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Lithogeochemical and Hyperspectral Halos to Ag-Zn-Au Mineralization at Nimbus in the Eastern Goldfields Superterrane, Western Australia

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Abstract: With new advances in rapid-acquisition geochemical and hyperspectral techniques, exploration companies are now able to detect subtle halos surrounding orebodies at minimal expense. The Nimbus Ag-Zn-(Au) deposit is unique in the Archean Yilgarn Craton of Western Australia. Due to its mineralogy, alteration assemblages, geochemical affinity, and tectonic setting, it is interpreted to represent a shallow water (~650 mbsl) and low-temperature (<250 °C) volcanogenic massive sulfide (VMS) deposit with epithermal characteristics (i.e., a hybrid bimodal felsic deposit). We present a detailed paragenetic account of the Nimbus deposit, and establish lithogeochemical and hyperspectral halos to mineralization to aid exploration. Mineralization at Nimbus is characterized by early units of barren massive pyrite that replace glassy dacitic lavas, and underlying zones of polymetallic sulfides that replace autoclastic monomict dacite breccias. The latter are dominated by pyrite-sphalerite-galena, a diverse suite of Ag-Sb ± Pb ± As ± (Cu)-bearing sulfosalts, minor pyrrhotite, arsenopyrite, and rare chalcopyrite. The main sulfosalt suite is characterized by pyrargyrite, and Ag-rich varieties of boulangerite, tetrahedrite, and bournonite. Zones of sulfide mineralization in quartz-sericite(±carbonate)-altered dacite are marked by significant mass gains in Fe, S, Zn, Pb, Sb, Ag, As, Cd, Ni, Cu, Ba, Co, Cr, Tl, Bi, and Au. Basaltic rocks show reduced mass gains in most elements, with zones of intense quartz-chlorite-carbonate ± fuchsite alteration restricted to thick sequences of hyaloclastite, and near contacts with dacitic rocks. Broad zones of intense silica-sericite alteration surround mineralization in dacite, and are marked by high Alteration Index and Chlorite-Carbonate-Pyrite Index (CCPI) values, strong Na-Ca depletion, and an absence of feldspar (albite) in thermal infrared (TIR) data. White mica compositions are predominantly muscovitic in weakly altered sections of the dacitic footwall sequence. More paragonitic compositions are associated with zones of increased sericitization and high-grade polymetallic sulfide mineralization. Chlorite in dacitic rocks often occurs adjacent to zones of sulfide mineralization and is restricted to narrow intervals. Carbonate abundance is sporadic in dacite, but is most abundant outside the main zones of Na-Ca depletion. Basaltic rocks are characterized by strongly paragonitic white mica compositions, and abundant chlorite and carbonate. Shifts from Ca carbonates and Fe-rich chlorites to more Mg-rich compositions of both minerals occur in more intensely hydrothermally altered basaltic hyaloclastite, and near contacts with dacitic rocks. Hanging-wall polymict conglomerates are characterized by minor amounts of muscovitic to phengitic white mica (2205–2220 nm), and an absence of chlorite and carbonate alteration.

Keywords: volcanogenic massive sulfide; VMS; volcanic-hosted massive sulfide; VHMS; Archean; lithogeochemistry; hyperspectral analysis; pXRF; geochemical halo

1. Introduction

Volcanogenic massive sulfide (VMS) deposits represent major resources of base and precious metals, and can also be significantly enriched in a number of critical metals (e.g., Co, In, Ga, Ge [1]), of which there is growing demand. Their formation is intrinsically linked to periods of extension, magmatism, and hydrothermal circulation in the upper crust, dating from the Archean (ca. 3.3 Ga [2]) to the present day [3,4]. Whether measured in number of deposits, tons of ore, or tons of metal, the distribution of these orebodies through time is episodic. One major peak occurs in the Late Archean [5].

In recent years, it has become increasingly apparent that VMS deposits of the Archean Yilgarn Craton of Western Australia (Figure 1) are limited to key episodes during its evolution. Two main zones of crust have been identified that encompass dozens of individual greenstone belts and deposits of varying age [6–8]. In the Youanmi Terrane, VMS mineralization is associated with the Cue zone, characterized by juvenile Sm-Nd (granite) and Pb (galena) isotopic ratios [6,7]. This zone extends from the Quinns VMS district in the northeast, to the Golden Grove camp in the southwest (Figure 2). In the Eastern Goldfields Superterrane, VMS mineralization is predominantly restricted to the Kurnalpi/Teutonic zone, which broadly corresponds to the mapped boundaries of the Kurnalpi Terrane (Figure 2). These regions of juvenile crust represent Archean paleo-rift zones, which, in the case of the Cue zone, was reactivated multiple times from ca. 2.95 to 2.72 Ga [8].

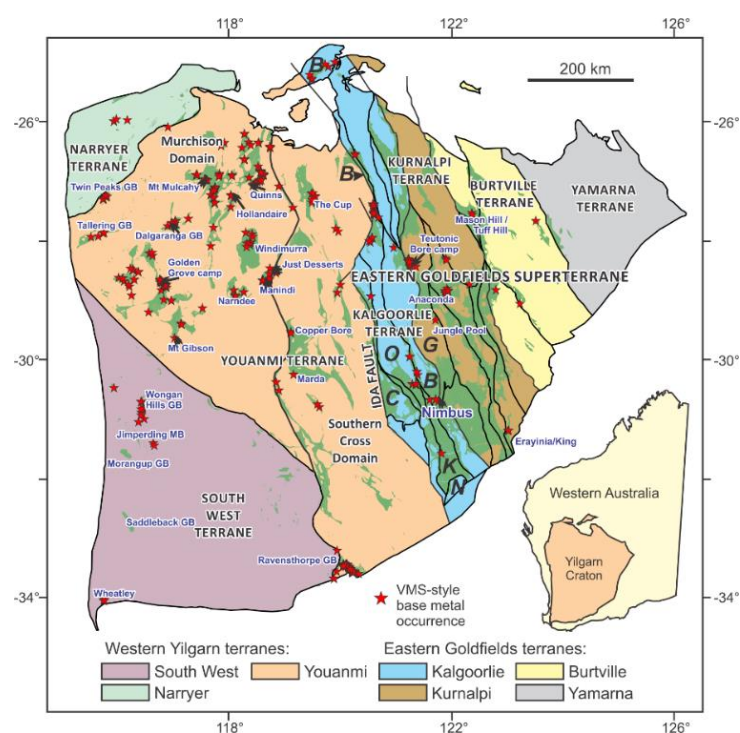


Figure 1. Major terrane and domain subdivisions of the Yilgarn Craton, Western Australia, showing the distribution of greenstone belts, and volcanogenic massive sulfide (VMS)-style base metal occurrences (red stars) after Hollis et al. [8]. Significant VMS deposits and prospective greenstone belts are labelled. Domains: B, Boorara; C, Coolgardie; G, Gindalbie; K, Kambalda; N, Norseman; O, Ora Banda. Abbreviations: GB, Greenstone belt; MB, Metamorphic belt.

The Nimbus Ag-Zn-(Au) deposit occurs ~10 km east of Kalgoorlie in the Eastern Goldfields Superterrane, on the margin of the Kurnalpi rift zone (Figure 2). Due to its polymetallic, Ag-rich nature, the deposit is unique in the Yilgarn Craton. Consequently, its origin has been contentious for a number of years with early models favoring either a VMS deposit [9,10] or a fault-hosted high sulfidation deposit [11]. Based on its tectono-stratigraphic position, paleo-environmental setting, the geochemistry of its host sequence (i.e., FI-affinity felsic volcanic rocks), sulfide mineralogy (e.g., Ag-Sb-Pb-As sulfosalts, high Hg, minor chalcopyrite), and chlorite-poor alteration assemblages, the Nimbus deposit has most recently been interpreted as a “hybrid” VMS deposit which displays a number of epithermal characteristics due to its inferred shallow water depth [12–16].

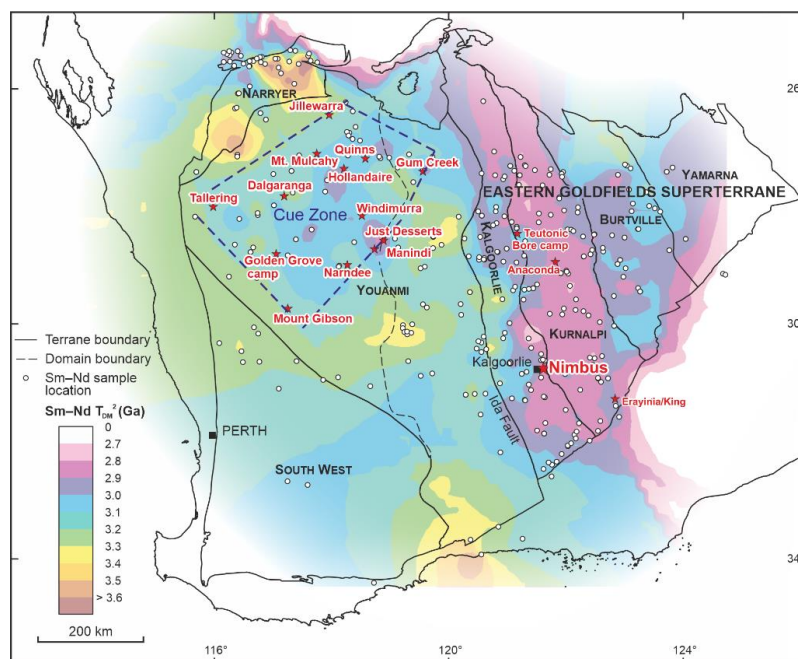


Figure 2. Regional Nd isotope variations of the Yilgarn Craton [17]. The positions of significant VMS occurrences and prospective greenstone belts associated with the Cue and Kurnalpi paleo-rift zones are indicated by red stars.

The recognition that the Nimbus deposit is hosted by the lower plume stratigraphy of the Kalgoorlie region has opened up ~500 km of stratigraphy for the discovery of similar deposits elsewhere along the margins of the Kurnalpi rift zone [13]. With new advances in rapid-acquisition, handheld geochemical and hyperspectral techniques, exploration companies are now able to detect subtle halos surrounding orebodies at minimal expense, using large datasets at the exploration camp. These techniques also allow targeting decisions to be made rapidly and be continuously refined during active drilling programs. Furthermore, hyperspectral halos surrounding VMS deposits have been detected in the Yilgarn Craton using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data once local variations to mineralization were understood [18]. Here, we present a detailed petrographic, lithogeochemical, and hyperspectral account of the Nimbus deposit using drillholes that are both proximal and distal to lenses of massive sulfide mineralization. This research will aid the targeting of high-grade Ag-Zn-Au deposits in the Yilgarn Craton along the margins of the Cue and Kurnalpi rift zones, and elsewhere such as the Superior Province of Canada.

2. Local Geology

The Nimbus deposit is located in a ~7 km wide felsic-dominated volcanic sequence of the Boorara Domain (Kalgoorlie Terrane; Figure 1), bound to the west and east by the

Boorara and Kanowna shear zones [13]. The Boorara Domain stratigraphy of the region has been described in detail elsewhere [19] and comprises: (1) a lower sedimentary package of sandstone, siltstone, and mudstone; (2) a lower tholeiitic basalt with localized hyaloclastite breccias; (3) quartz-feldspar phyric dacite with closely associated volcanoclastic deposits, and komatiite (with intrusive and extrusive facies); (4) an upper basalt; and (5) polymict conglomerates. The geology of this package is broadly similar to that in the eastern half of the Kalgoorlie Terrane (e.g., the Black Swan and Mount Keith regions), where komatiites were erupted contemporaneously with dacite [20–22].

Locally at Nimbus, mineralization occurs in a NW (to NNW)-trending and steeply dipping, bimodal felsic package of volcanic rocks (quartz-feldspar phyric dacite and lesser basalt, plus their autoclastic equivalents) with subordinate black carbonaceous mudstone, tuff, polymict conglomerates, and volcanic breccias [12,13]. The deposit stratigraphy is dominated by rocks of dacitic composition (Figure 3). Dacite ranges in texture from thick coherent units (possible flows and domes) to monomict clast-supported blocky breccias, grading to jigsaw-fit breccias with sharp and curvilinear edges [12,13]. The latter rocks are interpreted as autoclastic deposits (derived from non-explosive fragmentation) of the coherent dacite facies, specifically autobreccias and hyaloclastite breccias [12,13]. Peperitic contacts between mudstone and both dacitic and basaltic rocks [9,10] suggest the entire stratigraphy was coeval. SHRIMP U-Pb zircon geochronology of coherent dacite from Nimbus has yielded ages of 2702 ± 4 and 2703 ± 5 Ma [13]. In distal drillhole BODH015, ~1km SW of Nimbus (not shown on map), komatiite flows, volcanic sandstones/siltstones, polymict volcanic breccias, carbonaceous mudstone, basalt, and dolerite were intersected [12,13]. The immobile element geochemical characteristics of the rocks from drillhole BODH015 are identical to those from the deposit stratigraphy [13]. All rocks have been subjected to lower greenschist facies metamorphism.

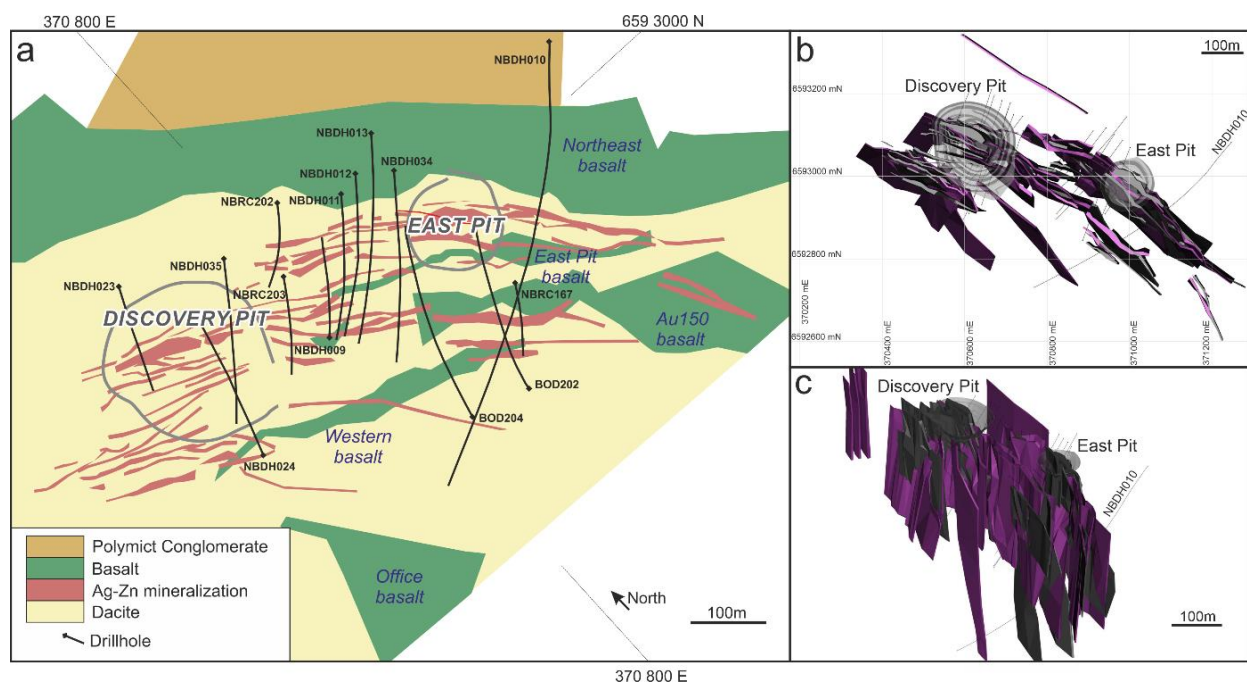


Figure 3. (a) Geological map of the Nimbus area (modified after Hollis et al. [13]). (b) Plan view of the mineralized lenses, diamond drillholes, and two open pits at Nimbus. Lenses of Ag mineralization are shown in silver, and Zn mineralization in purple. (c) Three-dimensional model showing the multiple, steeply dipping, and stacked lenses of primary sulfide mineralization. The depth of the Discovery Pit is approximately 90 m.

3. Previous Research and Methods

Early research on the Nimbus deposit is limited to several company reports by consulting geologists [9,10,23–27], one extended abstract [11], and an early deposit description [28]. Detailed descriptions of volcanic and sedimentary facies were subsequently made by Hill-drew [12]. The first comprehensive academic study of the Nimbus deposit was published by Hollis et al. [13], focusing on its age, host stratigraphy, tectonic setting, styles of hydrothermal alteration, and the nature of mineralization. Caruso et al. [14] subsequently provided an extensive multiple sulfur isotope and trace element study of all sulfide phases across the Nimbus deposit. Barrote et al. [15] recently presented new age constraints from the deposit (Re-Os pyrite, ^{40}Ar - ^{39}Ar sericite, and U-Pb monazite) and high-precision double-spike Pb isotope constraints, confirming early c. 2703 Ma VMS mineralization with a late c. 2630 Ma overprint. The latter event includes the resetting of sericite ^{40}Ar - ^{39}Ar ages and remobilization of minor base metals in quartz-carbonate veins [15]. Most recently, Barrote et al. [16] have detailed trace element variations in hanging-wall polymict conglomerates above the Nimbus deposit, providing further evidence that mineralization was syngenetic with the host stratigraphy. Here, we build on all these recent accounts, incorporating new petrographic observations with lithogeochemical and hyperspectral data.

3.1. Petrography

Quarter-core samples were obtained from 11 diamond drillholes across the Nimbus deposit (NBDH-009, -010, -011, -012, -013, -024, -025, -034, -035; BOD202; NBGT005, BODH015) to characterize all main styles of mineralization noted by company geologists. Rock chips from a Reverse Circulation (RC) drillhole (NBRC167) that intersected Au-rich polymetallic sulfide mineralization hosted in the Au150 basalt were also sampled (see Figure 3). Approximately 85 thin sections were examined in transmitted, cross-polarized, and reflected light.

Selected polished thin sections and half-core samples were mapped by micro X-Ray Fluorescence (μXRF) at the Australian Resources Research Centre (ARRC), Perth, Western Australia, to identify areas of interest for subsequent investigations. Samples were scanned using a Bruker M4 TORNADOTM (Bruker Corporation, Billerica, MA, USA) equipped with a rhodium target X-ray tube operating at 50 kV and 500 nA and an XFlash[®] silicon drift X-ray detector (as described in [29]). Elemental maps were created using a 25- μm spot size on a 25- μm raster with dwell times of 5 ms per pixel. Composite maps were produced using the Bruker ESPRIT software [29].

Areas of interest (as identified by thin section and μXRF) were examined by using a Hitachi TM3030Plus Tabletop Scanning Electron Microscope (SEM) (Hitachi, Tokyo, Japan) at University College Dublin, Ireland. SEM composite chemical maps were completed over 2–3 h each using a pixel dwell time of ~800 μs , resolution of 1024, and processing time of 4 s [17]. Composite color maps were produced by merging element concentration maps of interest in Oxford Instruments Aztec One (v.3.2) software.

3.2. Whole Rock Geochemistry

Forty-seven samples were analyzed for whole rock geochemistry from diamond drill cores across the Nimbus stratigraphy (holes BOD0202, NBDH-010, -013, -024, -035; see Figure 3 for locations) and distal drillhole BODH015. Samples were submitted to two laboratories for analysis. Thirty-two (IG-prefixed) samples were submitted to Intertek Genalysis, Perth. A further fifteen (ALS-prefixed) samples were submitted to ALS Laboratories, Perth. These data were previously presented by Hollis et al. [13], with discussion restricted to the immobile element geochemical characteristics of the host stratigraphy. Here, we discuss the mobile element geochemistry and halos to mineralization in detail for the first time.

To ensure the complete digestion of all mineral phases, rock powders were fused with lithium borate prior to analysis at both laboratories. Major elements were determined on fused glass beads by XRF at Intertek and inductively coupled plasma optical emission

spectroscopy (ICP-OES) at ALS. Minor, trace, high field strength element (HFSE), and rare earth element (REE) concentrations were determined through the digestion of fused glass beads in HCl and inductively coupled plasma mass spectrometry (ICP-MS) at both laboratories. Base and trace metals were analyzed by ICP-MS and ICP-OES (see [13] for further detail). Gold, Pt, and Pd concentrations were analyzed by fire assay and quantified either by ICP-MS (at Intertek) or ICP-OES (at ALS).

Accuracy (%RD) was monitored using mineralized and unmineralized international standards at both laboratories (e.g., OREAS-24b—granodiorite; OREAS-620—Golden Grove Cu-Zn-Pb-Ag-Au ore). Precision (%RSD) was monitored by repeat analysis of submitted samples, plus standards OREAS-24b, OREAS-25a (tholeiitic basalt), and BB1 (basalt). Precision and accuracy are considered excellent to good after Jenner [30] (i.e., within $\pm 10\%$ RSD and $<10\%$ RD) for the majority of elements from both datasets.

The whole rock geochemical data described above are complimented by 4959 company assay samples of diamond drill cores and rock chips. These samples were analyzed using a four-acid digest (perchloric, nitric, hydrofluoric, hydrochloric) at ALS Laboratories, Perth.

3.3. Portable XRF Analysis

Portable XRF (pXRF) measurements ($n = 6728$) from 31 drillholes were made by MacPhersons Ltd. (now Horizon Minerals) personnel between 2011 and 2014. Measurements were made every 1 to 2 m of core (or sporadically on older drillholes, e.g., BODH202) using an Olympus InnoveX Systems Delta series pXRF (Olympus, Waltham, MA, USA). The counting time for each analysis was 60 s on soil mode. Several studies using international reference materials have shown pXRF data to be precise for a number of major and trace elements, although the accuracy of data ranges widely from excellent ($<7\%$ RD) to poor ($\pm 20\%$ RD) [31]. Although a range of internationally certified standards were not analyzed for daily correction, as in comparable deposit-scale studies [17,29], downhole geochemical profiles still replicate the geometry of those obtained from conventional analyses. Portable XRF data for each element were compared to four-acid and lithogeochemical data from holes NBDH-010, -011, -012, -013, -021, -034, and -035. Elements with no or minimal offsets (considering the scatter in the pXRF analysis) included: Ca, K, Mn, S, Ag, As, Cu, Ni, Zn, Pb, Sr, Rb, Zr, and Y. Elements that displayed systematic offsets (Au, Co, Cr, Fe, Ti, Sb, and Sc) were bulk-corrected using four-acid and/or lithogeochemical data from the aforementioned drillholes. Portable XRF data for Bi, Cl, Hg, Mo, Nb, P, Sb, Se, Sn, Te, Th, and W were not able to be corrected and were, therefore, discarded.

3.4. Hyperspectral Analysis

Cores from four diamond drillholes (NBDH035, BOD202, NBDH010, BODH015) were scanned using the HyloggingTM system at the Geological Survey of Western Australia's (GSWA) core library in Perth. Cores were scanned using both the shortwave infrared (SWIR) and thermal infrared (TIR) spectrometers, with data analyzed using the Spectral Geologist software (Version 7.1). This program compares the spectra produced every ~ 8 mm of core with a database of known minerals and their characteristic absorption features [18,32]. For every spectra produced, the three main minerals contributing to its signature are identified in the TIR and two from the SWIR [18]. Summary plots are produced by averaging these over larger (1–3 m) intervals. SWIR may be used to identify micas, chlorite, and clay minerals; TIR for quartz, feldspars, pyroxenes, garnet, and phosphates; and both for Ca-amphiboles, talc, and carbonates [18].

The chemistry of chlorite, white mica, and carbonate was determined by shifts in the wavelengths of absorption features at ~ 2254 nm (chlorite, Fe-OH), ~ 2200 nm (white mica, Al-OH) and $\sim 11,300$ nm (carbonate). Shifts of these wavelength absorption features are associated with varying Fe/Mg ratios in chlorite and Al content in white mica [18,33–36]. Specific types of carbonates may be recognized by absorption features at both $\sim 11,300$ and $\sim 14,000$ nm [37].

4. Mineralization

The Ag-Zn-(Au) Nimbus deposit includes multiple lenses of primary sulfide mineralization, and overlying zones of oxide and supergene mineralization. The discovery of high-grade Ag mineralization at Nimbus occurred shortly after the recovery of 160 ounces of Au in 90 min by prospector Chris Hake from a quartz outcrop (300 m WNW of the Discovery zone) [23]. Silver chloride was recognized in panned drill cuttings in 1993, with the analysis of cuttings and nearby outcrops to 390 g/t Ag [28]. Soil geochemistry by Archean Gold NL in 1994 identified a number of Ag anomalies (to 13 g/t) in the vicinity of the Discovery outcrop, and by June 1995, Rotary Air Blast (RAB) drilling had intersected high grade Ag in the Discovery and Eastern zones [28]. Between 2004 and 2006, deeply weathered oxide and supergene material was mined by Polymetals WA from two small open pits (Discovery and East; Figure 3a) for a total production of 0.32 Mt at 352 g/t Ag and 6.5 t Hg. The mineralogy of oxide and supergene mineralization at Nimbus is described by Mulholland et al. [28] and is beyond the scope of this work.

MacPhersons Resources Ltd. acquired the property in May 2011, with exploration focusing on primary sulfide mineralization. Dozens of steeply dipping, stacked lenses have been discovered under the two open pits (Figure 3b,c). The Nimbus resource currently stands at 12.1 Mt at 52 g/t Ag, 0.9% Zn, and 0.2 g/t Au [38]. Several lodes of gold (2.45 Mt at 0.8 g/t Au) and silver-zinc (1.22 Mt at 175g/t Ag and 3.5% Zn) mineralization have been defined. Intersections of some ore lenses can be extremely high-grade and polymetallic (e.g., 17m at 1434g/t Ag, 23.6% Zn, 4.7% Pb; hole NBRC216). In 2019, MacPhersons Resources merged with Intermin Resources to form Horizon Minerals.

Primary Ag-Zn sulfide mineralization at Nimbus is predominantly hosted within dacitic rocks (Figure 3a). Several units of early, well-developed massive pyrite occur in the host stratigraphy (Figure 4a), with multiple units occurring in some drillholes separated by discordant zones of stringer pyrite and sphalerite. Underlying these lenses of barren massive pyrite, zones of polymetallic sulfide mineralization typically occur as 1) semi-massive, stringer, and breccia-type Ag-Zn $\pm$ Pb-(Cu-Au) sulfides associated with the replacement of monomict dacite breccias (Figures 2 and 4b–d) as discordant veins of stringer and disseminated sphalerite-pyrite in more coherent dacite (Figure 4e–h).

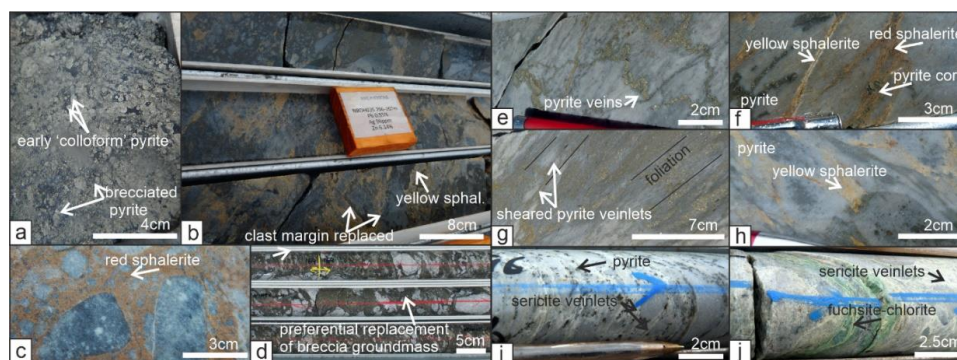


Figure 4. Representative photographs of hydrothermally altered and mineralized dacitic rocks from the Nimbus deposit. (a) Early “colloform” pyrite with zones of subsequent brecciation marked by euhedral pyrite. (b) Semi-massive sulfide showing the almost complete replacement of monomict dacite breccias. Note the preferential replacement of breccia groundmass. (c) Extensive replacement of dacite breccia by brick-red sphalerite. (d) Monomict dacite breccia facies with extensive pyrite replacement. (e) Intensely silicified coherent dacite with abundant undeformed pyrite veins. (f–h) Variably sheared pyrite and sphalerite veins in silicified dacite. (i) Silicified monomict dacite breccia cut by abundant sericite veinlets. (j) Narrow zone of intense chlorite-fuchsite alteration.

4.1. Early Pyrite and Sphalerite

Units of barren early “colloform” massive pyrite (Figure 4a) are typically 2 to 7 m thick, and are formed through the replacement of glassy dacitic lavas rather than open

space fill [9,10,27]. Caruso et al. [14] present a detailed account of early massive pyrite genesis at Nimbus with three distinct textures described in detail (“a”, “b”, and “c” types), along with their multiple sulfur isotope and trace element characteristics.

Early pyrite “a” consists of sub-millimeter agglomerates of 2–20 μm pyrite with abundant interstitial silicate. This is overgrown by radial fibrous/concentric banded pyrite “b”, which displays only minor silicate inclusions. Pyrite types “a” and “b” also contain diverse and knotty arrays of micron- to nanoscale carbon-rich pores underlying late annealing textures [14]. Nitric acid etching revealed abundant acid-resistant carbonaceous material in the deep (5–10 μm) corrosion pits. The μm -scale sheaths and fibrous-to-rope-like filaments, as well as the microcrystalline to smooth bulbous nm-scale coccoidal structures, are reminiscent of microbial forms [14].

A late-stage pyrite “c” occurs as inclusion-free euhedral grains filling fractures in association with quartz through a series of crack-seal events due to hydraulic fracturing [14] (Figure 6a). The coarser brecciated pyritic masses are often surrounded by recrystallized euhedral pyrite (Figure 4a) which contains trace amounts of tetrahedrite.

Following hydraulic quartz-pyrite brecciation of early pyrite, all phases were brecciated and replaced by abundant yellow sphalerite (Figure 5a). This sphalerite may contain rare inclusions of chalcopyrite, galena, and/or rare arsenopyrite (in order of decreasing abundance). Yellow sphalerite also replaces early “colloform” pyrite (types “a” and “b”) along growth traces and forms interstitially to the recrystallized euhedral pyrite (type “c”).

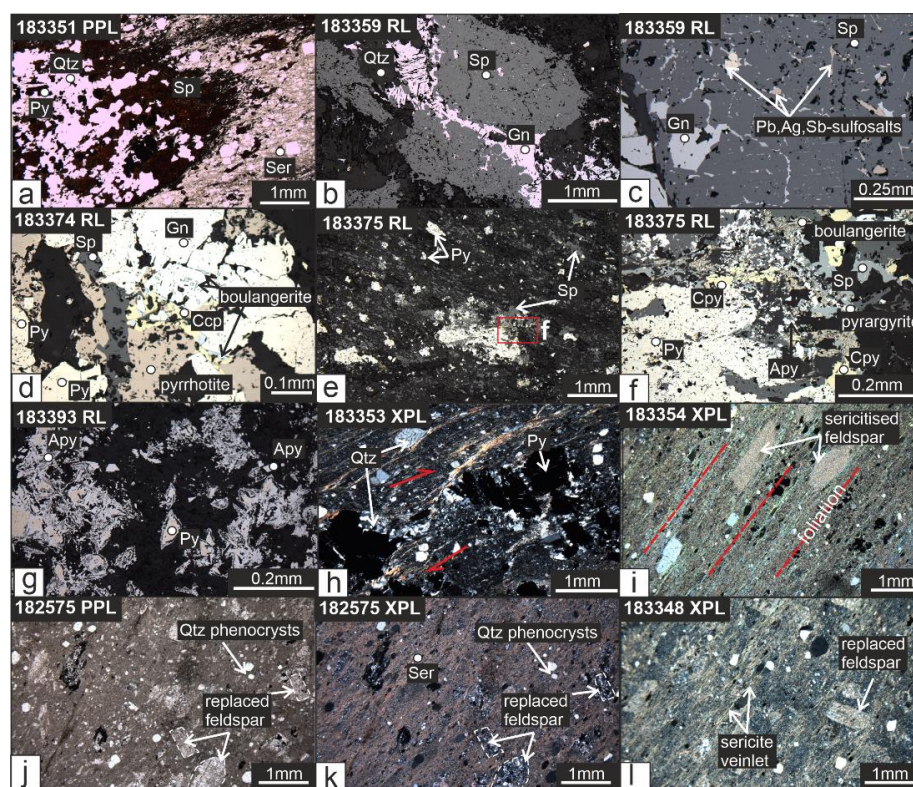


Figure 5. Photomicrographs of variably mineralized and hydrothermally altered dacite. (a) Sericitized dacite with early pyrite and quartz replaced by sphalerite. (b,c) Sphalerite brecciated by galena, which contains diverse inclusions of Pb, Ag, Sb-sulfosalts. (d–f) Minor interstitial pyrrhotite, chalcopyrite, boulangerite, and arsenopyrite to pyrite, sphalerite, and galena. (g) Arsenopyrite present as euhedral rhombs and overgrowths with tetrahedrite on earlier formed pyrite. (h) Sheared quartz±chlorite-carbonate-altered dacite containing euhedral pyrite. (i) Intensely sericitized dacite with altered feldspar laths orientated parallel to the main foliation. (j–l) Variably silica-sericite-altered dacite with randomly orientated feldspar phenocrysts. PPL, plane polarized light; RL, reflected light; XPL, cross polarized light.

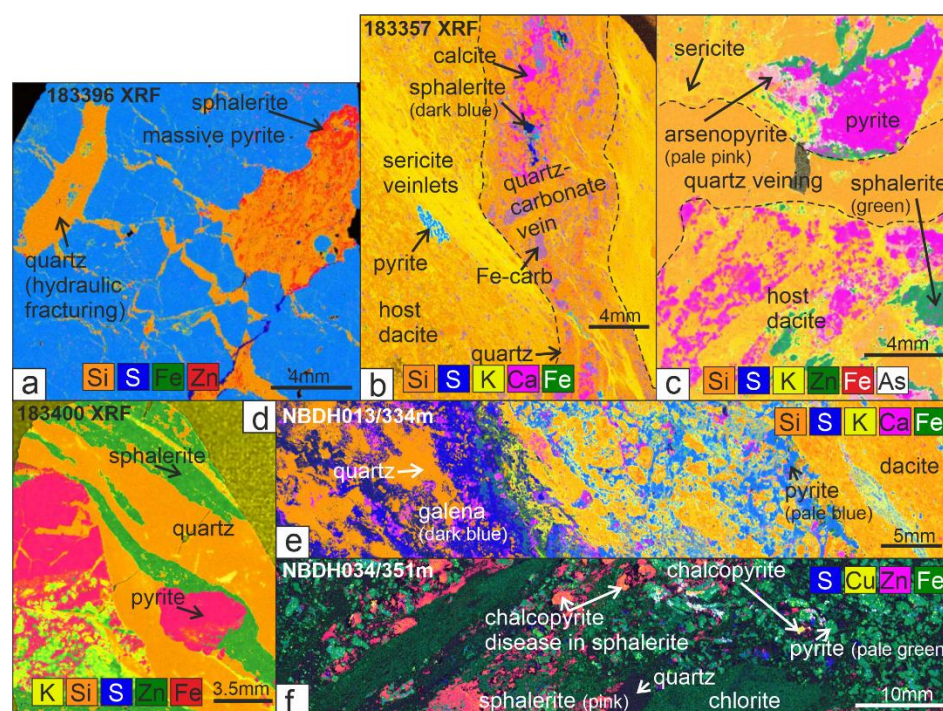


Figure 6. Composite μ XRF elemental maps of variably mineralized dacite. (a) Massive pyrite brecciated by early quartz with minor sphalerite. (b) Quartz-carbonate veining with minor pyrite-sphalerite-galena cutting silicified and sericitized dacite. (c) Hydrothermally altered dacite with large clots of pyrite rimmed by sphalerite and subsequently brecciated by arsenopyrite. All phases are cut by late quartz veins. (d) Sheared massive sulfide with shear sense indicators in recrystallized pyrite-sphalerite. (e,f) Slabbed sections of pyritic dacite with lesser sphalerite, galena, and chalcocopyrite.

4.2. Main Ore Phase

The main ore phase at Nimbus is marked by abundant yellow and honey to brick-red colored sphalerite (Figure 4c,h), galena (Figure 6d), a diverse sulfosalt assemblage, and lesser arsenopyrite, pyrrhotite, and chalcocopyrite. Sphalerite can be intergrown with galena, but is more often brecciated and replaced by it (Figure 5b). Galena is frequently intergrown with a diverse suite of Ag-Sb $\pm$ Pb $\pm$ As $\pm$ (Cu)-bearing sulfosalts (Figures 5c–f and 7), predominantly Ag-rich boulangerite [(Pb,Ag)₅Sb₄S₁₁], pyrargyrite [Ag₃SbS₃], Ag-rich tetrahedrite [(Cu,Fe,Zn,Ag)₁₂Sb₄S₁₃], and Ag-rich bournonite [PbCuSbS₃]. A number of other phases have also been noted from the main ore stage, some of which have only been described from a handful of samples. These phases include: marriite [AgPbAsS₃], covellite [CuS], enargite [Cu₃AsS₄], freibergite [(Ag,Cu,Fe)₁₂(As,Sb)₄S₁₃], meneghinite [Pb₁₃CuSb₇S₂₄], jalpaite [(Ag,Cu)₂S], owyheeite [Pb₇Ag₂(Sb,Bi)₈S₂₀], pyrostilpnite [Ag₃SbS₃], Fe-rich viaeneite [(Fe,Pb)₄S₈O], native silver, amalgam [Ag,Hg], and electrum. Cassiterite [Sn₂O] was additionally noted in one sample (183398; NBDH034 160m) from our study, replacing brick-red sphalerite, and intergrown with an assemblage of galena and pyrargyrite (Figure 7b). The honey to brick-red sphalerite appears to be younger than the straw-yellow phase, precipitated with galena and the various sulfosalt minerals during the main ore phase. The main ore stage was subsequently overprinted by several generations of pyrite, replacing both sphalerite and galena-sulfosalt assemblages [14]. Galena from the main ore stage has yielded Pb isotope (high precision, Southampton double-spike method) model ages of c. 2707 Ma (Abitibi-Wawa single stage Pb growth model), consistent with the age of the host stratigraphy [15].

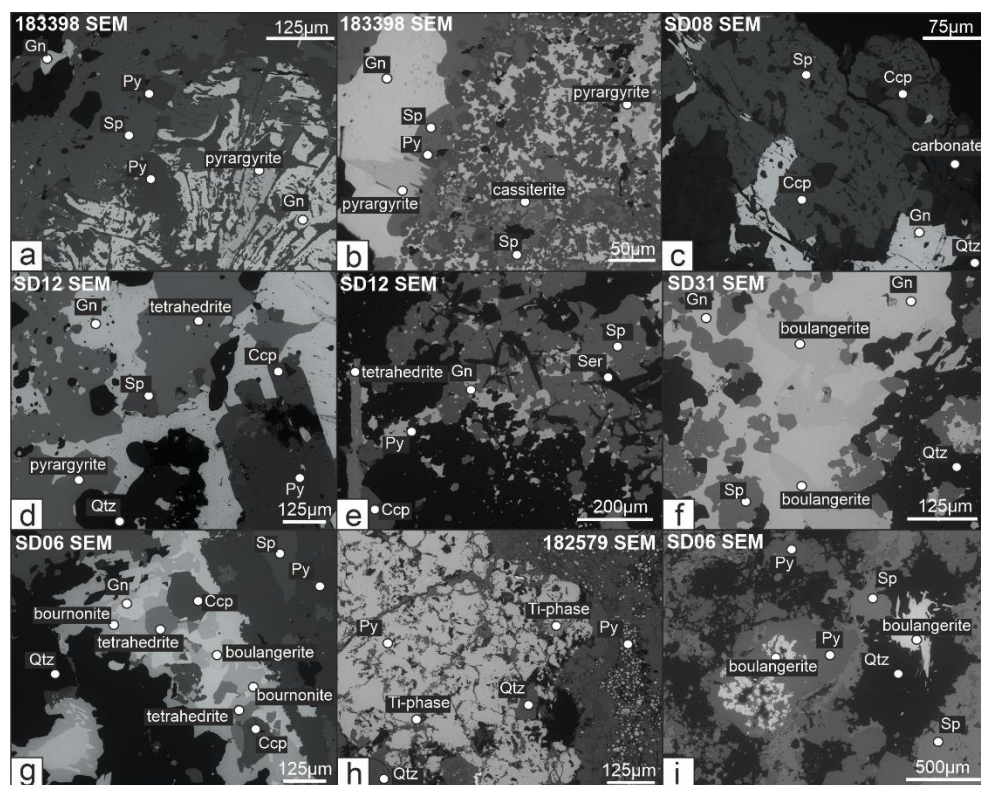


Figure 7. Backscatter SEM images of sulfide assemblages in mineralized dacite. (a,b) Early euhedral pyrite overgrown by sphalerite, which is replaced by an intergrowth of galena-pyrargyrite. Minor amounts of late cassiterite replace all earlier phases in Figure 7b. (c) Sphalerite intergrown with chalcopyrite in a quartz-carbonate gangue. Galena occurs as a replacive and fracture-filling phase in sphalerite-chalcopyrite. (d,e) Early formed pyrite overgrown by minor chalcopyrite. Subsequent sphalerite and tetrahedrite mineralization is replaced by galena. (f) Galena-boulangerite intergrowths replace early formed sphalerite. (g) Sphalerite is replaced by main ore stage pyrite. Chalcopyrite and tetrahedrite are replaced by galena (which is intergrown with boulangerite and bournonite). (h) Abundant fine diagenetic pyrite (right) and coarse hydrothermal pyrite (left) within silicified dacite. A widespread, but unknown, Ti-bearing phase occurs interstitially to masses of coarse pyrite. (i) Early formed coarse pyrite overgrown by sphalerite. Pyrite is replaced by boulangerite in the center of the image. To the right, boulangerite occurs interstitially and within quartz.

The distribution of arsenopyrite is irregular throughout the deposit, restricted to specific lenses [27]. Arsenopyrite typically overgrows/rims early formed pyrite (Figure 5g), and brecciates both early formed pyrite and sphalerite (Figure 6b). Where arsenopyrite is present, it often occurs with galena, Ag-rich tetrahedrite, and minor Ag-Sb sulfosalts [14]. Rare coarse patches of chalcopyrite (Figure 6f) are also associated with the main ore phase, forming composites with galena, Ag-rich tetrahedrite, Ag-rich boulangerite, and bournonite, occurring after sphalerite and pyrite (Figure 7c,g). Occasionally chalcopyrite is intergrown with pyrrhotite, which forms interstitially to galena and pyrite (Figure 5d).

A note on sphalerite color: Prior to the detailed LA-ICPMS trace element study of Caruso et al. [14], the straw-yellow sphalerite was referred to as “Fe-poor” or “low-Fe” [9,25,27], and the honey to brick-red sphalerite as “high-Fe” [13]. Recent sphalerite chemistry [14] has revealed that the yellow “Fe-poor” sphalerite (samples 8, 12, 25, 27 of [14]) has comparable Fe, Cd, and Hg contents to the redder variety (samples 3, 5, 14, 17, 18 of [14]). The terms Fe-poor and high-Fe of previous works are consequently not used here. However, it is worth noting that the straw-yellow variety is marked by significantly lower Cd/Fe (0.013–0.022, mean 0.018) and Cd/Hg ratios (0.23–0.57, mean 0.42) than the redder variety (Cd/Fe = 0.016–0.043, mean 0.029; Cd/Hg = 0.63–2.88, mean 1.08).

4.3. Stringer Sulfides

Zones of stringer and disseminated sulfides occur within units of variably silicified and sericitized coherent dacite (Figure 4i,j). Together, they form a sparse network of pyrite and sphalerite, with lesser galena, Ag-Sb sulfosalts, and rare interstitial chalcopyrite [14]. Sulfides can be sheared (Figure 6d), recrystallized and broken (Figure 5h), with veinlets orientated randomly (Figure 4e) or parallel to the regional foliation (Figure 4g).

4.4. Mafic-Hosted Mineralization

Mafic rocks at Nimbus are typically poorly mineralized (Figures 8 and 9a–e) compared to their felsic equivalents. Most mineralized samples examined contain only minor amounts of disseminated pyrite, sphalerite, and galena, with rare chalcopyrite [13]. In mafic hyaloclastite breccias (Figure 8a,b), these minerals are present at an increased abundance, preferentially disseminated throughout the altered groundmass. Recent RAB drilling intercepted Au-rich mineralization in the Au150 basalt (NBRC167, e.g., 10 m at 4.1 g/t Au) with rock chips associated with Au containing abundant pyrite, sphalerite, and galena (Figure 9g). The nature in which gold occurs in the few available samples was investigated by SEM. As no free-gold was identified in these samples, it is possibly hosted in pyrite either in a lattice-bound form, or as nano-inclusions [39].

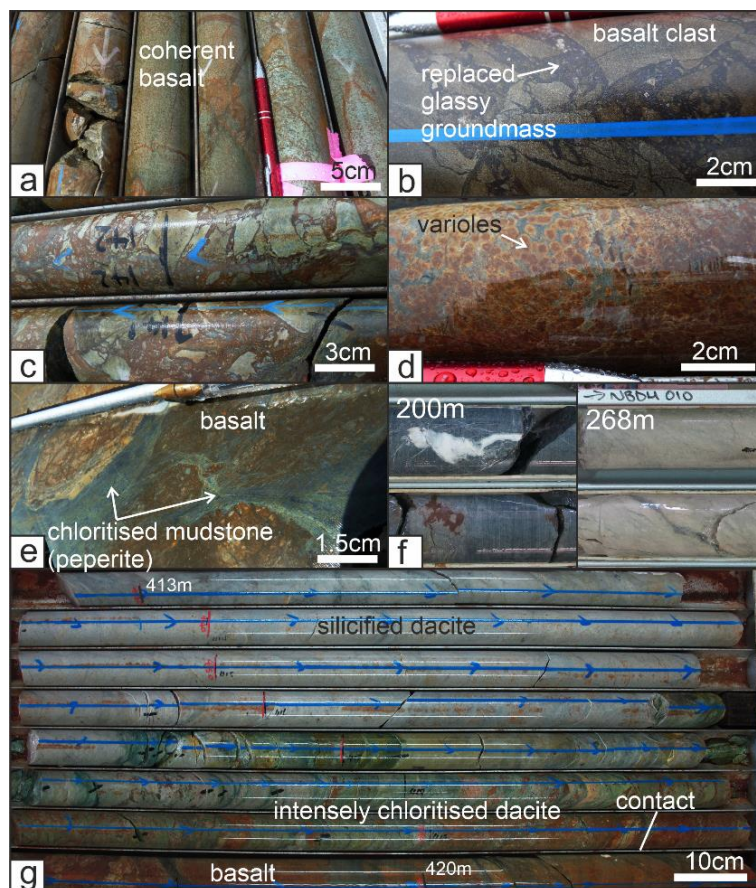


Figure 8. Representative photographs of hydrothermally altered mafic rocks from the Nimbus deposit. (a) Chlorite-carbonate-altered coherent basaltic sill (Western basalt; Figure 3a). (b) Basaltic hyaloclastite breccia with a replaced glassy groundmass. (c) Monomict basaltic breccia with the matrix preferentially altered to carbonate. (d) Carbonate-altered varioles within basalt. (e) Peperitic contact between carbonate-altered basalt and chloritized mudstone. (f) Two distinct styles of hydrothermally altered basalt in drillhole NBDH010. (g) Intense chloritization of dacite near the East Pit basalt (drillhole BOD202; Figure 3a).

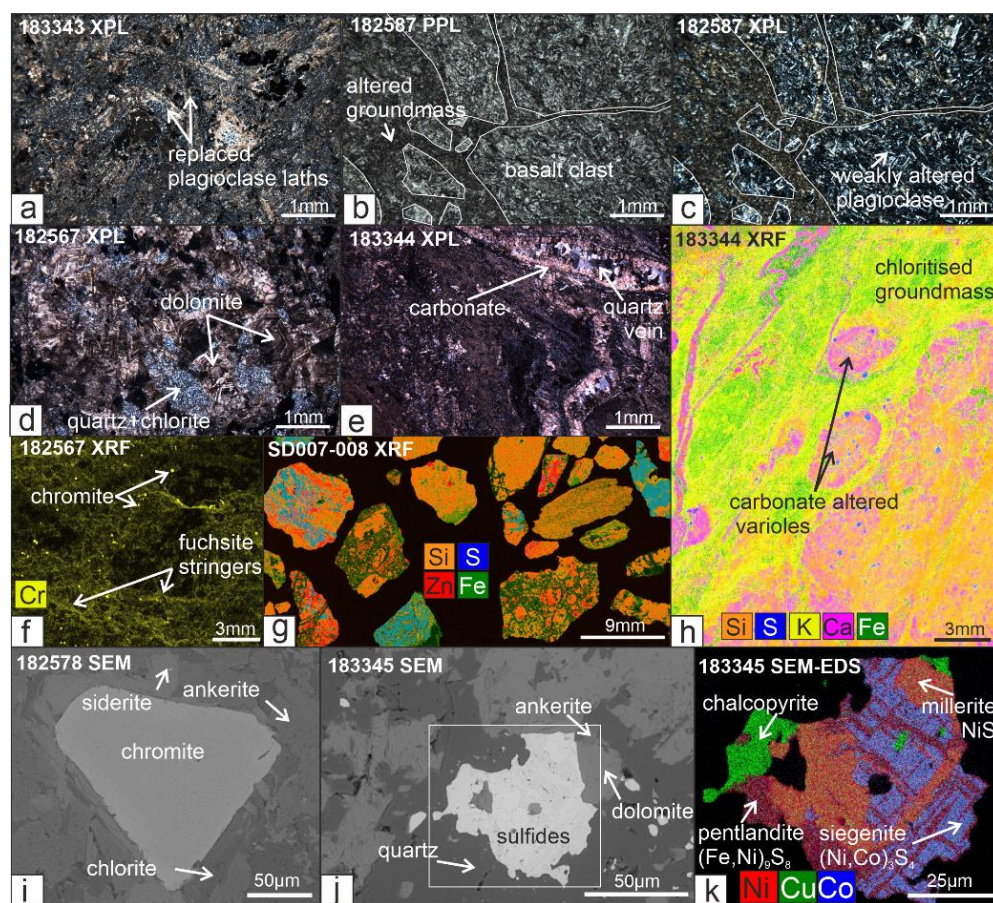


Figure 9. Photomicrographs, μ XRF maps, and SEM images of hydrothermally altered and mineralized mafic rocks from the Nimbus deposit. (a) Carbonate-altered coherent basalt with replaced plagioclase laths. (b,c) Hyaloclastite breccia with well-preserved igneous textures in clasts and an altered groundmass. (d) Dolomite-quartz-chlorite-altered coherent basalt. (e) Intensely altered and quartz-carbonate veined basalt. (f) Cr abundance in coherent basalt highlighting stringers of fuchsite (Cr-mica) and small chromite grains. (g) μ XRF maps of mineralized rock chips from the Au150 basalt (Figure 3a). (h) μ XRF map of carbonate varioles in a coherent mafic sill. (i) SEM image of disseminated chromite grains surrounded by chlorite and carbonate. (j,k) SEM images of millerite replacing early formed siegenite and pentlandite, which is overgrown by chalcopyrite.

Few other sulfide phases have been noted in mafic lithologies. In sample 183345 from drillhole NBDH010 (339m), where a peperitic texture was observed between quartz-carbonate (ankerite-dolomite)-altered basalt and carbonaceous mudstone, early siegenite $[(\text{Ni},\text{Co})_3\text{S}_4]$ was recognized with pentlandite $[(\text{Fe},\text{Ni})_9\text{S}_8]$ (Figure 9j,k). This was subsequently brecciated by millerite $[\text{NiS}]$ and overgrown by chalcopyrite (Figure 9k). Ullmannite $[\text{NiSbS}]$ (intergrown with quartz and chalcopyrite) was also observed in sample 182585 from a narrow band of mineralized mudstone surrounded by basalt (drillhole NBDH010, 287 m).

4.5. Late Stage Remobilization

Late blocky quartz-carbonate $\pm$ chlorite veins (Figure 6c) cut all aforementioned styles of mineralization and themselves contain remobilized pyrite with lesser galena, sphalerite, and rare chalcopyrite [13]. Sulfides in some instances have been sheared and recrystallized during regional deformation (Figure 6f). High-precision double-spike Pb isotope constraints on this galena are consistent with minor metal remobilization at c. 2.63 Ga associated with regional granite emplacement and deformation [15].

5. Hydrothermal Alteration

Several styles of hydrothermal alteration have been recognized at Nimbus, first described by Doyle [9] and Belford [10], and subsequently expanded upon by Hollis et al. [13]. Hydrothermal alteration is dominated by quartz-sericite($\pm$ carbonate) in dacitic rocks and quartz-carbonate-chlorite in mafic rocks.

Dacitic rocks at Nimbus are quartz-feldspar phyrlic, with phenocrysts randomly orientated and surrounded in a finely crystalline groundmass of varying composition (Figure 5i–l). Phenocrysts may be fractured and broken (particularly quartz), with feldspars often replaced by a combination of quartz, sericite, carbonate, and minor chlorite. The groundmass mineralogy can be dominated by any of the following minerals: quartz, sericite, carbonate, chlorite, and albite, with minor fuchsite, epidote, and carbon. Trace amounts of zircon, tourmaline, and rutile also occur. When dominated by quartz, the groundmass is only weakly foliated, but when sericitization is intense, volcanic textures are more readily destroyed. From samples distal to the orebody, Doyle [9] has described arcuate and concentric shapes consistent with perlite (i.e., a formerly glassy matrix), and albitic alteration is increasingly common.

In the autoclastic dacite facies, hydrothermal alteration is most intense within the matrix, which was the first phase to be altered [13]. Clasts show evidence for varying degrees of alteration and replacement in semi-massive sulfides [13] (Figure 4b–d). In coherent dacitic lithologies, hydrothermal alteration is more pervasive and evenly distributed. Contacts between zones of weak alteration and intense silicification and/or sericitization can be sharp. Narrow zones of intense chloritization also occur. Anatomizing networks of fuchsite-sericite veinlets together with silicification can produce pseudobreccia textures in dacite. Late anastomosing veinlets of yellow-green sericite cut all earlier phases and are themselves cut by late quartz-carbonate $\pm$ chlorite veins containing remobilized sulfides [13]. Contacts with mafic rocks are often marked by the intense chloritization of dacite which can be associated with significant quantities of fuchsite (Figure 8g).

Mafic rocks at Nimbus comprise variably sericite-altered or carbonate-altered plagioclase laths surrounded by a groundmass of varying composition—typically, quartz, carbonate, and chlorite (Figure 9a,b). In hyaloclastite breccias (Figure 8a,b), the matrix is preferentially altered, often leaving well-preserved igneous textures in the clasts (Figure 9c,d). By contrast, in coherent lithologies (Figure 8c), alteration is more evenly distributed (Figure 9e), though relict textures are also preserved. Where varioles are common, they are typically carbonate-altered, with the groundmass chloritized (Figures 8d and 9h). Chromite grains ($\sim 125\ \mu\text{m}$ in diameter) were identified in a number of samples associated with abundant stringers of fuchsite (Cr-mica) (Figure 9f,i).

6. Geochemistry

The immobile element geochemistry of the Nimbus deposit was recently discussed by Hollis et al. [13]. As the deposit stratigraphy is bimodal and felsic, and mafic rocks are readily discriminated by ratios such as Zr/Ti and La/Yb. Komatiites have only been identified in distal drillhole BODH015. Here, we focus on elements mobilized during hydrothermal activity [30,40] (Figures 10 and 11) to identify halos associated with mineralization.

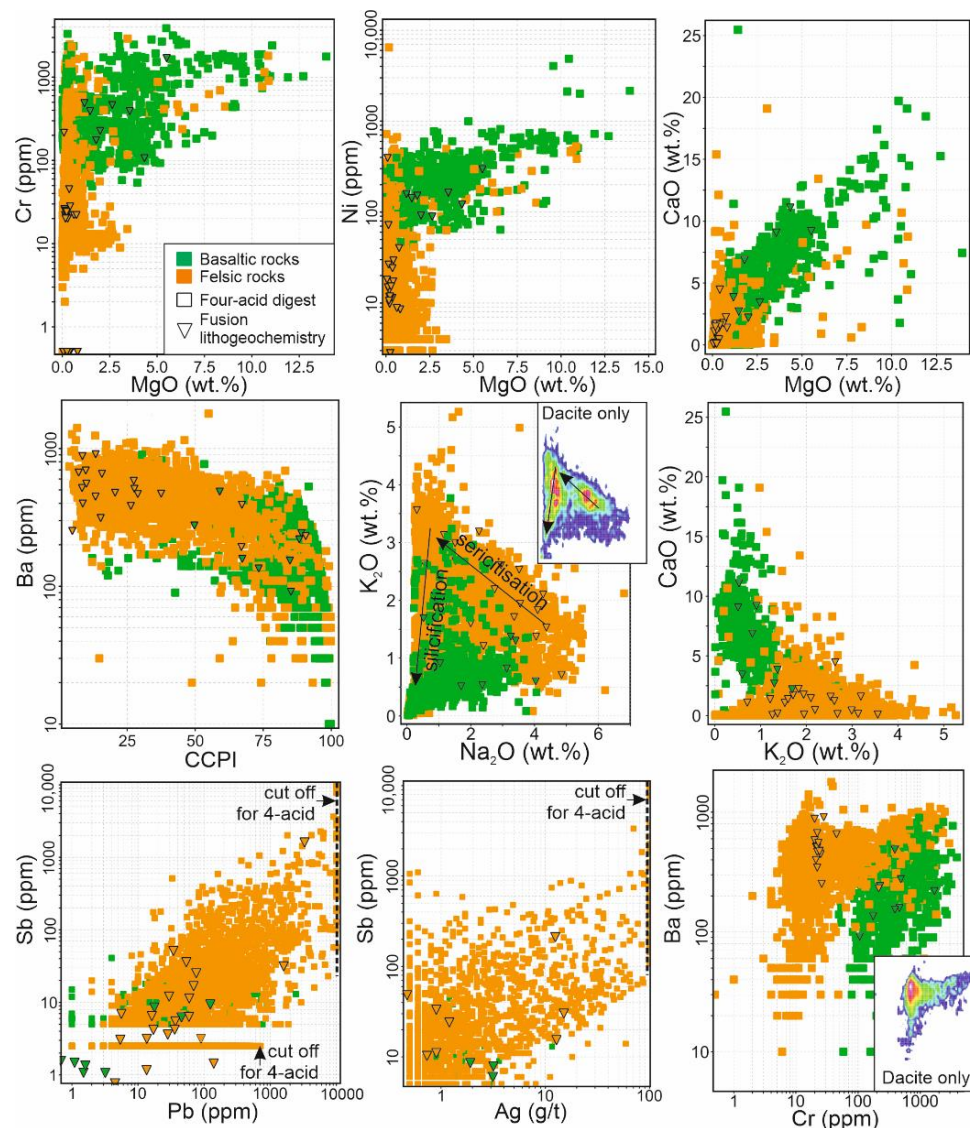


Figure 10. Major and minor element geochemistry of dacitic and basaltic rocks from the Nimbus deposit. Mafic rocks are associated with higher CCPI, Cr, Ni, CaO, and MgO, and lower Ba and K₂O, than dacitic rocks.

6.1. Dacitic Rocks

Forty-seven samples of variably hydrothermally altered and mineralized dacite were analyzed from the Nimbus host stratigraphy using Li-borate fusion lithogeochemistry. Due to the extensive silicification, sericitization, carbonate alteration, and sulfide mineralization present, concentrations of the following major elements vary significantly between samples: SiO₂ (41.9–80.2 wt%), Na₂O (0.05–4.85 wt%), K₂O (0.03–3.51 wt%), Fe₂O_{3T} (0.19–49.7 wt%), CaO (<0.01–5.15 wt%), S (<0.01–18.94 wt%). Loss on ignition values range from 1.27 to 13.69 wt%. Magnesium concentrations are low (0.02–0.81 wt% MgO) for all samples of dacite analyzed, highlighting the general absence of intense chloritic alteration. MgO locally reaches a maximum 13.9 wt% in the company four-acid geochemical data, where narrow zones of intensely chloritized dacite have been analyzed.

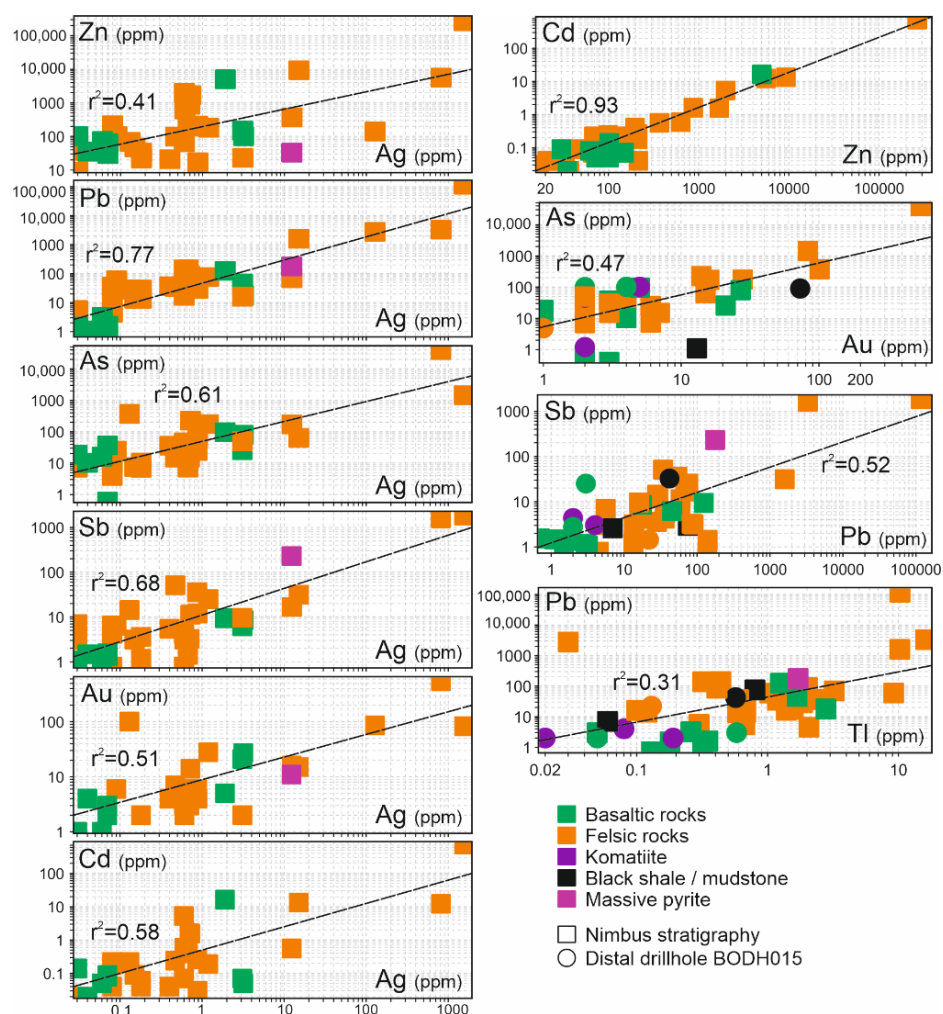


Figure 11. Significant correlations of ore and associated elements in fusion lithogeochemical data.

Transition metal and metalloid concentrations are low in most hydrothermally altered felsic rocks but reach significantly higher concentrations when associated with mineralization. Two samples of Ag-rich dacite were analyzed from diamond drillhole NBDH024. Sample IG-183387 contains 26.6 wt% Zn, 11.7 wt% Pb, 1560 ppm Ag, and 83 ppb Au, plus high concentrations of Sb (1837 ppm), As (1445 ppm), Cd (734 ppm), and Tl (10.3 ppm). Sample IG-183393 contains significantly lower concentrations of base metals (0.9 wt% Cu + Pb + Zn), slightly less Ag (814 ppm), Sb (1600 ppm), and Cd (12 ppm), but higher Au (546 ppb) associated with significant arsenopyrite (3.96 wt% As). The company four-acid geochemical data from dacite ($n = 3472$ analyses) include values up to 1.52 ppm Au, 6.7 wt% Cu, >1 wt% As, >1 wt% Sb, 6470 ppm Ni, 733 ppm Cd, 109 ppm Co, 51 ppm Bi, and 40 ppm Tl. One sample (NBDH011 180.6–180.65 m) yielded assays of 2.7 wt% Mo and 3770 ppm W associated with polymetallic sulfide mineralization (100 g/t Ag, 6.7 wt% Cu, 0.6 wt% Ni, 0.3 wt% Zn; note: the next highest Mo concentration is ~100 ppm). Trace elements showing strong to moderate correlations in dacite include Au-As, Cu-Mo-W-Ni, and Ag-Pb-Sn-Tl-Zn (Figure 11). High As concentrations (>1 wt%) are commonly associated with polymetallic sulfide (Ag-Zn-Pb-Cu-Au) mineralization in holes RC202 and RC203.

On the Box Plot of Large et al. [41], samples of hydrothermally altered and mineralized felsic rocks cluster in the least altered dacite field, with trends towards the chlorite/pyrite, sericite, and albite mineral nodes (Figure 12a). Scatter of the data occurs between three main trends: chlorite-pyrite-sericite, sericite-chlorite-pyrite, and sericite ± albite. Few samples plot towards the “ore corner”, dominated by high chlorite and pyrite, as from the Teutonic Bore and King VMS deposits [17]. This reflects the weaker hydrothermal alteration

at Nimbus, where relict volcanic textures are preserved in most samples even proximal to mineralization. A minor vertical trend towards the dolomite/ankerite mineral nodes reflects the weak carbonate alteration in most felsic samples. Samples plotted according to Zn grade are shown in Figure 12b. High concentrations of Zn and Ag are generally associated with high Chlorite-Carbonate-Pyrite Index (CCPI) values.

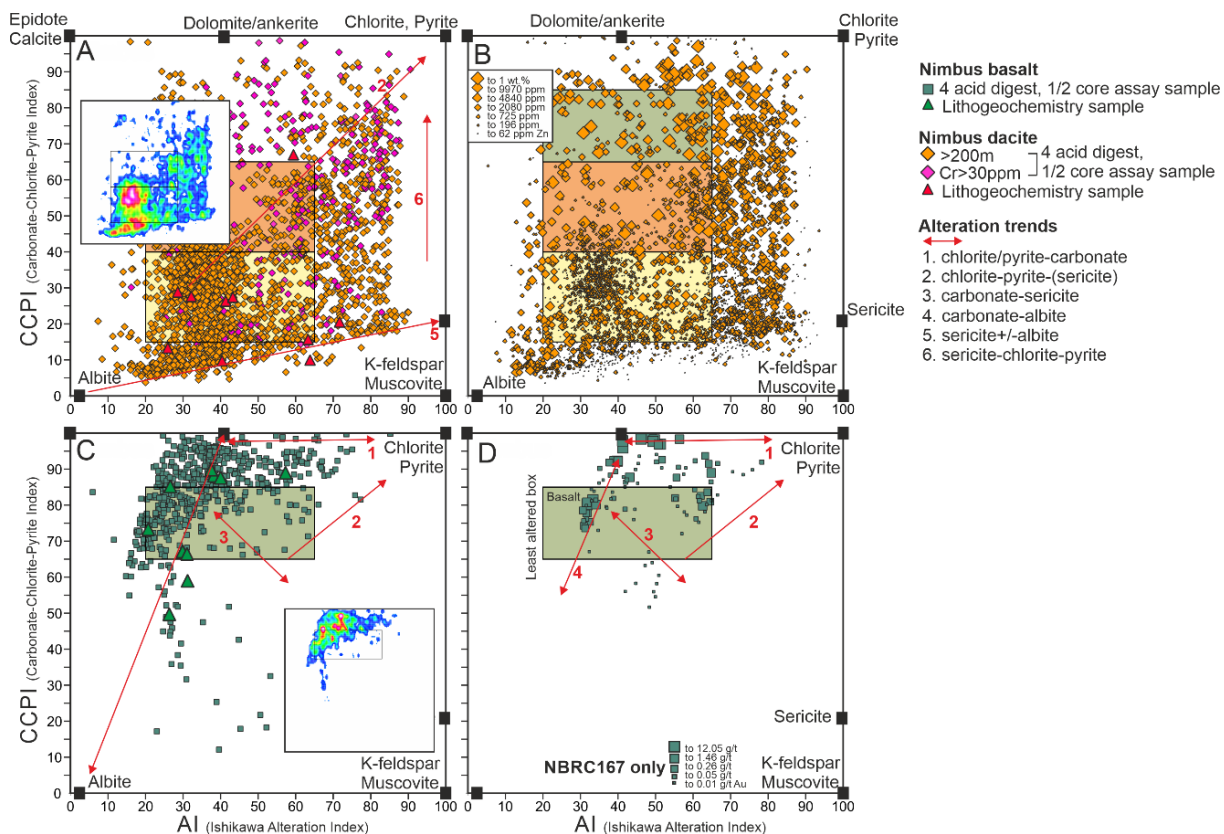


Figure 12. Box Plot diagrams after Large et al. [41] showing common major element geochemical trends associated with VMS mineralization at Nimbus for dacitic (A,B) and basaltic (C,D) rocks. The Box Plot uses two indices of alteration—the Alteration Index (AI) and Chlorite-Carbonate-Pyrite Index. Common alteration trends are shown and mineral nodes.

6.2. Mafic Rocks

Mafic rocks from the Nimbus deposit contain variable SiO_2 concentrations (37.4–63.5 wt%) with the lower values associated with higher CaO , $\text{Fe}_2\text{O}_{3\text{T}}$, MgO , and LOI . A strong positive correlation is recognized between CaO and LOI values. Due to the increased chlorite and carbonate alteration of mafic lithologies, these rocks are characterized by significantly higher CaO and MgO concentrations than their dacitic equivalents (Figure 10). Likewise, increased sericitization in dacitic lithologies is reflected in significantly higher K_2O and Ba concentrations. Felsic rocks are also characterized by markedly lower Cr and Ni concentrations, except near mafic contacts where they contain significant quantities of fuchsite.

Mafic rocks analyzed for lithogeochemistry contain low base metal concentrations (<0.02 wt% $\text{Cu} + \text{Pb} + \text{Zn}$), Ag (0.07–1.9 ppm), and Au (1–27 ppb). The company four-acid geochemical data from basalt ($n = 534$) include values up to 12.85 ppm Au , 4860 ppm Ni , 758 ppm Sb , 740 ppm Cd , 471 ppm As , 283 ppm Co , 181 ppm Mo , 170 ppm Sn , 50 ppm Tl , and 8 ppm Bi . Zinc is strongly correlated with Cd (R^2 of 0.99) and Ag with Sb (R^2 of 0.80), but there is a significantly poorer correlation between most other element pairs than in felsic rocks (As-Au R^2 of 0.23 in mafic rocks, 0.61 in felsic rocks; Ag-Pb R^2 of 0.29 vs. 0.82, respectively).

On the Box Plot of Large et al. [41], mafic samples cluster near the least altered basalt field, with major trends towards the albite, chlorite/pyrite, and dolomite/ankerite mineral nodes (Figure 12c,d). Minor scatter also occurs towards the sericite mineral node. Samples from drillhole NBRC167, intersecting the Au150 basalt, are plotted according to Au grade in Figure 12d. No relationship is apparent between Au grade and identified alteration trends. Au-rich samples cluster both within the “least altered” basalt field, and also towards intensely carbonate- and/or weakly chlorite-altered compositions (Figure 12d).

6.3. Mass Change

Using distal samples of unaltered lithologies from the Brindabella sequence (BODH015; [13]), mass change values were calculated using the isocon method of Grant [42,43]. Calculated mass change values for a range of hydrothermally altered and mineralized samples are summarized in Supplementary Tables S2 and S3, with selected isocon plots shown in Figure 13. Unsurprisingly, increased hydrothermal alteration in dacitic rocks is marked by mass gains in Si, Fe, K, and S, and losses of Ca and Na (Figure 13). This is reflected by the higher abundance of quartz, sericite, sulfide minerals, and feldspar destruction. Magnesium loss is consistent with the general absence of chlorite in most samples. Samples of massive pyrite and polymetallic Ag-rich ore are also dominated by large mass gains of Ag, As, Au, Cd, Co, Cr, Cu, Ni, Pb, Sb, and Zn (Supplementary Table S2, Figure 13). Tellurium is the only element which is more enriched in massive pyrite compared to Ag-rich polymetallic massive sulfide.

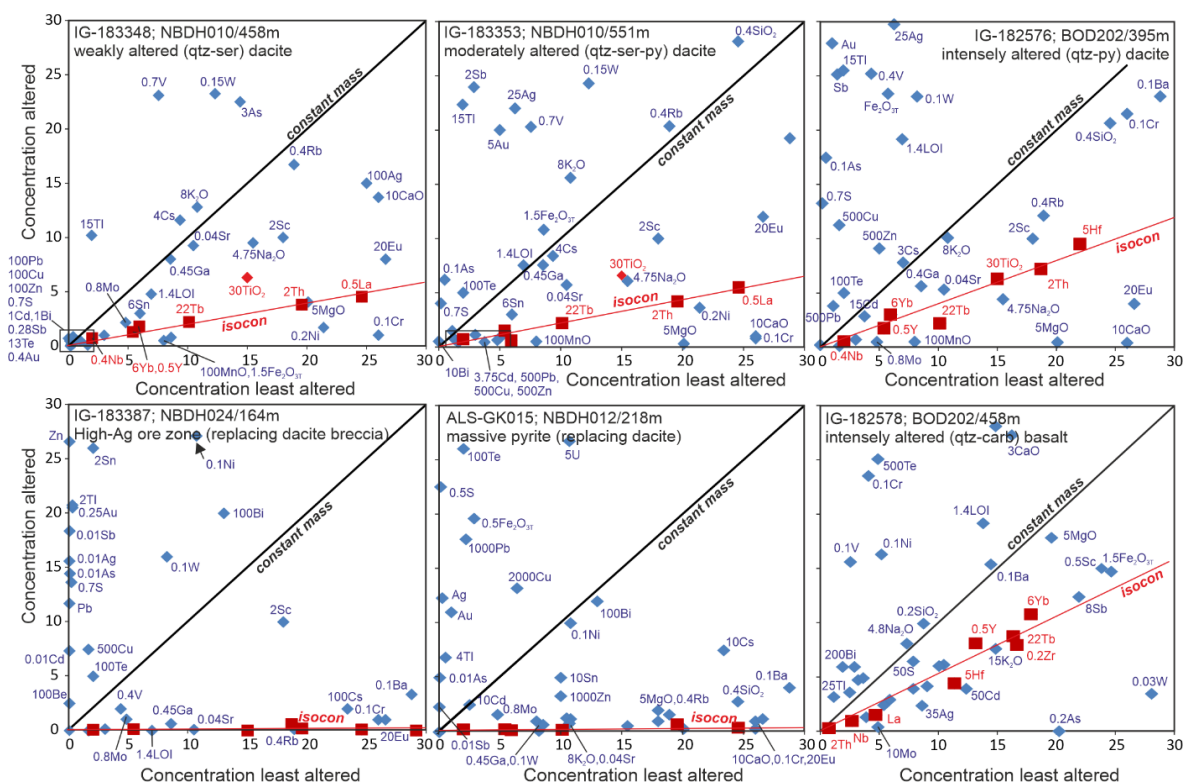


Figure 13. Isocon diagrams for representative samples from the Nimbus deposit (method after [42,43]). Isocons were fitted using a range of immobile elements, shown in red. Element concentrations are scaled for plotting convenience and to improve the clarity of the figure. If the element has been added to the rock, it will plot above the isocon (red line), and if it has been lost, it will plot below the isocon. Calculated mass change values are given in Supplementary Tables S2 and S3.

For mafic rocks, mass gains and losses correspond to the abundance of quartz, carbonate, and chlorite. In comparison to felsic rocks, Si gains are low. Increased hydrothermal alteration is marked by higher mass gains of Ca, and reduced gains of Na. (Supplementary

Table S3). Magnesium and Fe are lost in all three samples examined, although no intensely chloritized and strongly mineralized samples were analyzed for lithogeochemistry. Most of the metal suites significantly enriched in felsic rocks are either weakly added or lost in the mafic lithologies. These include: Ag, As, Au, Bi, Cd, Co, Pb, Sb, Te, Tl, Zn. Copper, Cr, and Ni are the only three trace metals significantly enriched in the intensely quartz-carbonate-altered mafic lithologies (Figure 13). As no high-quality fusion lithogeochemical data are available from the Au150 basalt or intensely chloritized units, mass change values were not calculated for these rock types.

7. Hyperspectral Data

Short-wave infrared (SWIR) and thermal infrared (TIR) spectral data from the Nimbus deposit are presented in Figures 14–17, with accompanying geological logs and downhole geochemical profiles. Through a comparison of cores from drillholes NBDH035, BOD202, NBDH010, and BODH015, common hyperspectral characteristics from a mineralization proximal setting can be identified and compared to those in a more distal setting.

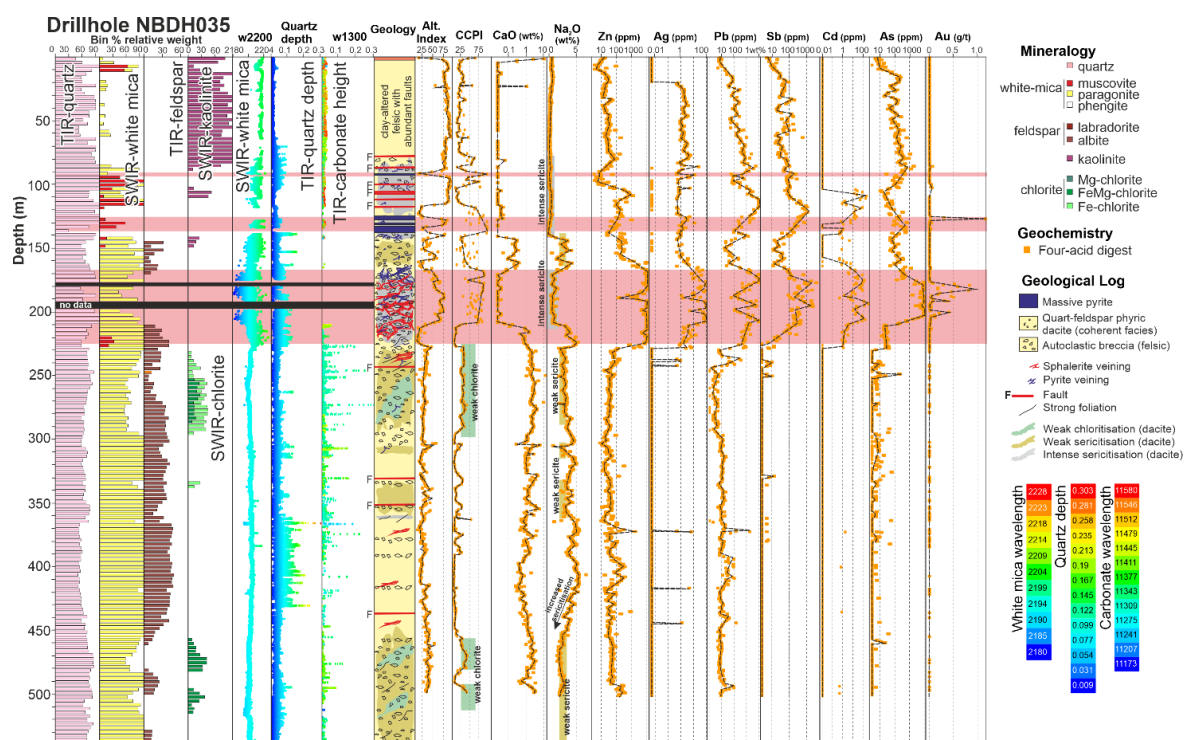


Figure 14. Hyperspectral and geochemical data for drillhole NBDH035 drilled under the Discovery Pit. Drillhole NBDH035 intersected massive polymetallic Zn-Ag-Pb ore and units of massive pyrite. The gangue mineralogy is dominated by quartz, white mica, feldspar, chlorite, carbonate, and kaolinite (near surface). Massive Zn-Ag-Pb sulfide mineralization is associated with elevated concentrations of Sb, Cd, As, and Au, depletions in CaO and Na₂O, and zones of intense sericitization. The latter is marked by a complete loss of feldspar in the TIR signal, and the most paragonitic white mica compositions. Chlorite (both FeMg and Mg-rich) is restricted to key intervals associated with zones of weak sericitization. Carbonate abundance is sporadic throughout the hole. SWIR, short-wave infrared; TIR, thermal infrared.

Drillhole NBDH035 intersected one major lens of polymetallic base metal mineralization in the west of the Nimbus deposit under the Discovery Pit (Figure 3a), and a number of overlying lenses of massive pyrite (Figure 14). The drillhole is entirely within dacitic rocks. The main zone of Zn-Ag-Pb mineralization occurs from ~170 to 225 m depth within the autoclastic dacite facies. This zone is also marked by significant enrichments in As (>1 wt%), Sb (to 3640 ppm), Cu (to 2760 ppm), Cd (to 345 ppm), Ni, (to 321 ppm), Co (to 313 ppm), Bi (to 24 ppm), and Au (to 1.16g/t) concentrations, and Na-Ca depletion

(Figure 14). TI is entirely below detection (<4 ppm) in company data. The lower zone of massive pyrite is also marked by strong enrichments of the same elements but at lower concentrations (e.g., to 1100 ppm Sb, 222 ppm Cd, 6 ppm Bi; Figure 14), except Cu which is higher (to 4130 ppm). Areas of intense sericitization surrounding mineralization are recorded in hyperspectral data by a reduction in feldspar (albite) content to zero, more variable white mica compositions, and abundant low-wavelength white mica (i.e., paragonite) (Figure 14). An increase in quartz abundance (TIR summary signal) is also associated with zones of mineralization. Carbonate abundance is sporadic throughout the hole, dominated by calcite with lesser ankerite and dolomite. The latter often occurs surrounding the Na-Ca depletion halos. Two broad zones of increased chloritic alteration occur from ~240 to 290 m and ~450 to 510 m marked by moderate CCPI and weak MnO enrichment (from <0.01 to 0.15 wt%). Whereas the upper zone contains both Fe- and FeMg-rich chlorite, the lower zone is characterized by Fe-chlorite. Abundant kaolinite occurs to ~90 m depth due to weathering.

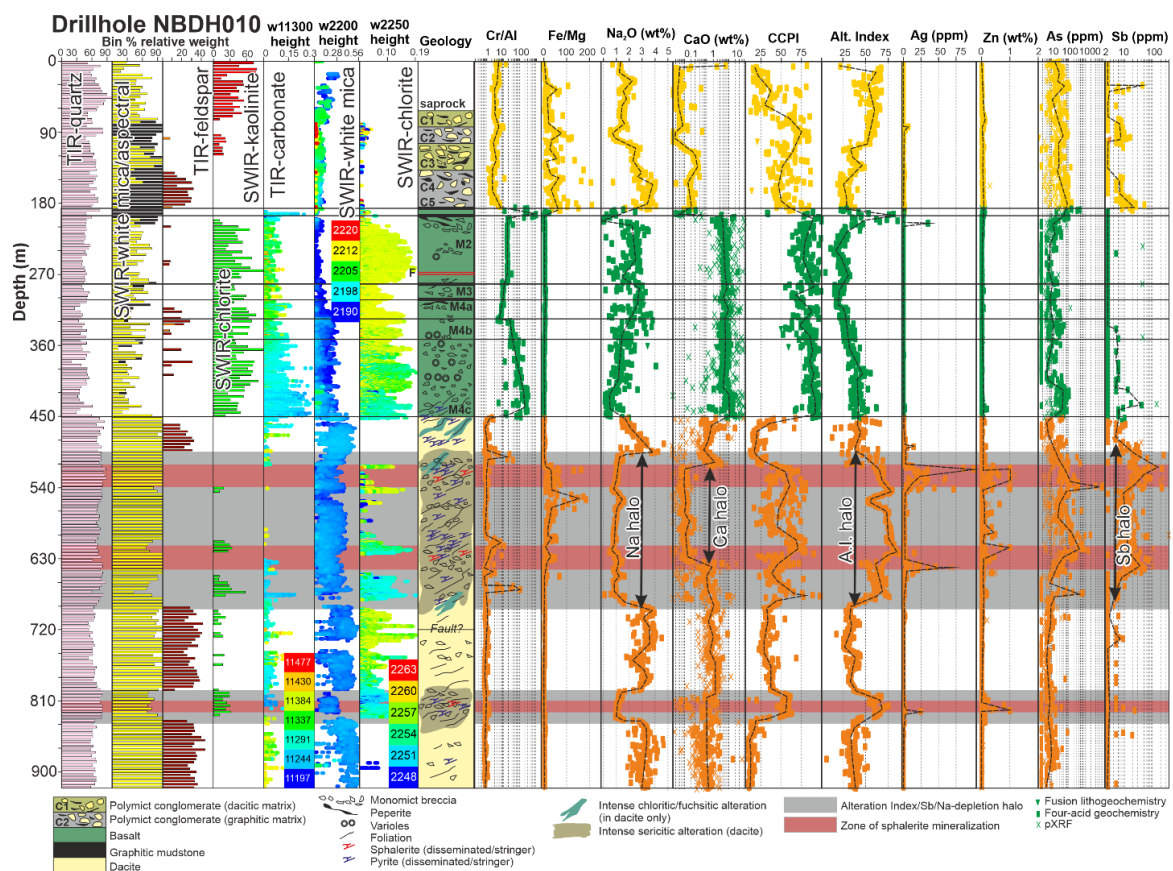


Figure 15. Hyperspectral and geochemical data for drillhole NBDH010 drilled under the East Pit. Geochemical data are colored according to lithology (polymict conglomerate, yellow; basalt, green; dacite, orange). Drillhole NBDH010 intersected narrow zones of stringer sulfides in monomict dacite breccias (marked by red shading). Zones of weak mineralization are surrounded by halos of As and Sb enrichment and Ca-Na depletion (marked by grey shading). Surrounding rocks are dominated by coherent weakly silica-sericite-altered dacite. The upper part of the drillhole is dominated by polymict conglomerates (units C1 to C5) and invasive mafic flows or sills (units M1 to M4), which are separated by narrow intervals of graphitic/carbonaceous mudstone. Shifts in white mica, chlorite, and carbonate chemistry are preferentially associated with basaltic hyaloclastite near the mafic–felsic contact (unit M4c), and within sericitized monomict dacite breccias. SWIR, Short-wave infrared; TIR, thermal infrared.

Drillhole NBDH010 under the East Pit (Figure 3a) is broadly divisible into three main lithological packages: (1) an upper zone of hanging-wall polymict volcanic conglomerates (divided into C1 to C5) which range from matrix- to clast-supported with a varying matrix

(of graphitic or dacitic composition); (2) a middle zone dominated by quartz-chlorite-carbonate-altered basaltic rocks; and (3) a lower zone of variably altered coherent dacite (Figure 15). It is likely that the thick sequence of mafic rocks includes those from the Northeast, East Pit, and Au150 basalts (Figure 3a), as several distinct styles of hydrothermal alteration are noted, restricted to individual flows or invasive sills (Figure 15: units M1 to M4). These units are separated by thin horizons of carbonaceous mudstone with peperitic contacts, and preserved textures indicative of varioles and hyaloclastite (Figure 15).

Mineralization in drillhole NBDH010 is hosted by monomict dacite breccias and is restricted to minor zones of stringer sphalerite at ~520, 630, and 820 m depth (Figure 15). The upper two zones are connected by a zone of weak stringer and disseminated pyrite. Broad regions of intense sericitization surround the upper two zones, and the lower zone. As in drillhole NBDH035, these rocks are characterized by Na-Ca depletion, high Alteration Index values, and high concentrations of Zn, Ag, Pb, As (to >1 wt%), Cu (to 916 ppm), Ni (to 456 ppm), Sb (to 258 ppm), Co (to 94 ppm), Cd (to 64 ppm), and Bi (to 28 ppm). Within the hyperspectral data, quartz is more abundant at these depths, feldspar is absent, white mica is of low wavelengths (~2190 to 2195 nm), and carbonate is generally absent or of low wavelength (~11,250 nm; dolomite). Coherent dacitic rocks are less altered (silica-sericite), with an increased abundance of carbonate which is characterized by higher wavelengths (e.g., ~11,350 to 11,400 nm; calcite). Chloritization in drillhole NBDH010 is restricted to narrow internals in dacite, but is abundant within overlying mafic lithologies. Shifts to lower wavelength chlorite (more Mg-rich; Figure 15) occur around the lower two zones of mineralization in dacite (~630 m, 820 m; Figure 15) and towards the contact between basaltic and dacitic rocks. These mafic rocks are also associated with elevated Pb (to 363 ppm) and Sb (to 41 ppm) concentrations, and high whole rock Mg/Fe ratios. Hanging-wall polymict conglomerates are characterized by minor amounts of muscovitic to phengitic white mica (2205–2220 nm), and an absence of chlorite or carbonate alteration.

Drillhole BOD202 is weakly mineralized, with narrow zones of pyrite-sphalerite veining. Mineralization is located under the East Pit (Figure 3a), with the most intense hydrothermal alteration (intense quartz-sericite $\pm$ pyrite) occurring from ~350 to 420 m within a sheared autoclastic dacite facies (Figure 16). This zone is marked by an increase in Alteration Index values, Na-Ca depletion, and anomalous contents of Ag, As, Au, Bi, Cd, Co, Cu, Ni, Pb, Tl, and Sb (Figure 16). Again, zones of intense sericitization are marked by a complete loss of feldspar (albite) in the TIR signal and high SWIR white mica abundance. Interestingly, throughout the uppermost felsic interval (~160 to 345 m), shifts are clear in the white mica signature which correspond to logged zones of sericitization and the visible loss of quartz and feldspar phenocrysts in the core. Whereas paragonitic white mica compositions are associated with increased sericitization, the least altered sections of core (where phenocrysts are still visible) are dominated by muscovite. The highest wavelength white mica compositions (muscovite) are also associated with minor amounts of oligoclase. Carbonate is sporadically present in felsic lithologies. Mafic lithologies in drillhole BOD202 are characterized by intense Fe-rich and FeMg chlorite alteration, high amounts of carbonate (dominated by dolomite and ankerite), and low abundances of quartz and feldspar. Mafic lithologies (hyaloclastite) are also characterized by the lowest wavelength white mica compositions (paragonite).

Drillhole BODH015 occurs ~1km SW of the Nimbus deposit and intersects a diverse stratigraphy as shown in Figure 17, including: komatiite flows, volcanic sandstones/siltstones, polymict volcanic breccias, carbonaceous mudstone, basalt, and dolerite [12,13]. Quartz abundance fluctuates significantly downhole, with feldspar content highest in sedimentary lithologies (laminated mudstone and quartz-rich sandstone). Feldspar compositions are dominated by albite in felsic rocks, with minor oligoclase and andesine present in laminated mudstones. Intense chloritic alteration (Fe- and FeMg-rich) is restricted predominantly to the intrusive dolerite at the top of the hole associated with gold mineralization. All underlying lithologies are marked by low chlorite abundance. White mica is restricted to

the uppermost section of core, with paragonitic compositions being replaced by muscovite. Minor phengite was recorded from several horizons in the core.

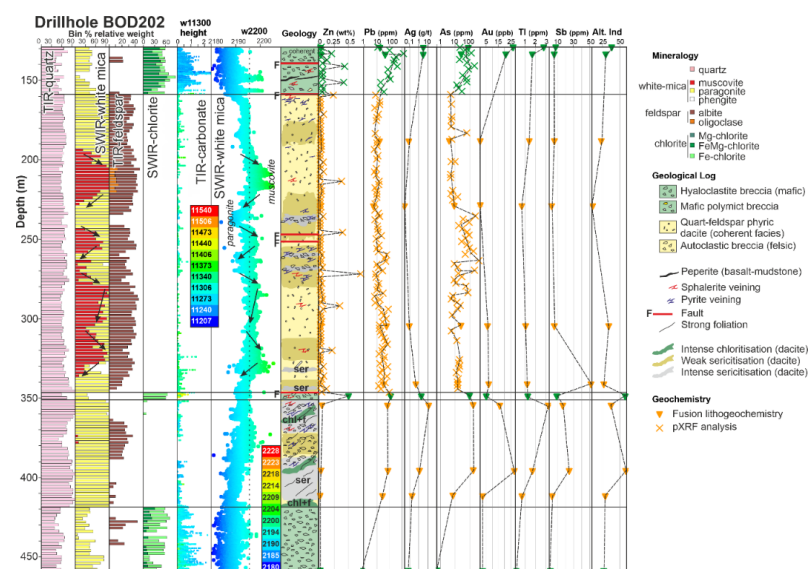


Figure 16. Hyperspectral and geochemical data for drillhole BOD202 from under the East Pit. Drillhole BOD202 intersected relatively fresh, weakly altered dacite, zones of intensely sericitized dacite with sulfide veins, and basaltic hyaloclastite. Basaltic rocks are characterized by higher abundances of chlorite and carbonate, whereas dacitic rocks are dominated by quartz, white mica, and/or feldspar. Zones of sericitization in dacite are marked by a reduction in feldspar content, more paragonitic white mica compositions, and a slightly higher quartz abundance. SWIR, Short-wave infrared; TIR, thermal infrared.

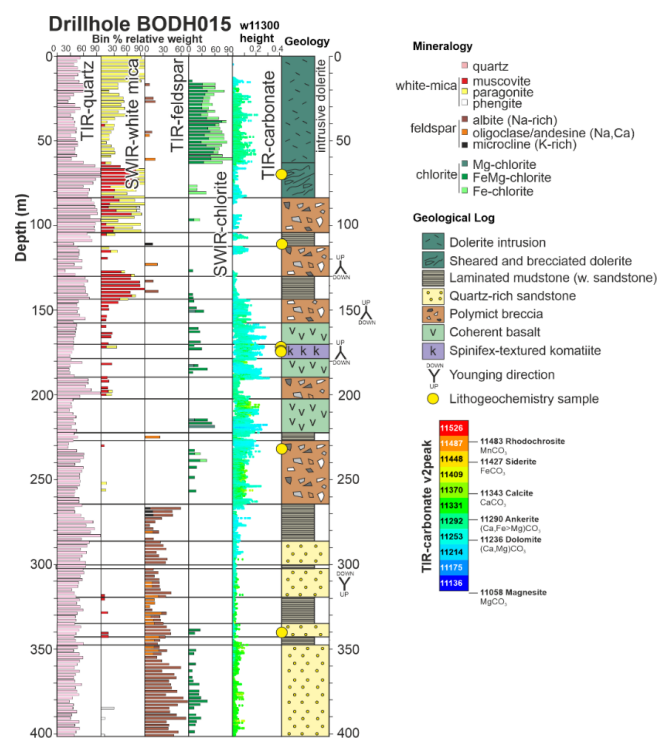


Figure 17. Hyperspectral data for drillhole BOD202 drilled 1km SW of the Nimbus deposit. The geological log is modified after Hildrew [12]. Note: younging directions change in the hole due to localized folding. SWIR, Short-wave infrared; TIR, thermal infrared.

8. Discussion

8.1. Ore Forming Conditions for the Nimbus Deposit

Hollis et al. [13] suggested that the mineralogy of the Nimbus deposit is consistent with formation at shallow water depths and low fluid temperatures, with a magmatic volatile input into the hydrothermal system. Evidence presented for low temperatures included: the main Ag-Sb-Pb-As sulfosalt assemblage (Section 4.2); high Hg and low Cu in the deposit; plus, similarities with ancient and modern systems such as the shallow water, low-temperature Palinuro deposit of Italy [44] (see Section 8.2), and the Eskay Creek deposit of Canada [45,46]. Caruso et al. [14] subsequently provided further evidence for low fluid temperatures, including high Ga and low Se contents in sphalerite, and the incorporation of significant Ag into tetrahedrite [47–50]. Whereas early microbial forms associated with early formed massive pyrite suggest formation at temperatures below ~121 °C, the main ore phase was envisaged to form between 170 and 250 °C [14]. The presence of minor early ore stage (Figure 7c,d,g) and late interstitial (Figure 5d,e) chalcopryrite also indicates that some fluids were slightly higher temperatures (perhaps ~280 °C).

Significant enrichments in the epithermal (Ag-Au-Sb-As-Hg-Bi) suite of elements and a lack of chloritic alteration in felsic rocks were suggested as evidence for a significant magmatic contribution to the hydrothermal system [13]. A large magmatic volatile component is also consistent with relict volcanic textures throughout much of the host stratigraphy (Figure 5i–l), and thus, lower fluid/rock ratios than most VMS systems [13]. This model was subsequently reinforced by the multiple S isotope study of Caruso et al. [14], who demonstrated that following the formation of early massive pyrite, the mineral system was largely sealed from descending ambient seawater and dominated by an ascending magmatic-hydrothermal fluid. The magmatic fluid most likely introduced the epithermal suite of elements during the main ore phase. Relatively oxidizing fluid conditions, from a magmatic contribution to the main ore fluid, are further indicated by low concentrations of Ag, Sb, and Bi in galena (references in [14]).

The presence of pyrite, tetrahedrite, and minor chalcopryrite in most lenses and the Fe content of sphalerite (~2 to 6 wt%, [14]) are indicative of intermediate sulfidation conditions for the bulk of mineralization at Nimbus [13]. However, the presence of freibergite $[(\text{Ag,Cu,Fe})_{12}(\text{As,Sb})_4\text{S}_{13}]$ and enargite $[\text{Cu}_3\text{AsS}_4]$, associated with covellite and chalcopryrite in holes NBRC202 and NBRC203 [51,52], points to a higher sulfidation and higher temperatures for some lenses immediately east of the Discovery Pit [13]. Somewhat oxidizing conditions are also indicated by the presence of very rare hypogene cassiterite associated with high Fe sphalerite (Figure 7b) in drillhole NBDH025 (~160 m). By contrast, pyrrhotite has been recognized in a small number of stringer zones (e.g., NBDH011; ~308 m) forming late with chalcopryrite after the main galena-sulfosalt ore phase (Figure 5d). This, in turn, indicates that transitions to low sulfidation conditions occurred in other areas, possibly as the magmatic contribution waned, but the principle ore fluid remained relatively hot.

Whereas some lenses at Nimbus contain significant Au and/or abundant arsenopyrite, others are either dominated by sphalerite and galena, or contain extremely complex sulfosalt assemblages. Such lens specific variations in mineralogy are comparable to both modern and ancient hybrid bimodal felsic VMS deposits, discussed below (e.g., Ming deposit; [53]). It is important to note that precious metal grades at Nimbus are also highly variable. Although precious metal enrichment occurs in a number of lenses (e.g., NBRC216—17 m at 1434g/t Ag; NBRC033—2 m at 54g/t Au), other lenses contain low grades of Au and/or Ag. Under low temperature conditions (<250 °C), significant precious metal enrichment by phase separation (i.e., boiling) can only be achieved by shallow water depths [54].

Boiling of the ascending hydrothermal fluids due to shallow water depths would lead to partitioning of metals between the liquid and vapor phases. For example, in the caldera of the Axial volcano, Juan de Fuca Ridge, boiling of hydrothermal fluids at 1500mbsl (meters below sea level) and ~350 °C resulted in a separation of Au from base metals, and partitioning of the volatiles into a vapor phase [55]. Very high Au grades and elevated

Ag-As-Sb-Hg concentrations were identified in anhydrite and barite chimneys [55]. At Nimbus, Au is strongly associated with As (less so with Zn-Pb-Ag), with the highest grades often in mafic rocks (e.g., Au150 basalt; Figure 3). The separation between Au-As and Ag-Pb-Sb-Zn in felsic and mafic rocks at Nimbus may be due to a combination of phase separation and/or local controls on mineral precipitation (e.g., fluid temperature, pH, fS_2).

We suggest that the Nimbus deposit formed in shallow water depths (c. 650 mbsl or less), which is the boiling point for seawater (3.2 wt% NaCl) at ~280 °C [56]. Hence, boiling at Nimbus would have been restricted to the slightly hotter fluids in the deposit (~280 °C), which also precipitated the minor amounts of chalcopyrite. High contents of dissolved gases may have lowered the temperature at which the hydrothermal fluids boiled [57]. Boiling below the seafloor would also result in widespread and vertically extensive stockwork-style mineralization [55], with multiple stacked orebodies developing (Figure 3).

While the Nimbus deposit largely formed through sub-seafloor replacement, there is also clear evidence that some of the metal-bearing fluids from the main ore phase reached un lithified hanging-wall polymict conglomerates at or just below the seafloor [15]. A ~3.5 m thick interval has been identified in the hanging-wall polymict conglomerates at ~185 m depth in drillhole NBDH010. This interval contains markedly higher total trace element contents, and higher ratios of Ag/Sb (similar to the high-grade polymetallic ore lenses), Ag/Au, Sb/Au, and Se/S in pyrite nodules; in addition to marked higher TOC, Mo and Co/Ni ratios in the graphitic matrix [15]. The latter are linked to increased bioactivity at the time, from the ascending metal-bearing, relatively oxidizing hydrothermal solutions [15].

8.2. A Hybrid Bimodal Felsic VMS Deposit

As discussed above, the Nimbus Ag-Zn-(Au) deposit exhibits hybrid mineralogical and geochemical characteristics between classic Cu-Zn VMS and epithermal styles of mineralization. Hollis et al. [13] consequently classified the Nimbus deposit as a hybrid bimodal felsic VMS deposit [1,55,58]. Such deposits are similar to classic bimodal felsic or Kuroko-type VMS deposits [1,59], with additional features such as: high precious metal contents; enrichments in the epithermal suite of elements (Hg-Sb-As-Bi-Te); a lack of chloritic alteration in felsic strata; and advanced argillic/aluminous alteration (e.g., pyrophyllite, clays, and alunite group minerals) [60]. They are envisaged to form in shallow submarine volcanic-dominated settings which facilitate fluid boiling, with significant magmatic contributions to the ore forming fluid.

Examples of hybrid bimodal felsic VMS deposits worldwide include: the precious metal-rich VMS deposits of the Bousquet-LaRonde camp [61]; Eskay Creek of British Columbia [62]; the Bobby's Pond and Daniels Pond deposits of the Tulls belt, Newfoundland [60,63]; Mount Lyell of Tasmania [64–66]; the Johnson River deposit of Alaska [67]; and Iron Dyke deposit of Oregon [68]. The Ming Deposit of Newfoundland, Canada, also contains high contents of precious metals due to a significant magmatic input into the system and possible shallow water conditions, but is hosted in a bimodal mafic sequence [53].

The absence of Mg gains in the Nimbus stratigraphy is consistent with hybrid bimodal felsic VMS deposits in general, which contain a lack of chlorite [1]. At Nimbus, chloritization in dacite is restricted to very narrow high-temperature fluid pathways [13]. Chlorite is more abundant in mafic rocks which reflects the higher Mg and Fe concentrations in the primary mineralogy. The Nimbus deposit also exhibits the classic quartz-sericite-pyrite alteration of a hybrid bimodal felsic VMS deposit (Figure 4), but lacks the advanced argillic alteration commonly associated with high-sulfidation feeder zones [1,55,69]. No significant enrichments in Al_2O_3 are noted in dacitic rocks (Table S2). Furthermore, as shown in Figure 18, while intensely altered samples at Nimbus trend towards high AI and Advanced Argillic Alteration Index (AAAI) values, the common mineralogy of such systems (e.g., pyrophyllite-kaolinite-sericite-alunite) and trend of decreasing AI associated with strongly acidic alteration [69] are absent.

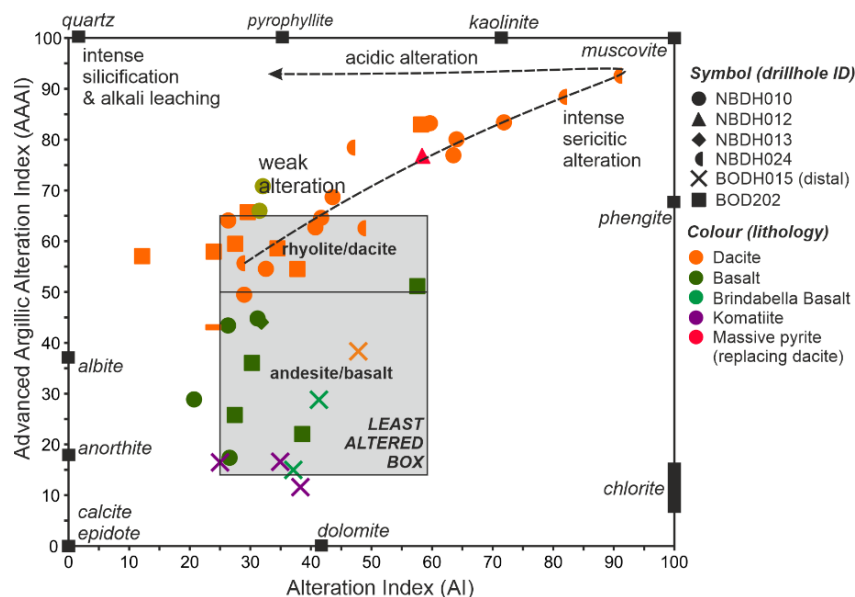


Figure 18. Lithogeochemical data from Nimbus plotted on the Advanced Argillic Alteration box plot of Williams and Davidson [69]. The Alteration Index (AI) reflects sericite and chlorite formation associated with the destruction of feldspar and volcanic glass [41]. The Advanced Argillic Alteration Index (AAAI) quantifies silica enrichment and the destruction of chlorite, carbonate, and feldspar. The least altered box is modified after [69] using unaltered international standard rock compositions from ioGAS (e.g., international unaltered standards JB-3, JA-2, JR-1).

For subaerial high-sulfidation epithermal systems, advanced argillic alteration results from the rapid cooling of volcanic gases (SO_2 , HCl) producing highly acidic and oxidizing (acid-sulfate) conditions [70]. The lack of advanced argillic alteration is most likely due to the fact that very low pH values (<3) were not reached for the bulk of the mineralization (due to the influence of seawater entrainment). Aluminum silicate alteration is absent in the Au-rich Horne, Estrades, and Eskay Creek VMS deposits, which contain significant amounts of Sb, As, and Hg, and are interpreted as shallow water hybrid VMS-epithermal deposits [71]. Alternately, the principal feeder zone associated with such aluminous alteration at Nimbus may await discovery, and be associated with the higher sulfidation lenses immediately east of the Discovery Pit (drillholes NBRC202 and NBRC203).

Nimbus is also interpreted to have formed on the margin of the main Kurnalpi rift zone in shallower water depths, over thicker crust, and significantly earlier (c.10 Myr) than the Zn-Cu VMS deposits of the Teutonic Bore camp (at 2703 and 2692 Ma, respectively; [13,72]). This is also consistent with the formation of precious metal-rich, hybrid bimodal felsic VMS deposits in Canada, which form away from the main rift zone and at different time periods to Cu-Zn deposits [61].

The relative scarcity of hybrid bimodal felsic VMS deposits in the Yilgarn Craton may be explained by one or both of the following mechanisms. Firstly, this might be due to limited exploration efforts, as VMS mineralization has historically been targeted in the Gindalbie domain in the Eastern Goldfields Superterrane ([8]; Figure 1), and many routine exploration criteria would not be applicable (e.g., FIII-affinity felsic rocks, intense chloritic alteration; [8,13]). An alternate suggestion, proposed by Mercier-Langevin et al. [61] for these deposits in general, is that their scarcity in geological records may reflect the enhanced likelihood for seafloor erosion in shallower water environments. Although this is certainly true, as mineralization at Nimbus occurred below the seafloor through replacive processes, we consider the lack of deposits in Western Australia to be a consequence of under-exploration. Nimbus-style deposits could exist along both margins of the Kurnalpi rift zone (in the Kalgoorlie and Burtville terranes), or the Cue zone (Figure 1).

8.3. A Modern Analogue

A clear modern analogue for the Nimbus deposit is the sulfide occurrences of the Palinuro Volcanic Complex, Aeolian arc, Italy [13]. Sub-seafloor mineralization has been identified in water depths of ~650 mbsl, with similar Ag-Au grades to Nimbus (average assay 0.4 g/t Au and 130 ppm Ag; to maximum 3.4 g/t Au and 925 ppm Ag [43]). Dredge samples recovered by Tufar [73] range to 7.1 g/t Au and 420 ppm Ag. Barite and sulfide occurrences at Palinuro are concealed by a thick cover of hemipelagic to pelagic mud and volcanoclastic deposits, with sulfides discovered during dredge sampling and gravity coring. No black smoker activity has been observed. Widespread discoloration of sediments, diffuse venting of low-temperature shimmering water, and the occurrence of living tube worm colonies were the only conclusive signs of ongoing hydrothermal activity [44,74–76].

A detailed paragenesis for mineralization at Palinuro was presented by Petersen et al. [44]. A barite cap formed early in the paragenesis of the deposit, most likely accompanied by the formation of massive pyrite at depth. The upper zone was cemented and brecciated by barite-pyrite, minor chalcopyrite, tetrahedrite, trace famatinite [$\text{Cu}_3\text{Sb}_3\text{S}_4$], and rare cinnabar [44]. A low-temperature phase of sphalerite, galena, opal-A, barite, and Pb-Sb-As sulfosalts (e.g., bournonite, semseyite [$\text{Pb}_9\text{Sb}_8\text{S}_{21}$]) occurred prior to a transition to very high sulfidation conditions (marked by enargite and hypogene covellite with galena and sphalerite) and the formation of late colloform pyrite and marcasite [44]. Whole rock concentrations at Palinuro reach 2.2 wt% Sb, 1.5 wt% As, 2920 ppm Hg, 1390 ppm Bi, 460 ppm Tl, 84 ppm Te, and 49 ppm Se. Nickel and cobalt contents are generally low (<1 to 45 ppm Ni, <1 to 52 ppm Co). Sulfur isotope systematics are indicative of a magmatic dominated hydrothermal fluid [44].

Evidently, there are a number of parallels between the Nimbus and Palinuro hydrothermal systems. These include the mineralogy, grades of mineralization, inferred shallow-water depths, low temperatures, dominantly intermediate sulfidation state (with transitions to higher conditions in some ore lenses), and magmatic contributions to the hydrothermal fluids (discussed above). Palinuro contains high contents of the epithermal suite of elements (As, Hg, Sb), and those more typical of subaerial felsic hosted magmatic-hydrothermal systems (Bi, Te, Se). Although Nimbus also contains high As, Sb, and Hg, the latter suite of elements is significantly lower concentrations at Nimbus (e.g., to 51 ppm Bi; to 22 ppm Se, most <2 ppm; <0.05 ppm Te). Nimbus also contains significantly higher concentrations of Ni and Co than Palinuro. Both of these features will be discussed below with respect to ancient VMS deposits.

In the Ming deposit of Newfoundland, metal enrichments of the precious and epithermal suite of elements (As, Bi, Hg, Sb, Se, Sn, Te) are ore lens specific, reflecting the local fluid conditions [53]. For example, in the 1807 zone, tennantite-tetrahedrite is Ag-poor and the ore lens is enriched in Te, Bi, and Se [53]. By contrast, in the 1806 zone, tennantite-tetrahedrite is Ag-rich, galena is rich in Ag (and low in Bi), and the ore lens is telluride-free, containing high Ag, Sb, Hg, and Au [53]. The lack of significant Te-Bi-Se enrichment and trace metal contents of galena and tetrahedrite in the 1806 zone is remarkably similar to the Nimbus deposit. Low Te-Bi-Se enrichment was explained by Brueckner et al. [53] as being due to hydrothermal fluids with low $f\text{Te}_2/f\text{S}_2$, $f\text{Se}_2/f\text{S}_2$, and $m\text{Bi}/m\text{Sb}$ ratios.

As stated above, Nimbus is also marked by high enrichments of Ni, and to a lesser extent, Co, as compared to the Palinuro deposit of Italy. Mass change calculations reveal significant gains of these elements to the host dacites (Table S2). As the Nimbus deposit is hosted by the lower plume stratigraphy of the Kambalda region, the deeper footwall stratigraphy of the Nimbus deposit is dominated by mafic and ultramafic rocks (Figure 2). Such rocks are likely to have been a major source for Ni and Co, in addition to Zn-Pb-Cu.

Cobalt enrichment is a well-documented feature of a number of mafic siliciclastic or Besshi-type VMS deposits. Such deposits occur in sedimented backarc or ocean rift environments, where the deep stratigraphy is likely to be dominated by mafic and ultramafic rocks. Examples of Besshi-type deposits include Windy Craggy of Canada, Besshi of Japan [1,77], and the DeGrussa deposit of Western Australia [78]. The Outokumpu-type

Cu-Co-Zn-Ni-Ag-Au deposits of Finland are hosted by serpentinized ultramafic rocks (mantle peridotites), within a metasedimentary sequence [79]. As Co is not easily mobilized by hydrothermal fluids, except at high fluid temperatures and salinities [77,80], this could explain the relatively low Co concentrations at Nimbus, compared to rocks with similar deep footwall sequences, but a general enrichment compared to Palinuro. The high abundance of Ni and Cr (fuchsite, chromite) in the deposit can also be explained through leaching from ultramafic and mafic lithologies at depth [13].

8.4. Geochemical Halos to Mineralization

Due to the unique mineralogy and styles of mineralization at Nimbus in the Eastern Goldfields Superterrane, we have identified geochemical and hyperspectral halos to aid the exploration of similar deposits elsewhere.

Polymetallic sulfide mineralization at Nimbus is characterized by pyrite, sphalerite, and galena with a diverse suite of Ag-Sb $\pm$ Pb $\pm$ As $\pm$ (Cu)-bearing sulfosalts, minor arsenopyrite, and chalcopyrite. The sulfosalt suite is dominated by Ag-rich boulangerite, pyrargyrite, Ag-rich tetrahedrite, and Ag-rich bournonite (Figure 7). Other minor sulfide and sulfosalt phases noted at Nimbus are listed in Table 1. Given the mineral assemblage, it is unsurprising that the main whole rock geochemical anomalies associated with sulfide mineralization at Nimbus are Fe-Zn-Ag-Pb-Au, accompanied by significant enrichments in As, Sb, Cu, Cd, Ni, Co, Cr, Sn, and Bi (Figures 14 and 15). Thallium is also often anomalous in lithogeochemistry samples (e.g., BOD202; Figure 16) and increases with base metal contents (Figure 11). However, anomalous Tl concentrations are difficult to detect at Nimbus using routine company four-acid assay data due to poorer detection limits. Significant whole rock enrichments in these elements occur even in zones of surrounding quartz-sericite-altered dacite without significant visible sulfides. Most of these elements are strongly correlated: Ag-Pb-Sn-Tl-Zn, Au-As, and Cu-Mo-W-Ni (Figure 11). Mass change calculations also show these elements were added to the dacitic rocks in large amounts (Figure 13, Table S2).

This suite of metal enrichment is also observed within the trace element phases of the sulfides themselves. Caruso et al. [14] presented a detailed trace element study of the main sulfide phases at Nimbus (listed in Table 1). Significant concentrations (mean >0.1 wt%) of Cd are hosted by sphalerite, galena, Ag-rich tetrahedrite, Ag-rich boulangerite, and pyrostilpnite. Ni is hosted by pyrrhotite, pentlandite, ullmannite, and Fe-rich viaeneite with minor millerite and siegenite. Ni contents also reach 0.6% in pyrite [14]. Bi is primarily hosted by Ag-rich tetrahedrite, boulangerite, pyrostilpnite, meneghinite, and owyheeite. The only Co and Sn phases noted were siegenite and cassiterite, respectively. Relatively high Co contents were also recorded in arsenopyrite (to 3.4%) and pyrite (to 0.4%) by Caruso et al. [14]. It is likely that significant Co is also hosted by pentlandite and pyrrhotite, which have not yet been analyzed for their trace element chemistry.

The broad zones of Fe, S, Zn, Pb, Sb, Ag, As, Cd, Ni, Cu, Ba, Co, Cr, Tl, Bi, and Au mass gains associated with mineralization at Nimbus are, in turn, surrounded by larger zones of Na and Ca depletion, and increases in SiO₂, CCPI, and Alteration Index values (Figures 14–16). Such geochemical halos are common for modern and ancient VMS deposits in general [1,4,17,18,41], and reflect feldspar destruction and the formation of silica, sericite, pyrite, and/or chlorite. The main alteration minerals are further reflected using molar ratio plots, as shown in Figure 19. On plots of (2Ca + Na + K)/Al and (Na + K)/Al against K/Al, samples of dacite are spread between the muscovite, paragonite, albite, and chlorite mineral nodes (note that carbonate and quartz are not expressed on this plot). A cluster in the point density cloud is present both for a weakly altered composition (higher Na+Ca, lower K) near a composition for unaltered dacite, and strongly altered composition. Such plots provide a useful guide for discriminating and classifying major alteration trends. Together with the hyperspectral characteristics of gangue phases (see following section), these signatures can be used to identify similar zones of mineralization elsewhere in the Yilgarn Craton. These geochemical and mineralogical halos surround lenses of

barren massive sulfide, high-grade polymetallic Ag-Zn-Pb-Au mineralization (Figure 14), and zones of weak and disseminated pyrite-sphalerite mineralization (Figures 15 and 16). However, the intensity is most pronounced in the zones of high-grade massive sulfides.

Table 1. Primary sulfide phases identified from the Nimbus deposit, with idealized formulae. Significant trace element concentrations are listed where mean values are >0.1 wt.% from [14].

Mineral Phase	Ideal Mineral Formula	Trace Element Concentration (for Elements with Mean Concentrations >0.1wt.%)
Pyrite (main ore stage)	FeS ₂	Varies upon type (e.g., As)
Sphalerite	(FeZn)S	Cd ~0.1
Galena	PbS	Fe 0.21, Cd 0.12
Chalcopyrite	CuFeS ₂	None.
Arsenopyrite	FeAsS	Zoned in Co, Ni, Sb.
Pyrrhotite	Fe _(1-x) S	Ni 0.27
Boulangerite	Pb ₅ Sb ₄ S ₁₁	As 0.17, Bi 0.14, Zn 0.14
Ag-rich Boulangerite	(Pb,Ag) ₅ Sb ₄ S ₁₁	As 0.22, Zn 0.12
Pyrargyrite	Ag ₃ SbS ₃	*
Ag-rich Tetrahedrite	(Cu,Fe,Zn,Ag) ₁₂ Sb ₄ S ₁₃	As 0.36, Fe 5.68, Zn 2.21, Ag 14.25, Cd 0.1, Bi 0.21, Hg 0.42
Ag-rich Bournonite	(Pb,Ag)CuSbS ₃	Fe 4.66, Pb 1.46, Zn 3.34, Cd 0.24, 0.16, Hg 0.51.
Marrite	AgPbAsS ₃	*
Freibergite	(Ag,Cu,Fe) ₁₂ (As,Sb) ₄ S ₁₃	*
Owyheeite	Pb ₇ Ag ₂ (Sb,Bi) ₈ S ₂₀	*
Pyrostilpnite	Ag ₃ SbS ₃	Pb 2.16, Cd 0.34, Bi 0.27, Hg 0.22
Covellite	CuS	*
Enargite	Cu ₃ AsS ₄	*
Pentlandite	(Fe,Ni) ₉ S ₈	*
Jalpaite	(Ag,Cu) ₂ S	*
Meneghinite	Pb ₁₃ CuSb ₇ S ₂₄	Bi 0.35, 0.64 Cu
Millerite	NiS	*
Siegenite	(Ni,Co) ₃ S ₄	*
Ullmannite	NiSbS	Fe 6.88, Cu 4.68, Pb 0.52, Zn 1.66, Ag 10.2, Hg 0.18
Fe-rich Viaeneite	(Fe,Pb) ₄ S ₈ O	Sb 4.79, Pb 3.8, Ni 2.76
Cassiterite	Sn ₂ O	*

* no mineral chemical data available.

Although mafic rocks can also show significant metal enrichments in the same suite of elements (e.g., Au150 basalt), they are generally less mineralized than dacitic rocks. As described previously, in mafic rocks hydrothermal fluids appear to have been preferentially focused through hyaloclastite and/or along contacts with dacitic rocks. Molar ratio plots for mafic rocks (Figure 19) show major trends towards chlorite, albite, and to a lesser extent muscovite from the least altered composition. In Figure 15, the lowermost mafic unit from drillhole NBDH010 is dominated by hyaloclastite with a shift to higher As, Sb, Alteration Index, and Cr/Al values, and lower Na₂O, near its underlying felsic contact. This zone is also marked by shifts in the chemistry of white mica, chlorite, and carbonate (discussed in the following section).

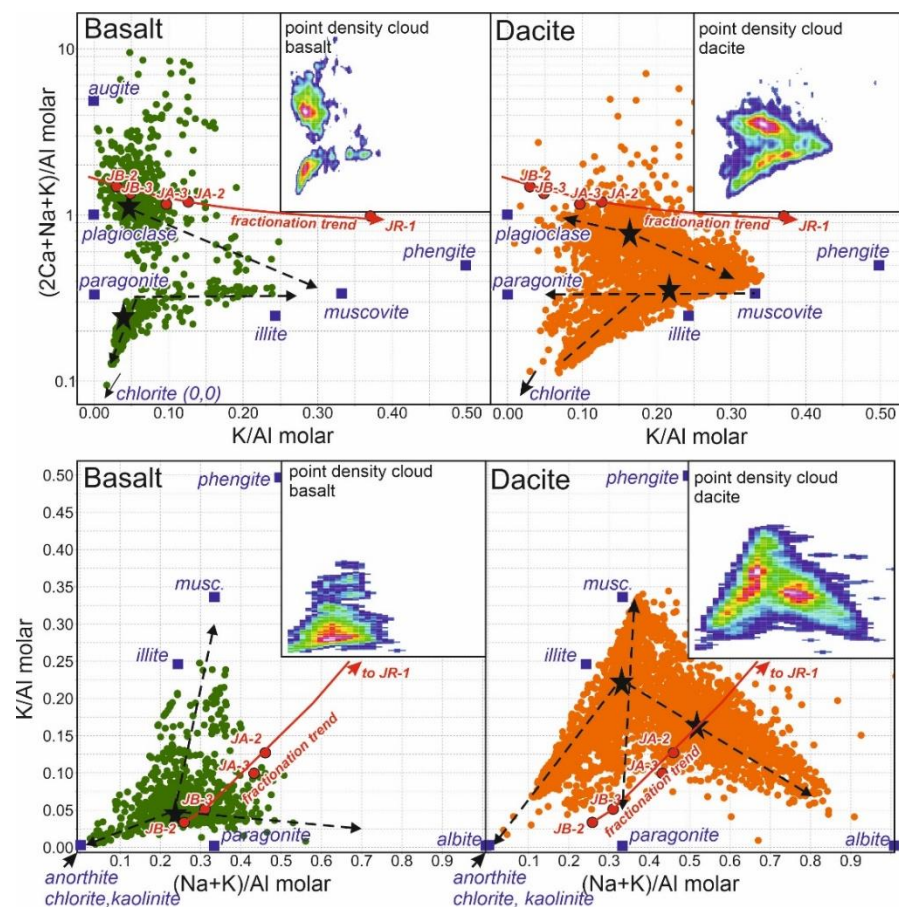


Figure 19. Molar ratio plots for basaltic and dacitic rocks from the Nimbus deposit (using four-acid and fusion lithogeochemistry data). Mineral nodes shown are from ioGAS, along with the composition of major unaltered igneous rock compositions (basalt JB-2, JB-3; andesite JA-2, JA-3; rhyolite JR-1). A typical igneous fractionation trend is shown from basalt (JB-2) to rhyolite (JR-1). Least altered samples of Nimbus basalt and dacite are plotted close to this trend. Dashed lines represent major trends of hydrothermal alteration in the data. Stars represent major clusters in the data, as shown from the inset point density clouds.

8.5. Hyperspectral Halos to Mineralization

Due to the relatively simple gangue mineralogy at Nimbus, the style and intensity of hydrothermal alteration can be characterized through hyperspectral analysis of the drill core in the SWIR and TIR. Such hyperspectral data also provide an opportunity to identify mineral chemical halos using white mica, chlorite, and carbonate compositions.

VMS deposits worldwide can show various shifts in white mica, chlorite, and carbonate compositions. Approaching mineralization, white mica compositions typically show either: 1) more Ba-rich phengitic (K-bearing, Al-poor) compositions (e.g., Hellyer, Rosebery, Neves-Corvo deposits); 2) muscovitic (K-bearing, Al-rich; ~2200–2208 nm) white mica compositions (e.g., Mt. Lyell, Mt. Windsor, Erayinia NW deposits); or 3) low wavelength “paragonitic” (Na-bearing, Al-rich; 2180–2195 nm) compositions (e.g., Myra Falls, Golden Grove, Daniels Pond, Boomerang deposits) [35,81–86]. In other deposits, where felsic rocks are not a major component of the host stratigraphy, white mica might not be a major alteration phase (e.g., Yuinmery [87]).

On a similar note, chlorite can become more Mg-rich or Fe-rich approaching VMS ore lenses and/or the core of feeder zones, or show no such trend at all. Examples of Mg/Mg+Fe enrichment in chlorite towards VMS mineralization include: the Seneca, Southbay, and Corbet deposits of Canada, and the Hellyer, Thalanga, and Quinns deposits

of Australia [18,84,85]. Examples of high Fe/Mg + Fe ratios in chlorite associated with VMS mineralization include the Kuroko deposits of Japan; Horne and Matagami deposits of the Abitibi greenstone belt; Brunswick No. 12, Caribou, Halfmile Lake, and Heath Steele deposits of the Bathurst Mining Camp, Canada; and the Hercules and Golden Grove deposits of Australia (referenced in [83,85]). When coupled with systematic variations in carbonate chemistry, such inter-deposit variations in mineral chemistry highlight the importance of local investigations. Local characterization of the gangue mineralogy is fundamental to correctly assess regional exploration targets using SWIR and TIR data, and identify potential near misses in exploration drill programs [18,84].

As demonstrated in Figures 14–17, with increased proximity to mineralization at Nimbus, the intensity of quartz-sericite alteration increases significantly in dacitic rocks. Mineralization occurred through the replacement of the original volcanic stratigraphy in a sub-seafloor environment in the felsic-dominated stratigraphy [9,10,13]. Hydrothermal fluids were preferentially focused through autoclastic deposits, with zones of massive/semi-massive sulfides preferentially replacing monomict dacite breccias [13]. In the least altered sections of drill core, often in the coherent dacite facies (e.g., BOD202 ~200 m, Figure 16), volcanic textures are still apparent. These rocks have muscovitic (>2195 to ~2205 nm) white mica compositions, and have relatively high feldspar contents (albite, with rare oligoclase). By contrast, low-wavelength or “paragonitic” compositions of white mica are common in silica-sericite-altered strata where monomict dacite breccias are well developed (e.g., BOD202 ~375 m; autoclastic facies). In weakly sericitized dacite, the ALOH wavelength absorption feature typically occurs at 2190 m to 2195 nm. White mica compositions from zones of intense sericitisation, surrounding stringer and semi-massive/massive base metal mineralization, are characterized by a shift to even lower wavelengths approaching ~2185 nm (Figure 16 at 410 m). These same zones are also marked by a higher abundance of quartz in the TIR, due to intense silicification. Very high wavelength absorption features (at ~2205 m to 2220 nm) were only identified towards the top of hole NBDH010, associated with polymict conglomerates, which form the least altered hanging-wall of the Nimbus deposit [13,16].

Carbonate occurs sporadically in dacitic rocks, but in drillhole NBDH010, it appears to be preferentially restricted to the weakly quartz-sericite-altered zones, outside of the main Na-Ca depletion halos (Figure 15). As it approaches these zones of stringer sulfides, the wavelength of the carbonate shifts from ~11,300–11,400 nm (calcite/ankerite; green-yellow colors) to ~11,250 nm (dolomite; blue colors). Chlorite abundance in dacite is restricted to narrow intervals, which can be dominated by either Fe-chlorite or FeMg-chlorite.

In basaltic rocks, hydrothermal fluids were similarly preferentially focused through breccia facies (i.e., hyaloclastite; Figure 8a–c). Lithological contacts between basaltic and dacitic rocks also appear to have focused hydrothermal fluids and these contacts are obscured by intense quartz-chlorite-fuchsite alteration (Figure 8g). Basaltic rocks at Nimbus are characterized by high chlorite-carbonate abundance, and low feldspar (albite)-quartz abundance (Figures 15 and 16). Basaltic rocks are also characterized by having the most paragonitic white mica compositions (down to ~2180 nm), at lower wavelengths than intensely altered dacitic rocks (Figures 15 and 16). Shifts from Ca-carbonates and Fe-chlorites to more Mg-rich compositions of both minerals occur in drillhole NBDH010, reflecting the change from coherent basalt to basaltic hyaloclastite (Figure 15: 200 vs. 400 m depth).

Together, these features highlight that the hyperspectral characteristics are controlled by host rock composition (i.e., basalt/dacite), the intensity of alteration (which, at Nimbus, is largely controlled by volcanic facies), and proximity to mineralization. The observed hyperspectral characteristics for white mica at Nimbus are somewhat similar to those of the Golden Grove camp. Guillianse [35] investigated c. 2.9 Ga VMS mineralization in the Murchison Domain at both the Golden Grove camp (Gossan Hill and Scuddles deposits) and the Glenview prospect ~200 km NNE. Holes at Golden Grove revealed shifts in white mica compositions with respect to host rock composition, the intensity of

alteration, and distance towards mineralization. For example, in holes through mineralized lenses at Gossan Hill, a shift in the AIOH absorption feature was identified from muscovitic to paragonitic compositions within 50 to 100 m of sulfide mineralization. By contrast, late intrusions of dacite and rhyodacite and hanging-wall lithologies were dominated by muscovite, and feldspar was more abundant. Furthermore, in a non-mineralized drillhole 1 km south of Gossan Hill, white mica compositions are dominantly muscovitic (with only minor phengite and paragonite).

The identification of such hyperspectral and geochemical halos elsewhere along the margins of the Kurnalpi rift zone, in the Kalgoorlie or Burtville terranes, would indicate the position of Nimbus-style mineralization. Similar styles of mineralization might also occur along the margins of the Cue zone in the Youanmi Terrane. However, as metamorphism is highly variable across the EGS, these hyperspectral halos are only applicable at greenschist facies and lower metamorphic grades. If the c. 2705 Ma host stratigraphy became strongly metamorphosed, these identified hyperspectral halos might not be applicable. In high-grade metamorphic terranes, fine-grained white mica is often a retrograde phase due to the breakdown of prograde metamorphic minerals, such as muscovite, cordierite, and kyanite [1,87]. In such instances, the effects of metamorphism would have to be decoupled from hydrothermal processes. However, metamorphism itself provides other opportunities for chemical vectoring. For example, at Wheatley (upper amphibolite to locally granulite grade), compositional changes in garnet chemistry with respect to mineralization (e.g., more spessartine rich) and host rock composition have been identified using Hylogger and EMPA data [88].

9. Conclusions

Through our research, we have further characterized the formation of the Nimbus deposit, and established geochemical and hyperspectral halos to mineralization. Conclusions drawn from our research are as follows:

- Nimbus exhibits features typical of a hybrid bimodal felsic VMS deposit. It is interpreted as a shallow water (c. 650 mbsl) and low-temperature (<250 °C) VMS deposit, which formed along the margin of the Kurnalpi rift zone. A significant magmatic input into the hydrothermal system occurred during the main ore stage.
- Mineralization at Nimbus is characterized by early units of barren massive pyrite that replace glassy dacitic lavas, and underlying zones of polymetallic sulfides that replace autoclastic monomict dacite breccias. The latter are dominated by pyrite-sphalerite-galena, a diverse suite of Ag-Sb ± Pb ± As ± (Cu)-bearing sulfosalts, minor pyrrhotite, arsenopyrite, and rare chalcopyrite. The main sulfosalt suite is characterized by pyrargyrite, and Ag-rich varieties of boulangerite, tetrahedrite, and bournonite.
- Zones of sulfide mineralization are marked by significant mass gains in Fe, S, Zn, Pb, Sb, Ag, As, Cd, Ni, Cu, Ba, Co, Cr, Tl, Bi, and Au (in order of decreasing gains). Basaltic rocks show reduced mass gains in most elements, with zones of intense hydrothermal alteration/mineralization restricted to thick sequences of hyaloclastite, and near contacts with dacitic rocks.
- Broad zones of intense silica-sericite alteration surround mineralization in dacite, marked by high Alteration Index and CCPI values, strong Na-Ca depletion, an absence of feldspar (albite) in thermal infrared (TIR) hyperspectral data, and increases in quartz and white mica contents.
- In dacitic rocks, white mica ranges from muscovitic compositions in weakly altered sections of core and distal positions to mineralization, to increasingly paragonitic compositions that are associated with zones of increased sericitization and sulfide mineralization.
- Chlorite in dacitic rocks often occurs adjacent to zones of sulfide mineralization and is restricted to narrow intervals, possibly linked to higher temperature fluid pathways. Carbonate abundance is sporadic in dacite, but is most abundant outside the main

zones of Na-Ca depletion. Towards these halos, carbonate TIR spectra show a shift to lower wavelengths (from Ca-rich to more Mg-rich compositions).

- Basaltic rocks are characterized by strongly paragonitic white mica compositions, and abundant chlorite and carbonate. Shifts from Ca-carbonates and Fe-chlorites to more Mg-rich compositions of both minerals occur in basaltic hyaloclastite and near dacitic contacts.
- Hanging-wall polymict conglomerates are characterized by minor amounts of muscovitic to phengitic white mica, and an absence of chlorite or carbonate alteration.
- The identification of such geochemical and hyperspectral halos elsewhere along the margins of the Kurnalpi rift zone, in either the Kalgoorlie or Burtville terranes, would indicate the position of Nimbus-style mineralization. Similar styles of mineralization might also occur along the margins of the Cue zone in the Youanmi Terrane.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2075-163X/11/3/254/s1>, Table S1: whole rock geochemical data; Tables S2 and S3: mass change calculations for dacitic and basaltic rocks respectively.

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