Discriminating magmatic and hydrothermal processes in borehole data: implications for orogenic gold in Yilgarn Craton, Western Australia

Mosayeb Khademi Zahedi
Mineral Exploration Cooperative Research Centre (MinEx CRC), Future Industries Institute, UniSA
Mawson Lakes SA 5095
mosayeb.khademi_zahedi@mymail.unisa.edu.au

David Giles
Mineral Exploration Cooperative Research Centre (MinEx CRC), Future Industries Institute, UniSA
Mawson Lakes SA 5095
David.Giles@unisa.edu.au

Caroline Tiddy
Mineral Exploration Cooperative Research Centre (MinEx CRC), Future Industries Institute, UniSA
Mawson Lakes SA 5095
Caroline.Tiddy@unisa.edu.au

Mark Lindsay
Mineral Exploration Cooperative Research Centre (MinEx CRC), CSIRO Mineral Resources,
Kensington WA 6151
mark.lindsay@csiro.au

Andrej Bona
Mineral Exploration Cooperative Research Centre (MinEx CRC), Curtin University,
Kensington WA 6151
A.Bona@curtin.edu.au

SUMMARY

In this paper we give an example from the Fortitude North prospect in the Kurnalpi Terrane of the eastern Yilgarn Craton, where the integration of geochemistry with borehole petrophysics can be used to identify lithological units, infer geological processes (e.g., magmatic differentiation, alteration and weathering) and constrain geological and geophysical models of the prospect. We use major and immobile trace element concentrations to discriminate between primary lithologies and identify differentiation trends in the mafic magmatic units. Density and seismic velocity measurements show broad correlation with primary rock types, with unaltered dolerite tending to have higher density and velocity compared to basalts and altered rocks. Magnetic susceptibility measurements are used to corroborate geochemical differentiation trends, specifically magnetite fractionation in dolerite units. A range of gold pathfinder and chalcophile elements are used to identify hydrothermal alteration related to gold mineralisation. Integrating geochemistry and petrophysics at drillhole- and prospect-scales helps to constrain important geological processes and demonstrates how those processes can be interpreted from geophysical data sets.

Key words: geochemistry, petrophysics, magmatic differentiation, mafic rocks, dolerites

INTRODUCTION

The Fortitude North prospect is located in the highly mineralised Laverton Tectonic Zone (Cassidy et al., 2006), in the Kurnalpi Terrane of the Eastern Goldfields superterrane of the Archean Yilgarn Craton in Western Australia (Figure 1). The regional geology is characterised by elongated granite domes surrounded by supracrustal greenstone belts. The Laverton Tectonic Zone (LTZ) is a structurally complex north-south trending belt located along the eastern margin of the Kurnalpi terrane. Numerous greenstone-hosted, structurally controlled gold deposits including Wallaby and Sunrise Dam, two of the most significant gold deposits in Western Australia, occur within the LTZ.

Fortitude North Rock Types

Three major protolith rock types are identified in drill core from Fortitude North - dolerite, basalt and felsic magmatic rocks (Figure 2). Dolerite and basalt units constitute 51% and 21% by volume respectively. Dolerite is fine to medium-grained, and basalt is fine grained with grey to dark olive-green colour and mostly of mylonitic textured, as logged by Matsa Resources. The subordinate group of felsic magmatic and volcano-sedimentary units (6% by volume) are primarily identified by their pale colour.

Figure 2 shows the rock types logged in three drill cores along a Northwest-Southeast traverse. The drill holes are dominated by dolerite and basalt with minor interpreted felsic rocks throughout. Rocks in the upper sections of the drill holes are weathered.

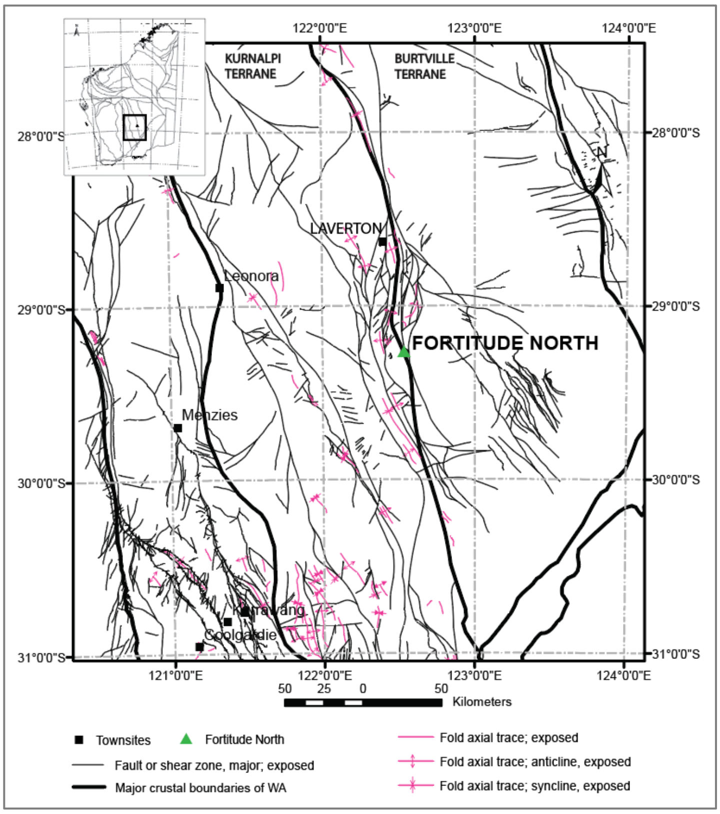

Figure 1. Location of Fortitude North in Eastern Goldfields superterrane of the Archean Yilgarn Craton in Western Australia (modified from GSWA's 1:500k interpreted bedrock geology structural lines, 2020 and 1:2.5M major crustal boundaries of Western Australia, 2020 GIS layers

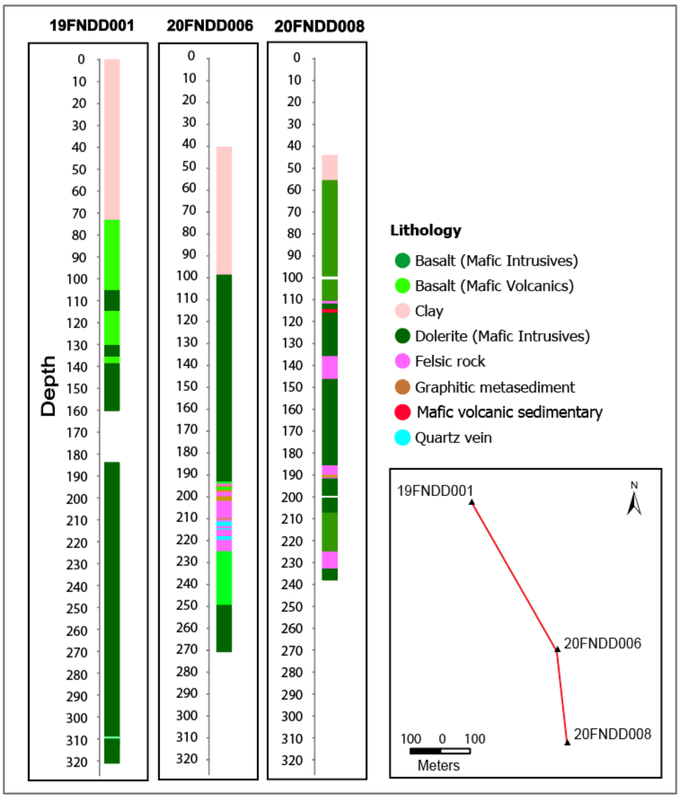

Figure 2. Distribution of logged lithologies in three drillholes from Fortitude North. Dolerite and basalt rocks are the dominant lithologies logged by Matsa Resources

RELATIONSHIPS BETWEEN PETROPHYSICAL AND GEOCHEMICAL PROPERTIES

Major and immobile element chemistry

The main rock types of dolerite and basalt identified in drill core preserve distinctive major and immobile element geochemical characteristics. Dolerite and basalt rock types have almost complete overlap in terms of major and immobile element chemistry with at least four identifiable geochemical subgroups with distinct ratios of Ti, Nb and P vs Al (Figure 3). The interpreted felsic rock types have major and immobile element concentrations comparable to the low Ti:Al mafic subgroup, but have elevated concentrations of potassium. The majority of rocks from Fortitude North, including some logged as felsic magmatic and volcano-sedimentary rocks, plot in the basalt field based on the immobile element discrimination diagram of Pearce (1996) (Figure 4).

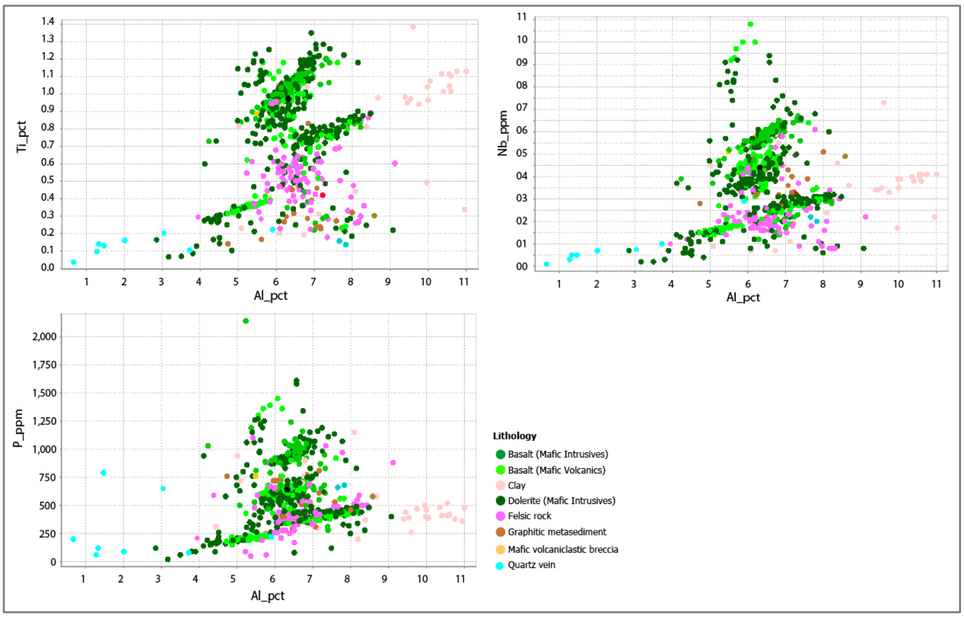

Figure 3. Cross plots of laboratory assay Ti, Nb and P vs Al from boreholes at the Fortitude North prospect color-coded by logged rock type.

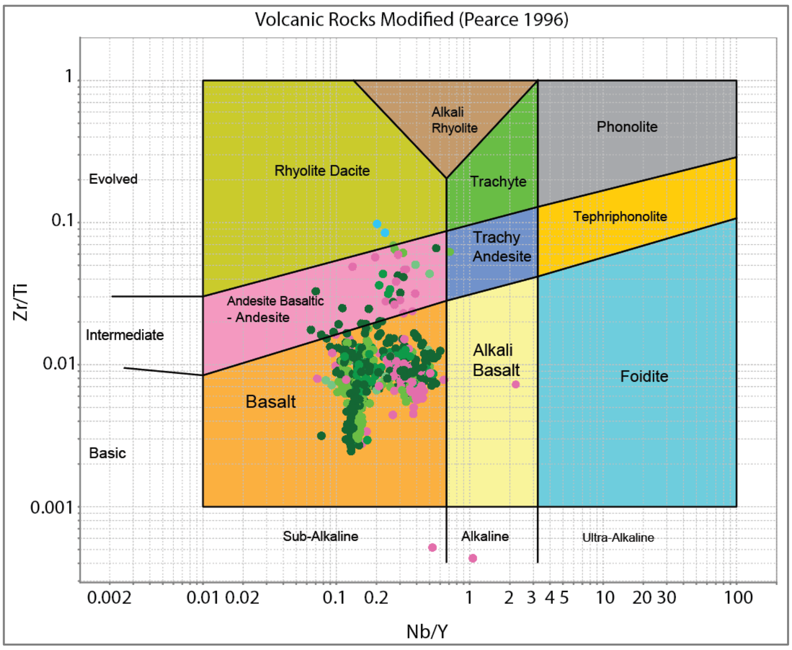

Figure 4. Immobile element discrimination diagram for volcanic rocks after Pearce (1996) showing laboratory geochemical data from diamond drillholes at the Fortitude North prospect colour coded by logged rock type (refer to the legend shown in Figure 3).

A plot of Fe against Zr shows the mafic magmatic rock types display a positive correlation up to Zr concentrations of approximately 90ppm, a plateau between 90 and 130ppm followed by slight negative trend above 130ppm (Figure 5). These trends are consistent with fractional crystallisation where there is a relative increase in Fe as Mg-rich phases crystallised from the melt, followed by saturation of a Fe-rich phase at Fe concentrations of ~ 12% and corresponding to Zr concentration window of 90 to 130ppm. In contrast the felsic magmatic rocks form a distinct high-K group on the plot of K vs Zr with concentrations ranging from 0.25 to 2.5%.

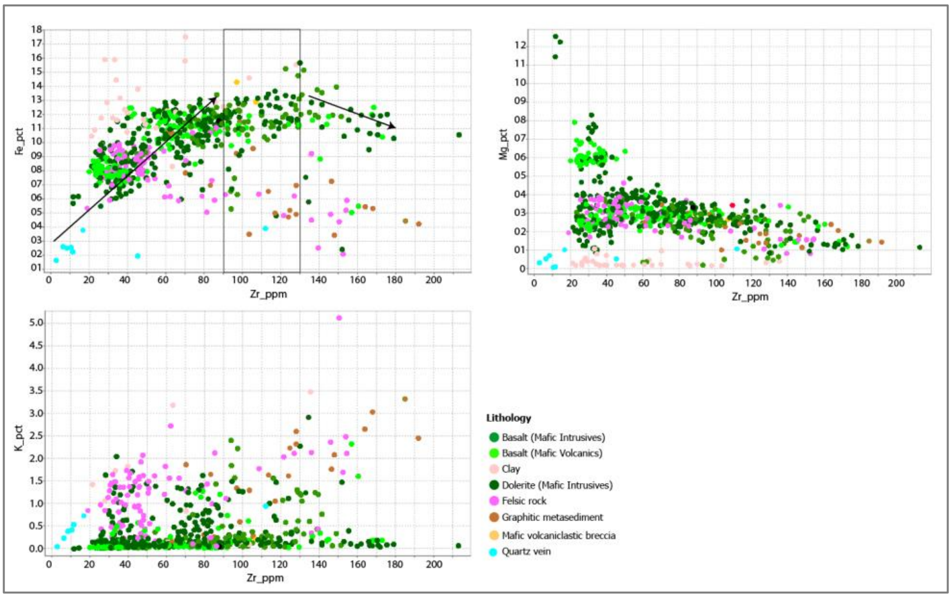

Figure 5. Plots of laboratory geochemical analyses of Fe, Mg and K vs Zr from drill holes at the Fortitude North prospect, colour coded by logged rock type.

Pathfinder elements related to Au systems

Potassium, Cu, Te, As, S, Sb and W are found to be alteration indices for Au deposition in Fortitude North area. A principal component analysis (PCA) plot shows elevated concentrations in pathfinder elements related to Au system (Figure 6). Given that orogenic gold deposits are mainly formed through hydrothermal alteration processes in structures associated with shear zones (Groves et al., 1998), identifying pathfinder elements for gold are most useful to delimit targets and narrow the search space (Nichols, 2016).

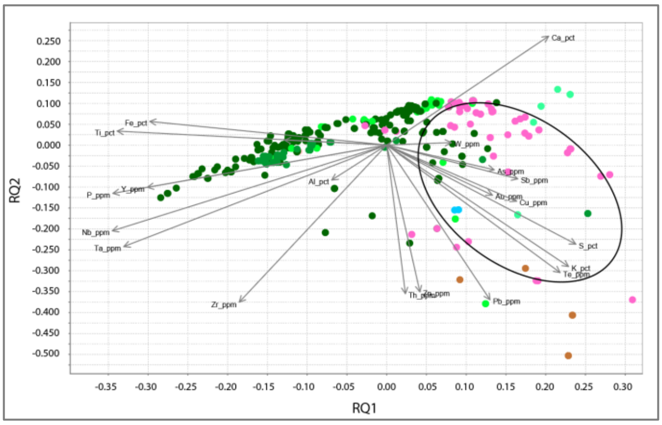

Figure 6. Principal component analysis of geochemical elements. Eigenvectors highlighted by the oval indicate elevated concentrations of pathfinder elements related to an Au system (refer to legend from Figure 5 for lithology colour code).

Petrophysics

Magnetic susceptibility measurements collected from the Fortitude North drill core range between -2 and +2 log_{10}SI units with a prominent mode at approximately -0.2 log_{10}SI units and a discrete population of elevated values between 0.5 and 2 log_{10}SI units (Figure 7a). The dominant population (with mode at -0.2 log_{10}SI units) includes all protolith rock types whereas the higher magnetic susceptibility population includes only dolerite and basalt protoliths. These magnetically susceptible rock types are concentrated in discrete 10s of meter wide zones.

The density measurements from Fortitude North drill core range between 2.3 and 3.1 g/cm^3 with prominent modes at ~2.85 and 3.00 g/cm^3 (Figure 7b). The mode at ~2.85 g/cm^3 includes all magmatic rock types, whereas the 3.00 g/cm^3 mode is dominated by dolerite. Intervals logged as felsic rocks have lower density than the enclosing mafic rocks with particularly sharp contrast where they are in contact with dolerite (e.g., at 150m depth in 20FNDD008, Figure 7b).

The seismic velocity measurements collected from three drillholes range between 2000 and 6500 m/s, with prominent modes at 5500 and ~6000 m/s (Figure 7c) and a lower velocity population tail (<4000 m/s). The higher velocity population includes only dolerite and basalt mafic intrusive rocks whereas the 5500 m/s mode includes all magmatic rock types.

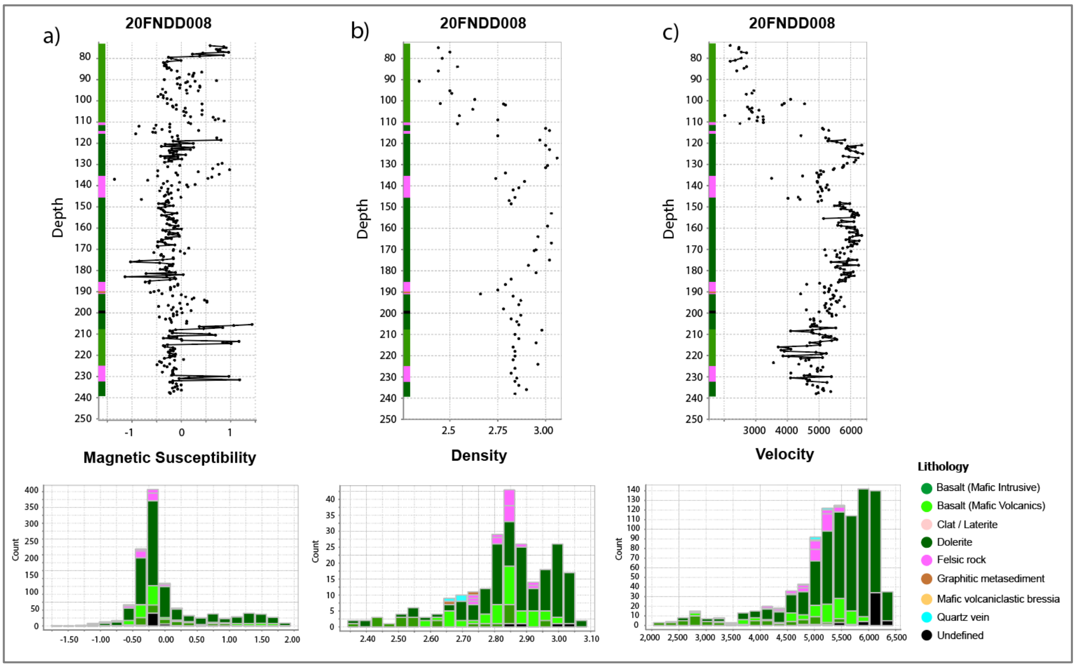

Figure 7. Downhole display and histograms of a: magnetic properties, b: compressional velocity and, c: bulk density in 20FNDD008 borehole.

The plot of magnetic susceptibility vs Zr concentration (Figure 8) shows a band of high magnetic susceptibility (up to 70 x 10^{-3} SI units) in the range of Zr concentration between 90 and 130ppm. The samples with magnetic susceptibility > 30 x 10^{-3} SI units correspond to the higher magnetic susceptibility population in Figure 7. The range of Zr concentrations corresponds to the tipping point in the plots of Fe vs Zr (Figure 5) consistent with the precipitation of magnetite from the mafic melt via fractional crystallisation.

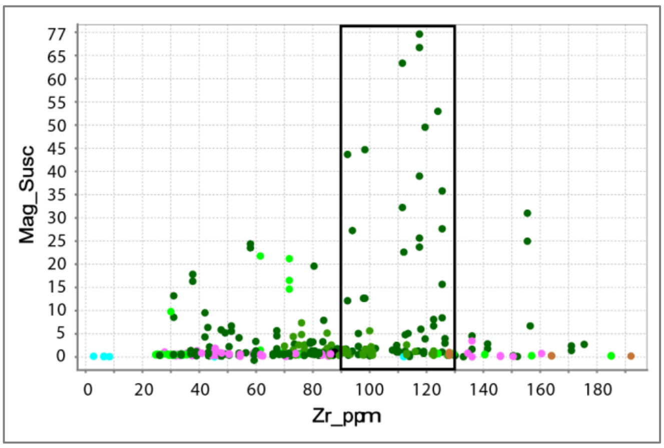

Figure 8. Cross plot of Zr concentration and magnetic susceptibility (10^{-3}SI) (rectangle indicates the zone of higher magnetic susceptibility coinciding with the "tipping point" interval indicated on Fe versus Zr diagram (refer to legend from Figure 5 for lithology colour code)

CONCLUSIONS

The observed geochemical trends in Mg, Fe vs Zr are indicative of magmatic fractional crystallisation in which there was crystallisation of Mg-rich phases (e.g., olivine and pyroxene) and retention of Fe and Zr in the melt phase during the early stages of fractionation. During the latter stages of fractionation there was precipitation of an Fe-rich phase (corresponding to the tipping point at Zr concentrations of 90 to 130ppm). Higher magnetic susceptibility values are consistently associated with the interval of 90 to 130 ppm Zr content (Figure 8) and there is a strong spatial correlation between magnetic susceptibility and Fe indicating that precipitation of magnetite is responsible for the observed geochemical trends. This phenomenon is well-established in mafic intrusions undergoing in-situ fractional crystallisation (e.g., Pearce and Norry, 1979) and has been linked to zones of gold mineralisation elsewhere in the Yilgarn Craton (Hayman et al., 2021).

The group of rocks logged as felsic magmatic rocks have immobile element chemistry overlapping with the bulk of mafic magmatic rocks from Fortitude North, but are enriched in K, S, As, Te, Sb, Cu and Au compared to their mafic counterparts (Figures 6). These are most likely altered mafic rocks which show enrichment in alteration elements such as K, S, Sb, As, Cu, Te, W and Au as (Figure 6). This is a common suite of alteration elements associated with orogenic gold systems in Yilgarn Craton (Bateman & Hagemann, 2004; Colvine et al., 1984; Eilu & Groves, 2001; Groves et al., 1998; Patten et al., 2020). The majority of felsic samples lie on magmatic fractionation trends of Mg and Fe vs Zr (Figure 5) at concentrations typical of basalt (30-50ppm Zr) as opposed to felsic volcanic rocks that are generally enriched in Zr relative to mafic lithologies (Mielke, 1979). Additionally, the felsic samples have densities of ~ 2.85 gm/cm^3 (Figure 7b) which are atypical of felsic volcanic rocks and more consistent with altered mafic rocks (Telford et al., 1990). Therefore, on geochemical and petrophysical evidence, it seems likely that the bulk of rocks logged as felsic magmatic rocks are actually altered mafic rocks, with a subordinate number of felsic volcanic or metasedimentary rocks.

The positive relationship between density and velocity in our dataset indicates that these petrophysical properties are mostly related to primary lithology, although alteration, fractures and shear zones affect these parameters to some extent depending on their intensity. The highest densities and velocities are encountered in dolerite units. This facilitates the interpretation of boundaries between dolerites and other lithotypes from reflections in seismic data as the combination of these properties would be expected to create an impedance contrast.

The relationship between magnetic susceptibility and geochemical measurements indicates variations related to magmatic processes. This relationship is mainly observed in dolerite and basalt units and can be used for better delineation of the top of sills from high-resolution magnetic data. Hayman et al. (2021) argue that dolerites have favourable characteristics for orogenic gold mineralisation and hence mapping their distribution can identify prospective locations.

ACKNOWLEDGMENTS

We thank Matsa Resources for providing the Fortitude North dataset and MinEx CRC for the support and permission to publish this work. Data analysis and plots for this paper were generated using ArcGIS and ioGAS Software.

REFERENCES

Bateman, R., & Hagemann, S. (2004). Gold mineralisation throughout about 45 Ma of Archaean orogenesis: protracted flux of gold in the Golden Mile, Yilgarn craton, Western Australia. Mineralium Deposita, 39(5), 536-559.

Blewett, R. (2010). Archean gold mineral systems in the eastern Yilgarn Craton. AUSGEO news, 100.

Cassidy, K., Champion, D., Krapez, B., Barley, M., Brown, S., Blewett, R., Groenewald, P., & Tyler, I. (2006). A revised geological framework for the Yilgarn Craton, Western Australia. Geological Survey of Western Australia, Record, 8(8).

Chen, S. F., Witt, W. K., & Liu, S. (2001). Transpression and restraining jogs in the northeastern Yilgarn craton, Western Australia. Precambrian Research, 106(3-4), 309-328.

Colvine, A. C., Andrews, A. J., Cherry, M. E., Durocher, M. E., Fyon, J. A., Lavigne, M. J., Macdonald, A. J., Marmont, S., Poulsen, K. H., Springer, J. S., & Troop, D. G. (1984). An integrated model for the origin of Archean lode gold deposits (Vol. 5524). In: Ontario Geological Survey Open-File Report.

Eilu, P., & Groves, D. (2001). Primary alteration and geochemical dispersion haloes of Archaean orogenic gold deposits in the Yilgarn Craton: the pre-weathering scenario. Geochemistry: Exploration, Environment, Analysis, 1(3), 183-200.

Emerson, D. (1990). Notes on mass properties of rocks - density, porosity, permeability. Exploration Geophysics, 21(4), 209-216.

Groves, Goldfarb, R., Gebre-Mariam, M., Hagemann, S. G., & Robert, F. (1998). Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews, 13(1-5), 7-27.

Hayman, P., Campbell, I. H., Cas, R. A., Squire, R. J., Doutch, D., & Outhwaite, M. (2021). Differentiated Archean dolerites: igneous and emplacement processes that enhance prospectivity for orogenic gold. Economic Geology, 116(8), 1949-1980.

Jackson, J. E. (1991). A Use's Guide to Principal Components.

Jolliffe, I. T. (1986). Principal component analysis / I. T. Jolliffe (1st ed. 1986. ed.). New York, New York : Springer.

Le Maitre, R. W., Streckeisen, A., Zanettin, B., Le Bas, M., Bonin, B., & Bateman, P. (2005). Igneous rocks: a classification and glossary of terms: recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks. Cambridge University Press.

Lemiere, B. (2018). A review of pXRF (field portable X-ray fluorescence) applications for applied geochemistry. Journal of Geochemical Exploration, 188, 350-363.

Mielke, J. (1979). Composition of the Earth's crust and distribution of the elements.

Nichols, B. I. (2016). Hydrothermal alteration mineralogy and zonation in the orogenic Frog's Leg gold deposit, Yilgarn craton, Western Australia Master thesis, University of Western Australia, 188p].

Patten, C., Pitcairn, I. K., Molnár, F., Kolb, J., Beaudoin, G., Guilmette, C., & Peillod, A. (2020). Gold mobilization during metamorphic devolatilization of Archean and Paleoproterozoic metavolcanic rocks. Geology, 48(11), 1110-1114.

Pearce, J. A. (1996). A user’s guide to basalt discrimination diagrams. Trace element geochemistry of volcanic rocks: applications for massive sulphide exploration. Geological Association of Canada, Short Course Notes, 12(79), 113.

Pearce, J. A., & Norry, M. J. (1979). Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. Contributions to mineralogy and petrology, 69(1), 33-47.

Schofield, A., Roach, I., Czarnota, K., O'Rourke, A., Wynne, P., Jiang, W., Duan, J., Pitt, L., Cross, A., & Goodwin, J. (2020). Data integration for greenfields exploration: an example from the East Tennant region, Northern Territory. Geoscience Australia.

Telford, W. M., Telford, W., Geldart, L., & Sheriff, R. E. (1990). Applied geophysics. Cambridge university press.

Tripp, G. I., Tosdal, R. M., Blenkinsop, T., Rogers, J. R., & Halley, S. (2020). Neoarchean eastern goldfields of Western Australia.