GEOLOGY, HOST ROCK SUCCESSION, AND HYDROTHERMAL ALTERATION OF THE WATERLOO VOLCANIC-HOSTED MASSIVE SULPHIDE DEPOSIT (NORTHERN QUEENSLAND, AUSTRALIA)

Der Fakultät für Geowissenschaften, Geotechnik und Bergbau

der Technischen Universität Bergakademie Freiberg

eingereichte

DISSERTATION

zur Erlangung des akademischen Grades

doctor rerum naturalium

Dr. rer. nat.

vorgelegt

von Diplom-Mineraloge Thomas Monecke

geboren am 18. September 1972 in Ilmenau/Thüringen

Freiberg, den 3.10.2002

ABSTRACT

The Waterloo volcanic-hosted massive sulphide (VHMS) deposit is located in the Charters Towers Region in northern Queensland, Australia. The deposit forms part of the Cambro-Ordovician Seventy Mile Range Group that represents a major belt of E-W striking and subvertical dipping volcanic-sedimentary rocks. The volcanic host rocks and the base metal mineralisation of the Waterloo deposit are not exposed in surface outcrops because of a thick cover by Pliocene fluvial sedimentary rocks. Exploration diamond drilling (total ~10 km of core) led to the delineation of a relatively small high-grade base metal resource of 243,500 tonnes ore grading 3.8 % Cu, 13.8 % Zn, 3.0 % Pb, 74 g/t Ag, and 1.2 g/t Au. The mineralisation comprises several small semiconnected stratiform, blanket-like, pyrite-chalcopyrite-sphalerite-galena massive sulphide lenses.

The structural style of the Early Ordovician Waterloo sequence has been constrained using macroscopic structural techniques. The massive sulphides at Waterloo are interpreted to be syn-volcanic in origin because they have been overprinted by the same generations of tectonic structures as the host stratigraphy. The Waterloo sequence was tilted into a subvertical position during north-south compression that is possibly Mid- to Late Ordovician in age. This regional folding event also resulted in the development of an axial plane cleavage that is particularly well developed in a high strain zone surrounding the massive sulphides. The spatial relationship between the folded bedding plane and the axial plane cleavage as well as the consistent south facing of the bedding of volcaniclastic sediments indicate that the deposit is located at the southern limb of a major east-west trending antiform. This antiform has a shallow plunge to the west. The Waterloo sequence was affected by two faulting events that are younger than the regional folding. Early steeply dipping ENE striking faults interpreted to be Silurian or Devonian were accompanied by significant dip-slip normal movement, whereas younger strike-slip faults have no affect to the geometry of the Waterloo sequence.

Based on the improved understanding of the structural style of the Waterloo sequence, the volcanic facies architecture of the host sequence was investigated to unravel the temporal and spatial relationships between volcanism and massive sulphide formation. The massive sulphides formed in a below storm wave base depositional environment on top of a non-explosive, near-vent, andesite-dominated facies association containing coherent volcanic units and related juvenile volcaniclastic rocks. The massive sulphide lenses are overlain, and partially hosted in, a coarse quartz-feldspar crystal-rich sandstone and breccia facies. These rocks are interpreted to be mass flows that record contemporaneous probably explosive dacitic to rhyolitic volcanism outside the Waterloo area. The still wet and unconsolidated coarse sediment in the immediate hanging wall of the massive sulphides was intruded by a feldspar porphyritic dacite cryptodome that was partly emergent at the ancient seafloor. The emplacement of the cryptodome indicates that the magmatic source feeding the volcanism within the Waterloo area shifted towards an acidic composition at the time of massive sulphide formation. Dacite cryptodome volcanism at Waterloo was followed by the waning of the hydrothermal activities. The subsequent period of relatively quite sedimentation was occasionally interrupted by the emplacement of syn-sedimentary basaltic to andesitic sills and was followed by the mass flow deposition of a coarse feldspar-quartz sandstone and breccia facies. Finally there was a period of intense non-explosive, near-vent basalt to andesite-dominated volcanism.

Petrochemical investigations demonstrated that the coherent volcanic rocks of the Waterloo sequence belong to a subalkaline volcanic suite. The basalt, andesite, and dacite of the Waterloo sequence are cogenetic. The petrographic and petrochemical characteristics of the reworked volcaniclastic facies suggest that the material was derived from a petrogenetically similar volcanic source of dacitic to rhyolitic composition. The geochemical signatures of the most primitive volcanic rocks from the Waterloo sequence are similar to modern subduction-related volcanics, such as back-arc basin basalts forming during the early stages of back-arc basin evolution. Based on these findings and the results of previous regional studies, it is suggested that volcanism in the Waterloo area occurred in a bac - arc basin that developed on thinned Precambrian continental lithosphere flanking a continental margin volcanic arc.

Mineralogical investigations on the volcanic rocks hosting the massive sulphides revealed that two types of alteration can be distinguished. Least altered rocks were affected by weak regional alteration that was caused by the combined effects of devitrification, hydration, burial diagenesis, seawater interaction, regional metamorphism of the lower greenschist facies, and deformation. In contrast, volcanic rocks located in the footwall and the immediate hanging wall of the massive sulphides were subject to a combination of hydrothermal and regional alteration.

The spatial distribution of alteration mineral associations as well as the mineralogical and geochemical attributes of the hydrothermal altered rocks constrain the environment of hydrothermal alteration. The massive sulphide lenses at Waterloo are underlain by an extensive footwall alteration halo that is typified by a semiconformable zonation defined by an inner zone of silicic-altered volcanics (pyrite-quartz-muscovite) that laterally passes into a zone of phyllic alteration (pyrite-muscovite-chlorite-quartz, pyrite-paragonite-muscovite-chlorite-intermediate Na/K mica-quartz, and pyrite-muscovite-albite-chlorite-paragonite-intermediate Na/K mica-quartz-calcite) and a zone consisting of propylitic-altered volcanics (albite-chlorite-epidote-muscovite-paragonite-quartz-calcite-pyrite and albite-chlorite-epidote-quartz-calcite). It is demonstrated that the development of the zonation of the alteration halo can be directly linked to the nature and evolution of the fluids interacting with the volcanic rocks in the different parts of the hydrothermal alteration halo. Hydrothermal alteration in the upflow zones of the mineralising fluids resulted in the formation of large amounts of muscovite on the expense of primary rock-forming silicates by the combined effects of potassium and hydrogen metasomatism. This type of alteration was principally linked to the acidity of the mineralising hydrothermal fluids. The alteration in the upflow zones also involved a sulphidisation of the rocks due to the reaction of ferrous iron contained in rock-forming silicates and the volcanic glass matrix with H_2S supplied by the hydrothermal fluids. Silicification was pronounced in the upflow zones because the mineralising fluids cooled by moving down a temperature gradient. Outward percolation of the hydrothermal fluids into zones surrounding the thermal upflow was accompanied by a rapid neutralisation of the strong acids and, therefore, an increasing reactivity of CO_2 with respect to hydrogen metasomatism. The percolation of seawater into the zones surrounding the high temperature upflow zones was intrinsically involved in the development of the alteration zonation. Heating of seawater, by moving up a temperature gradient, resulted in a pronounced sodium metasomatism in the outer parts of the alteration halo that caused the formation of sodium silicates (albite, intermediate Na/K mica, and paragonite) at the expense of primary rock-forming silicates such as feldspars and earlier formed products of hydrothermal alteration, such as muscovite. In contrast to the footwall alteration halo, alteration of the volcanic facies overlying the ore horizon is limited in extent and rapidly fades in intensity with increasing distance from the sulphides. The zonation of the hanging wall alteration is defined by an inner zone of phyllic alteration (pyrite-muscovite-quartz, pyrite-muscovite-paragonite-intermediate Na/K mica-chlorite-quartz, muscovite-chlorite-quartz, and muscovite-paragonite-intermediate Na/K mica-chlorite-quartz) and an outer zone comprising propylitic-altered volcanics (albite-muscovite-chlorite-paragonite-intermediate Na/K mica-quartz-calcite and albite-muscovite-chlorite-epidote-quartz-calcite). Phyllic alteration in the immediate hanging wall of the massive sulphides can be accounted for by the ongoing intense alteration following the burial of the ores by the mass flow derived coarse quartz-feldspar sandstone and breccia facies and the emplacement of the dacitic cryptodome, whereas the outer zone of propylitic alteration records the waning of the hydrothermal activities where alteration occurred at successively decreasing temperatures in a more oxidising environment.

Based on the results of this study it is suggested that the genetic relationship between volcanism and massive sulphide formation can be constrained by integrating volcanological studies on the host rock sequence with detailed mineralogical and geochemical investigations of the hydrothermally altered rocks. The volcanological investigations demonstrate that the mineralisation event occurred in close temporal and spatial relationship to felsic volcanism culminating in the emplacement of a dacite cryptodome in the immediate hanging wall to the massive sulphides. The findings of the alteration halo study are consistent with this observation because the mantle-derived volcanism in the Waterloo area may not only have provided the heat to drive the hydrothermal system, but may also have acted as a source of chemical components, such as volatile species that controlled the acidity of the mineralising hydrothermal fluids.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisors Prof. Peter Herzig and Prof. Bruce Gemmell for advice, helpful discussions, and review of the thesis. It would not have been possible to undertake this research without their continuous interest in this study, their encouragement, and scientific guidance. Special thanks are due to Bruce Gemmell for his exceptional support and his initial assistance during core logging at Charters Towers. I thank Prof. Peter Stoffers for careful review of the thesis.

I gratefully acknowledge a scholarship provided by the Studienstiftung des Deutschen Volkes. In particular, the continuous interest in the progress of this study by Max Brocker is appreciated. The Studienstiftung des Deutschen Volkes also most kindly provided travel funds to Tasmania and supported my participation at national and international scientific conferences. Analytical data acquisition was sponsored as a part of the AMIRA project P439 by Aberfoyle Resources, Copper Mines of Tasmania, Denehurst, Mineral Resources Tasmania, Normandy Exploration, Pasminco Exploration, Queensland Metal Corporation, RGC Exploration, and Rio Tinto Exploration. I wish to thank Prof. Ross Large for his interest in this thesis and for his efforts to set up the AMIRA project P439. A grant by the Australian Research Councils Research Centres Program is also acknowledged. It supported field work at Charters Towers and made the acquisition of additional geochemical data possible. I thank RGC Exploration for their logistical support during the two field seasons at Charters Towers. The XRD work greatly benefited from grants by the Deutsche Forschungsgemeinschaft (KL 1286/1-1 and KL 1286/1-2). The trace element determinations at the Large Scale Geochemical Facility at the University of Bristol were supported by the European Community-Access to Research Infrastructure action of the Improving Human Potential Programme. I also acknowledge a travel grant to Tasmania provided by the Deutsche Forschungsgemeinschaft (MO 972/1-1).

I am indebted to several people who made significant contributions to the thesis by providing their analytical expertise and helped me to critically asses the quality of the analytical results. Specifically, I like to thank Phil Robinson for the excellent major and trace element analyses by means of XRF. The precision and accuracy of his measurements always impressed me. Reinhard Kleeberg profoundly contributed to the results of the qualitative and quantitative XRD analysis by introducing me to the Rietveld method. I thank Reinhard Kleeberg for endless discussions and help provided during numerous experiments to reduce systematic errors that are caused by layer disorder of phyllosilicates, preferred orientation of particles, and microabsorption. I also appreciate the help provided by Sibylle Köhler during quantitative analysis and implementation of starting structures into the Rietveld software. I profited from the development of the excellent Rietveld programs BGMN by Jörg Bergmann. His comments improved my understanding of the software and of some crystallographic and mathematical aspects of the Rietveld method.

Chung Choi and Tony Kemp aided me during ICP-MS measurements at Bristol. Special thanks are also due to Ulf Kempe, David Steel, and Klaus-Peter Becker for their help during the SEM and EMP work. Particularly, I acknowledge the marvellous BSE pictures Ulf Kempe has taken. The cathodoluminescence work was carried out together with Jens Götze. I think that his magnificent CL images and the information gathered from these pictures form an important part of the study. I wish to thank the RGC Exploration staff at Charters Towers, particularly Craig Miller and Leanne Carr, for discussion on the geology of the Waterloo deposit and organisation of the field seasons, respectively. In this context I would also like to thank Joe Stolz for his support to organise the first field season at Charters Towers and his superb introduction to the geology of the Waterloo deposit. I acknowledge very useful comments by Ron Berry on the structural geology of the Waterloo deposit. Jocelyn McPhie most kindly helped me to interpret some of the most difficult volcanic textures that I have found in diamond drill core from the Waterloo deposit.

It would not have been possible to assemble the analytical data of this study without the help of several people, especially Nilar Hlaing and Katie McGoldrick (XRF preparation), Ingeborg Gerlach, Gerhild Landers, and Gudrun Weiser (XRD preparation), Sandy Haßler (XRD), Pamela Kaiser and Anja Obst (SEM operation), Michael Magnus and Simon Stevens (thin section preparation), June Pongratz (computer support), Peter Cornish, Marilyn Feast, Gisela Neubert, Kathi Stait, and Manuela Wagner (administrative and logistical support).

My colleagues at the Freiberg University of Mining and Technology, in particular Klaus-Peter Becker, Bernd Buschmann, Leander Franz, Jens Götze, Torsten Graupner, Torsten Gruner, Ulf Kempe, Reinhard Kleeberg, Thomas Kuhn, Daniel Müller, Holger Paulick, Sven Petersen, Axel Renno, Uli Schwarz-Schampera, and Thomas Seifert are thanked for their company and critical and constructive comments on different aspects of my research work. I thank Reinhard Kleeberg for review of parts of the thesis. The past and present postgraduate students at the University of Tasmania, in particular Bruce Anderson, Steve Bodon, Cathryn Gifkins, Steve Hunns, Holger Paulick, David Rawlings, Robina Sharpe, Kirstie Simpson, Rohan Wolfe, and Bill Wyman made my time in Tasmania more than enjoyable. I am indebted to my partner Sibylle Köhler for her great patience, encouragement, and support provided over the past years. I particularly thank my parents for their help and support through the many years of my education.

TABLE OF CONTENTS