a drill intersection in late 2001 of 508 m of 0.81% Cu and 1.17 g/t Au, from 70 m, which was the discovery hole at Southwest Oyu, and in September 2002, a hole that passed through 638 m @ 1.6% Cu, from 230 m, and was the first intersection of what was to later be known as the Hugo Dummett South deposit. Drilling moved progressively to the north, until in January 2003, a 300 m step-out from known mineralisation intersected 164 m @ 4.0% Cu, 1.42 g/t Au, which was within the Hugo Dummett North deposit. Exploration on titles held in joint venture with Entrée Gold to test a deep, 3 km long, geophysical (IP) anomaly extending south from Southwest Oyu, discovered the Heruga deposit in 2007, with intersections such as 298 m @ 0.63% Cu, 0.29 g/t Au, 229 ppm Mo from a depth of 636 m.

In 2006, Rio Tinto entered into an agreement with Ivanhoe Mines and in July 2012 obtained majority control of the latter which was renamed Turquoise Hill Resources. In early 2011, a joint venture between Ivanhoe and BHP Billiton Ltd. discovered a new zone of shallow Cu-Au-Mo mineralisation, Ulaan Khud North, ~11 km north of the Hugo North deposit. The first copper concentrate was produced from the Oyu Tolgoi mine and exported in 2013. For more detail see Crane and Kavalieris (2012).

This paper has been prepared in response to an invitation from the editors of this volume. It is intended as a detailed description of the deposits of the Oyu Tolgoi mineralised trend, their regional to local scale setting, geology, structure, mineralisation and alteration. It is based on the Oyu Tolgoi and Heruga entries on the Porter GeoConsultancy Pty Ltd ore deposit database available online from www.portergeo.com.au, and is published with the permission of that company. The information is synthesised from available literature, particularly Perelló et al. (2001), Kirwin et al. (2005a), Crane and Kavalieris (2012), and technical reports for Ivanhoe Mines and Turquoise Hill Resources, including Peters et al. (2012) and Peters and Sylvester (2014). The appreciation of that literature has been enhanced by technical visits to the deposit in 2004 and 2010.

2. Regional setting

The Oyu Tolgoi deposits lie within the middle to late Palaeozoic Kazakh-Mongol magmatic arc, part of the Transbaikal-Mongolian orogenic collage (Yakubchuk, 2002, 2005), which with the Altaid tectonic collage to the west (Sengör et al., 1993; Sengör and Natal'in, 1996; Yakubchuk, 2004), forms the 5000 km long, by up to 1000 km wide, Central Asian Orogenic Belt (Jahn et al., 2000) that extends from the Urals in the west to the Pacific coast in the east (Fig. 1).

Within the Central Asian Orogenic Belt, a string of major porphyry copper deposits (e.g., *Almalyk* or *Kal'makyr-Dalnee* in Uzbekistan, *Bozshakol, Kounrad, Koksai* and *Aktogai* in Kazakhstan, *Aksug* in Russia, *Tuwu* and *Duobaoshan* in China, and *Erdenet* and *Oyu Tolgoi* in Mongolia) are hosted by subduction related magmatic arcs that developed from the late Neoproterozoic, through the early, mid and late Palaeozoic, up to the Jurassic intra-cratonic extension. Deposits are predominantly on the southern palaeo-Tethys Ocean margin of the proto-Asian continent, but are also associated with the closure of two rifted back-arc basins that had opened behind that ocean-facing margin (e.g., Yakubchuk, 2004; Seltmann and Porter, 2005; Seltmann et al., 2014).

Although major deposits occur from the Ordovician (e.g., *Bozshakol*) through to the Triassic (e.g., *Erdenet*), the most prolific interval of ore formation, including the largest deposits, was during the late Devonian and early Carboniferous (Yakubchuk et al., 2002), prior to the amalgamation of Pangea during the late Carboniferous. Major orogenic gold deposits (e.g., the Permian *Muruntau* in Uzbekistan and *Kumtor* in Kyrgyzstan) also occur within the Central Asian Orogenic Belt.

Mongolia has been subdivided into two domains by the continental scale Irtysh fault (Fig. 1; Yakubchuk et al., 2012), locally known as the main Mongolian lineament in Mongolia (Fig. 2; Badarch, 2005). This structure has a sinistral offset of several hundred kilometres in eastern Mongolia, while in western China, it has been shown to comprise a crustal-scale, north vergent thrust that was active in the Permian (Briggs et al., 2007). It most likely telescoped and juxtaposed the two domains from different sections of the orogenic belt, rather than exerting an original temporal control on arc development.

The northern domain in Mongolia is characteristically a Caledonian orogen, containing Proterozoic and lower Palaeozoic rocks, including the extensive late Neoproterozoic to Ordovician Tuva-Mongol magmatic arc (Fig. 2). This includes a major, fault dislocated cratonic fragment of Precambrian rocks, and a series of back- and fore-arc sequences, Proterozoic to lower Palaeozoic intrusions, and accretionary wedge sequences that include late Neoproterozoic (Vendian) to early Cambrian ophiolites.

The southern domain is largely a mid to late Palaeozoic (Hercynian) orogen, dominated by the Kazakh-Mongol magmatic arc. This magmatic arc comprises a 100 to 275 km wide arcuate swathe of fault separated, arc-related following the southern border between Mongolia and China, with a trend that curves from NE in the east of Mongolia, to WNW where it passes into western China. The individual terranes are predominantly composed of Devonian to Carboniferous island arc volcanic rocks, but also include sporadic Ordovician and Silurian volcanism, as well as Ordovician to Carboniferous sedimentary rocks, and are extensively intruded by