**Economic Geology**

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

VOL. 106 September–October No. 6

# Epithermal Gold-Silver Deposits of the Hauraki Goldfield, New Zealand: An Introduction

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## Geology and Mineral Deposits of the Hauraki Goldfield

The five papers that follow describe diverse aspects of epithermal gold-silver deposits and genetically related hydrothermal systems in the Hauraki goldfield on the Coromandel peninsula of the North Island of New Zealand (Fig. 1). The Hauraki goldfield contains more than 50 Miocene and Pliocene epithermal Au-Ag deposits and several porphyry Cu-Au-Mo occurrences in a 200-km-long by 40-km-wide north-south–trending belt (Fig. 1C; Christie et al., 2007). Production from these deposits between 1862 and 2009 totaled approx. 335,000 kg (10.8 Moz) of Au and 1.6 million kg (51.4 Moz) of Ag (Mauk et al., 2011). The epithermal deposits are related to subaerial hydrothermal systems hosted in rocks of the early Miocene to late Pliocene (~18–1.9 Ma) Coromandel volcanic zone (Skinner, 1986).

Placer gold was first discovered near Coromandel township in 1852, but because of the small size of these placers, little mining activity occurred until the discovery of Au-bearing quartz veins in 1861 at the site of the Kapanga mine (Fig. 1C). Prospecting elsewhere on the Coromandel peninsula resulted in the opening of mines at Thames in 1865, Karangahake in 1875, and Waihi (Martha) in 1878. The major period of gold mining ended with the closure of the underground Martha mine at Waihi in 1952. Total production during this period was more than 250,000 kg (8.0 Moz) of Au and 1,100,000 kg (35.3 Moz) of Ag (Christie et al., 2007). Higher gold prices in the 1980s led to renewed exploration, and the recent phase of gold mining began in 1988 with opening of the Martha open-pit mine at Waihi. This was followed by a combined open-pit and underground operation at Golden Cross from 1991 to 1998 and discovery of the Favona deposit, 1.5 km from the Martha open pit, which opened as an underground mine in 2006. Mining continues today at the Martha mine, and the Trio deposit, which lies between the Martha and Favona mines, is being developed through underground workings extending from the Favona mine. The Martha mine is by far the largest producer in the Hauraki goldfield, with total production through 2009 of ~220,000 kg (7.1 Moz) of Au and 1,430,000 kg (46 Moz) of Ag (Newmont Waihi Gold Limited, 2010), which accounts for approximately 66 percent of the total Au and 89 percent of the total Ag production of the Hauraki goldfield. Other major past producers were the Thames, Golden Cross, and Karangahake mines.

The Coromandel peninsula is composed of Miocene and Pliocene subaerial volcanic rocks and volcaniclastic deposits of the Coromandel volcanic zone that unconformably overlie Late Jurassic graywacke and argillite basement (Fig. 1C; Skinner, 1986; Christie et al., 2007). Rocks of the Coromandel volcanic zone merge with and are overlain by Quaternary volcanic deposits of the Taupo volcanic zone at the southern end of the Coromandel peninsula. The Coromandel volcanic zone is a subduction-related magmatic arc whose eruptive products are medium-K and calc-alkaline with compositions that range from basaltic andesite to rhyolite. The main ore hosts are basaltic andesite, andesite, and dacite units in the 18 to 2.5 Ma Coromandel Group (Booden et al., 2011). The exact origin of the Coromandel volcanic zone is controversial. Mauk et al. (2011) summarize available evidence and interpretations and suggest that the Coromandel volcanic zone represents products of both the Northland and Colville arcs and that reorganization of these arcs may have occurred at about 10 Ma, just prior to a shift from andesite-dacite to bimodal andesite-rhyolite volcanism in the Coromandel volcanic zone. The active Taupo volcanic zone is at the southwest end of the Tonga-Kermadec-Taupo volcanic zone arc (Fig. 1B).

The Coromandel volcanic zone is cut by north-northwest– and north-northeast– to east-northeast–striking faults (Fig. 1C). Most northeast- and east-northeast–striking faults are downthrown to the south, thereby lowering the Jurassic basement to the south, thickening the volcanic sequence toward the Taupo volcanic zone, and tilting these volcanic rocks gently eastward. Several major structural corridors cross the peninsula and may reflect major basement structures (Fig. 1D). Morrell et al. (2011) describe geophysical features in the Waihi-Waitekauri area in the central part of the Karangahake-Ohui structural trend that may have localized numerous late Miocene hydrothermal systems.

The Coromandel peninsula is bounded to the west by the Hauraki rift (Fig. 1D), in which the Miocene to Pliocene volcanic rocks are downthrown by 1 to 4 km (Hochstein and Ballance, 1993). The initiation of the Hauraki rift may have been

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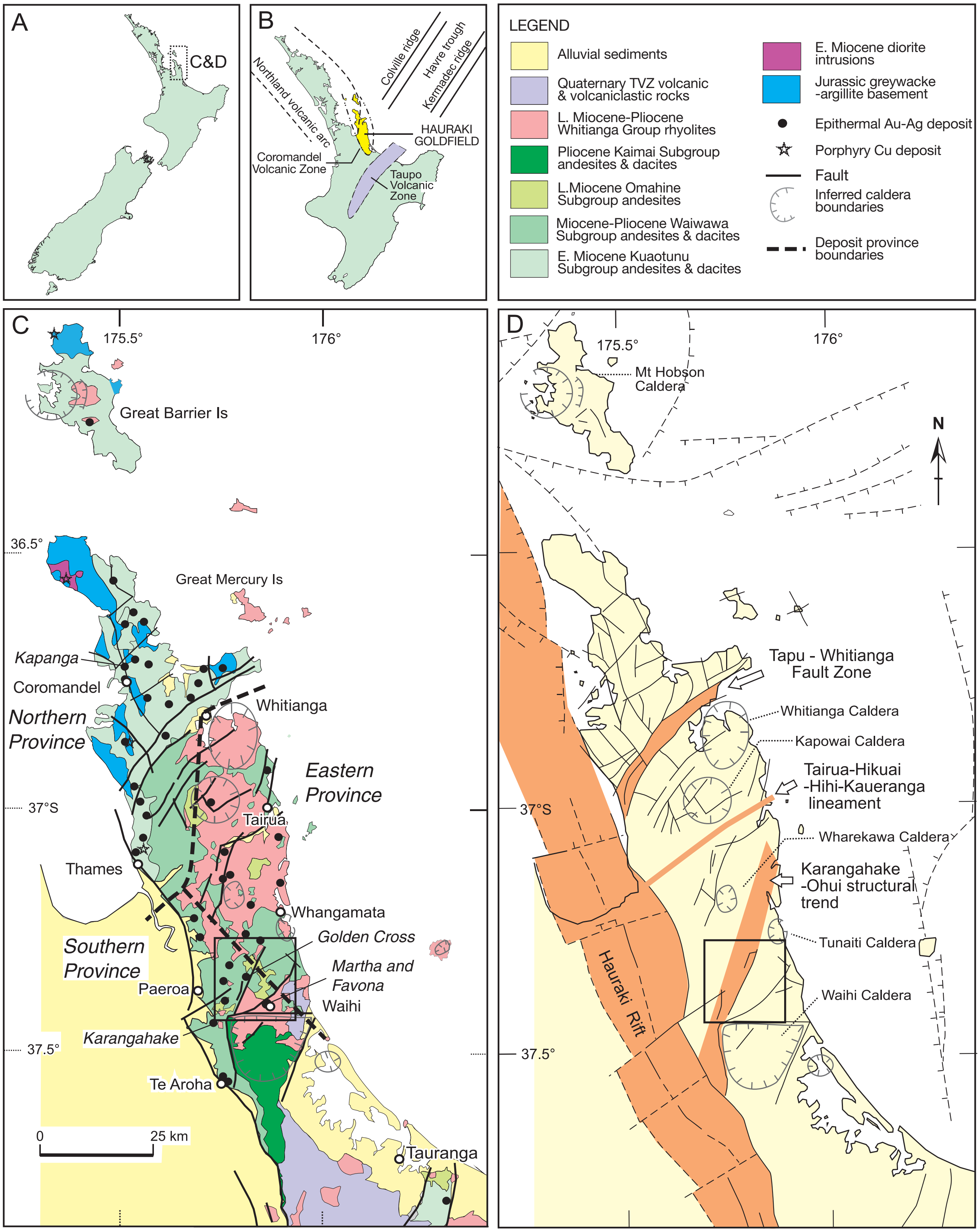


FIG 1. A and B. Location of the Hauraki goldfield and Coromandel volcanic zone. C. Regional geology, mineral deposits, and provinces. D. Structural features of the Coromandel volcanic zone and Hauraki goldfield. Black open box in C and D shows location of Waihi-Waitekauri geophysical study area of Morrell et al. (2011). Figure modified from Christie et al. (2007).

around 7 Ma, but the main subsidence in the southern part of the Hauraki rift occurred between 1 and 2 Ma (Briggs et al., 2005).

More than 50 separate epithermal Au-Ag deposits occur along the Coromandel peninsula. Mineralization is restricted to steeply dipping quartz veins hosted mainly in andesites and dacites of the Coromandel Group (~95% of the total production), although rhyolites of the 12 to 1.9 Ma Whitianga Group and Jurassic graywacke basement host mineralization in some areas. The gold field consists of 3 provinces, the northern, eastern, and southern, which vary in age and style of mineralization (Fig. 1C; Christie et al., 2007). The K-Ar and $^{40}Ar/^{39}Ar$ dates of hydrothermal minerals show that the deposits formed between about 16 and 2 Ma, with deposits in the northern province distinctly older (~16–11 Ma) than deposits in the southern and eastern provinces (mostly ~7–6 Ma; Mauk et al., 2011). Most deposits are the adularia-sericite type of Heald et al. (1987; equivalent to quartz ± calcite ± adularia ± illite type of Simmons et al., 2005).

Epithermal Au-Ag deposits in the Hauraki goldfield have been studied for many years. The geologic setting and characteristics of these deposits were first systematically described in a series of New Zealand Geological Survey Bulletins (e.g., Fraser and Adams, 1907; Bell and Fraser, 1912). Hydrothermal alteration at Waihi and Thames was first described by Finlayson (1909), and the first published geophysical investigation of adularia-sericite epithermal deposits was by Modriniak and Marsden (1938) at Waihi. Epithermal deposits of the "Hauraki" peninsula were described as a type example of "gold-quartz veins in andesite," and a cross section of the Waihi (Martha) mine was included in Waldemar Lindgren's classic textbook, *Mineral Deposits* (1933). A second phase of study began with renewed exploration and mining in the 1980s and resulted in numerous publications and university theses that were reviewed by Brathwaite et al. (1989) and Christie et al. (2007). Crown Minerals (2003) and Rattenbury and Partington (2003) presented a digital compilation of geologic and exploration data in a GIS format and carried out prospectivity modeling for undiscovered epithermal Au-Ag deposits in the Hauraki goldfield. Most recently, Christie et al. (2007) extended the GIS data compilation of Crown Minerals (2003), added new data sets for mineralogy, mineral chemistry, geochronology, fluid inclusions, and stable isotopes, and synthesized these data for the entire gold field.

## Papers in This Volume

The papers in this volume represent recent studies of epithermal deposits in the Hauraki goldfield undertaken at the University of Auckland. The studies range from regional to deposit scale. Mauk et al. (2011) present new $^{40}Ar/^{39}Ar$ and Re/Os ages for many epithermal deposits in the gold field. Papers by Morrell et al. (2011), Booden et al. (2011), and Simpson and Mauk (2011) present integrated geologic, geochemical, and geophysical studies of mineralized hydrothermal systems across part of the Waitekauri corridor, which approximately corresponds to the central part of the Karangahake-Ohui structural trend (Fig. 1D) and contains the Karangahake, Golden Cross, Sovereign, and Jubilee deposits. Morrell et al. (2011) also discuss a detailed geophysical study of the Waihi area, which contains the Martha and Favona deposits. Finally, Spörli and Cargill (2011) examine the complex structure of the upper parts of the Martha deposit.

Mauk et al. (2011) present high-precision $^{40}Ar/^{39}Ar$ ages for adularia from quartz-adularia veins in 15 deposits in the Hauraki goldfield; they also report two molybdenite Re-Os ages. Their age data, combined with previous K-Ar and Ar-Ar dating (summarized in Christie et al., 2007), indicate that mineralization in the Hauraki goldfield ranges from about 16.3 Ma in the north to 2 Ma in the south, and clusters into two distinct groups that correlate with location, volcanic stratigraphy, and mineralization style. The older group, from ~16.3 to ~10.8 Ma, contains epithermal veins, including bonanza-style veins, and porphyry-style mineralization that formed in the northern province when arc magmatism was dominated by andesitic volcanism. The second period of mineralization occurred primarily from 6.9 to 6.0 Ma in the eastern and southern provinces, when precious metals were deposited into thicker banded veins that formed in extensional settings in an arc that was erupting bimodal andesite-rhyolite compositions. Their data show that, although volcanism in the Coromandel volcanic zone was active from 18 to 2 Ma and mineralization discontinuously lasted 11 m.y., Au-Ag mineralization was focused into two discrete periods, and that more than 80 percent of the known gold endowment was deposited in a brief 0.9-m.y. window between 6.0 and 6.9 Ma.

Morrell et al. (2011) describe geophysical studies of the Waihi-Waitekauri area (Fig. 1) and use geophysical data and derivative maps to delineate distinct anomalies that are associated with pervasive hydrothermal alteration and epithermal Au-Ag mineralization. Aeromagnetic maps outline six magnetic "quiet zones," which result from destruction of magnetite in host rocks and correlate well with areas of hydrothermally altered rocks mapped on the surface. These quiet zones are similar in size (≤10 km$^2$) to modern-day geothermal systems in the Taupo volcanic zone. Larger zones of relatively low magnetic intensity that extend outward from the quiet zones are interpreted as areas of hydrothermally altered rock that lie beneath younger, unaltered volcanic cover. Airborne radiometric data locally delineate high-potassium anomalies in the centers of the magnetic quiet zones that reflect significant potassium enrichment and formation of adularia and illite. Using the results of the geochemical study of Booden et al. (2011), Morrell et al. (2011) show that a broad K/Th anomaly (K/Th>~5,000) correlates with the extent of the magnetic quiet zones and indicates widespread potassium enrichment. Detailed surface gravity data in the Waihi district define a positive residual anomaly that correlates closely with the extent of the magnetic quiet zone and with the locations of the Waihi and Favona deposits. Although the causative source of the gravity high is ambiguous, its northeast elongation may reflect underlying structures that focused hydrothermal activity. This study demonstrates the power of close integration of district- to regional-scale geophysical data with geologic and geochemical studies in the exploration for epithermal mineral deposits.

Enrichment of "pathfinder" elements, such as As, Hg, and Sb, is well known in epithermal Au-Ag deposits. However, these elements are seldom enriched at distances greater than a few hundred meters from ore zones. Booden et al. (2011) examined the effects of hydrothermal alteration on major and trace element compositions of Coromandel Group volcanic rocks that host epithermal mineralization in the Waitekauri area, and the potential use of changes in major element composition to extend the range of geochemical exploration for epithermal deposits to 1 to 10 km. They show that major element compositions of unaltered Coromandel Group volcanic rocks correlate with whole-rock $Zr/TiO_2$ and that this ratio is preserved during K metasomatism, which is the characteristic alteration related to epithermal mineralization in the area. They used $Zr/TiO_2$ values in altered rocks to estimate initial rock composition and calculate mass balances for altered rocks along a 3-km-wide section that extends from the central Waitekauri fault to the periphery of the alteration zone. The greatest K and Si gains occur in adularia-rich rocks that surround Au deposits along the Waitekauri fault, whereas K gains are progressively lower and Si gains are mostly small in deposits and prospects farther east where illite or interstratified illite-smectite is the dominant K-bearing mineral. In contrast, Na and Ca losses are commonly complete and thus do not increase significantly from the periphery to the core of the altered zone in the Waitekauri area. However, K and Si gains correlate with other measures of K metasomatism, including K/Sr and Rb/Sr values and molar K/(K+Na+2Ca) values. Together, these parameters vector from the barren periphery to the mineralized center of the Waitekauri area and are potentially useful for geochemical exploration in other adularia-sericite-type hydrothermal systems.

Simpson and Mauk (2011) describe hydrothermal alteration in the Waitekauri area, which includes several small epithermal deposits and prospects (Sovereign, Jubilee, Scimitar, Scotia, Teutonic, and Jasper Creek). Utilizing drill core samples from the same 3-km-long composite cross section through the area studied by Booden et al. (2011), they describe the spatial and temporal zonation of hydrothermal alteration and veins. Using the distribution of hydrothermal minerals, vein assemblages, and fluid inclusion data, they estimate the position of the paleowater table and suggest that these deposits and prospects formed over a 600-m vertical interval. They show that the Sovereign and Jubilee deposits likely formed in the main zone of fluid upflow along the Waitekauri fault, whereas the Teutonic and Jasper Creek prospects probably formed toward the margins of the hydrothermal system. The greatest amount of erosion has occurred at the Jubilee and Sovereign deposits (~300–400 m), and these deposits may represent the roots of a more extensive vein network that has been mostly eroded. Fluid inclusion and stable isotope data indicate that hydrothermal fluids are dominantly composed of dilute meteoric water.

Spörli and Cargill (2011) describe complex three-dimensional structure in the shallowest (now mined-out) levels of the Martha mine. They studied a northeast-striking block of rock 360-m long and up to 100-m wide that was occupied by a complex vein network dominated by the northeast-striking Martha and Welcome lodes, which were up to 30-m thick. Veins occupied fractures and followed a network of small-displacement (generally less than a few meters), mostly normal faults. Variable vein and breccia textures indicate multiple stages of open-space filling by vein minerals that were associated with changes in the physical and chemical conditions of the mineralizing fluid. Kinematic analysis of faults shows that the veins formed in response to northwest-southeast, north-south, and east-west extension, thereby implying complex three-dimensional strain. The overall tectonic control on vein formation is dominated by northwest-southeast extension and dip-slip deformation. Spörli and Cargill (2011) show that three-dimensional strain in this area is not only due to local interference of differently oriented structural features, but also to the superposition of regional north-northwest and northeast tectonic trends associated with migration of a subduction zone past the Coromandel peninsula. This study demonstrates that structural control of epithermal mineralization may originate from a variety of tectonic controls at different scales.

Renewed mining in the late 20$^{th}$ and early 21$^{st}$ centuries in the Hauraki goldfield has provided extraordinary opportunities for research in some of the most classic epithermal deposits of the Hauraki goldfield, including Martha, Favona, Golden Cross, Karangahake, and Broken Hills. This research has been strongly supported by mining and exploration companies in the region, which have provided access to data, drill core, and mine workings, co-funding for research, and collaborative input from mine and exploration staff into research projects. This gracious and generous sharing of data and these collaborative efforts have made the papers in this volume possible, and ongoing collaborations continue to provide significant research opportunities. Close partnership between researchers and industry worldwide has enormous potential to significantly increase our understanding of Earth systems and resources.

## Acknowledgments

This collection of papers on the Hauraki goldfield would not have been possible without the timely and thorough reviews provided by Greg Arehart, Barney Berger, Bob Brathwaite, Steve Box, Mike Dentith, Nellie Olsen, Jim Saunders, Terry Spell, Peter Vikre, and Ian Warren. Peter Vikre and Jeff Mauk provided helpful comments on this introduction. I thank Larry Meinert for supporting publication of this collection of papers in *Economic Geology*.

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