WHOLE ROCK GEOCHEMISTRY AND MINERAL CHEMISTRY OF THE HANGINGWALL SEQUENCE, HELLYER DEPOSIT, TASMANIA

by

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Submitted in partial fulfillment of the requirements for the degree of Master of Economic Geology

University of Tasmania

Hobart

August, 1999
DECLARATION

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Russell Fulton
31st August, 1999.
ABSTRACT

Hellyer is a 17 Mt, high-grade, polymetallic VHMS-style deposit containing 13.0% Zn, 6.8% Pb, 0.3% Cu, 160 g/t Ag and 2.3 g/t Au (Gemmell and Large, 1992) located in western Tasmania’s Mt. Read Volcanics belt.

Analysis of the Hellyer core log database shows that there are five main types of alteration within the Hellyer basalt; (1) silica-albite, (2) fuchsite (± carbonate), (3) chlorite, (4) carbonate and (5) sericite, of which the first two are the most significant volumetrically. The pillow lava facies of the Hellyer hangingwall basalt has principally undergone fuchsite and chlorite dominant alteration, whereas the massive lava facies is typically affected by carbonate, silica-albite, or epidote dominant alteration. The breccia facies behaves similarly to the massive lava facies but sericite dominant alteration also occurs.

Three-dimensional computer modelling of the database indicates that silica-albite-dominant alteration is best developed on the flanks of the ore body and to the south and west. Fuchsite dominant alteration, is well developed vertically above the ore body. Carbonate dominant alteration is sparsely distributed about the ore body. Chlorite-dominant alteration is best developed above the ore body and more laterally than the fuchsite-dominant alteration. Sericite-dominant alteration occurs to the south of the ore body and laterally above the northern end of the orebody.

A lithogeochemical halo of Sb occurs within the basalt from immediately above the ore deposit to immediately beneath the overlying Que River Shale and provides an excellent vector to the Hellyer deposit. The halo spreads out beneath the Que River Shale for at least 400 metres west, and up to 900 metres north-east. Other geochemical parameters which show
are useful in defining the halo are Tl, As, Ba, Ba/Sr and Cs. The halo has been previously defined by apple green “fuchsite” alteration visible in hand specimen. The commodity elements Cu, Pb and Zn are rarely elevated within the Hellyer basalt.

The Ba content of white mica has been found to increase with proximity to the Hellyer deposit and this is the only mineral chemistry vector to the deposit identified. Although widely recorded in core logs and visible in hand specimen, fuchsite-altered rocks contain very little true fuchsite. Most white mica is chromian muscovite, with Cr$_2$O$_3$ less than 1%. Chlorites have been found to contain up to 2.44% Cr$_2$O$_3$. Barium-rich samples of basalt have been found to contain barium-rich feldspars with up to 5.58% BaO, similar to feldspars reported from the Hellyer footwall and the nearby Que River deposit.
Acknowledgments

I would like to thank my supervisors, Dr. Bruce Gemmell and Professor Ross Large for guidance and support.

I am grateful also for financial assistance provided through the AMIRA/ARC P439 budget.

At Aberfoyle’s Burnie office I am indebted to the help of Gary MacArthur, Steve Richardson, Richard De Bomford and Andrew MacNeil, whilst at Waratah and around the core shed Gary Cooper was most helpful. Aberfoyle Resources Ltd. also provided food and accommodation at Waratah.

I would like to thank all who helped me at CODES and in the Geology Department, in particular, Rick Varne for support stretching back over many years; Simon Stephens and his offsiders in lapidary; Phil Robinson, Nilah Hlang and Katie McGoldrick for help with sample preparation and the like; June Pongratz, Mike Blake and Wally Hermann for various things; Wislav Jablonski and David Steele for help with the Cameca; my fellow occupants of the room next to the big globe, especially Ali for doing some photocopying; and anyone else who lent a hand, knowingly or otherwise.

Finally, a special big thanks to Vanessa Lee for her support.
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And = unaltered andesite, SEZ = stringer envelope zone, Si = siliceous core, Se = sericite, Cl = chlorite, Co = carbonate (primarily dolomite).

From Gemmell and Large (1992).

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<tr>
<td>3.3</td>
<td>Percentage of different alteration types for each rock type.</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>Percentage of different rock types for each alteration type.</td>
<td>23</td>
</tr>
<tr>
<td>5.1</td>
<td>Range, average and standard deviation for MgCO₃ content of carbonates</td>
<td>297</td>
</tr>
<tr>
<td>5.2</td>
<td>Range, average and standard deviation for MnCO₃ content of carbonates</td>
<td>298</td>
</tr>
<tr>
<td>5.3</td>
<td>Range, average and standard deviation for FeCO₃ content of carbonates</td>
<td>298</td>
</tr>
</tbody>
</table>
3a Split core and thin section of *unaltered* sample of Hellyer basalt. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.

3b Split core and thin section of *silica-albite* altered sample of Hellyer basalt. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.

3c Split core and thin section of *fuchsite-carbonate* altered sample of Hellyer basalt. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.

3d Split core and thin section of *chlorite* altered sample of Hellyer basalt. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.

3e Split core and thin section of *carbonate* altered sample of Hellyer basalt. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.
CHAPTER 1

INTRODUCTION

Background

The research undertaken for this thesis formed part of the ore deposit case studies module of a major AMIRA/ARC project, P439, entitled "Studies of VHMS-related alteration: geochemical and mineralogical vectors to ore", which ended in May, 1998. Substantial amounts of the research undertaken by the author has appeared in the six-monthly reports to sponsors of P439 an/or been presented at sponsors meetings.

The Hellyer mine is located approximately 60 kilometres south of Burnie in an area of rugged terrain, clothed in dense rain forest, with patches of moorland, typical of western Tasmania. The surface workings are located on the western slopes of the Southwell river gorge and on the edge of the plateau above which undulates at 680 to 720 metres above sea level. The climate is cool temperate, with annual rainfall of around 2100 mm per annum (Jack, 1986), falling mainly in the winter months. Snow lies on the ground for a few days every year.

Hellyer is a 17 Mt, high-grade, polymetallic VHMS-style deposit containing 13.0% Zn, 6.8% Pb, 0.3% Cu, 160 g/t Ag and 2.3 g/t Au (Gemmell and Large, 1992). The mine is due to finish production in mid-2000. The deposit was discovered in 1983, initial drilling based on an electromagnetic (UTEM) anomaly, a soil lead anomaly, barite veining and bright chrome-green alteration in the hangingwall basalt. The deposit is three kilometres north of the 2.6 Mt, high grade, polymetallic Que River VHMS occurrence.
Aims

The aims of this study are to attempt to discriminate between the effects of Cambrian hydrothermal alteration associated with Hellyer mineralisation, Cambrian diagenetic alteration, and Devonian regional metamorphism within the hangingwall basalt; to map any hydrothermal alteration around the ore deposit; and to determine the character, extent and magnitude of any vectors to ore apparent within the hangingwall basalt.

Methods and Work Undertaken

Mapping of alteration within the hangingwall was done by accessing the Hellyer core log database at Aberfoyle's Burnie office and, with the help of Aberfoyle staff there, reducing the 365 different types of alteration assemblage recorded as occurring within the 96+ kilometres of Hellyer basalt logged to a manageable number. The reduced data was then plotted up at the University of Tasmania using Stanford Graphics software to produce 3-D models of the hangingwall alteration.

For geochemical purposes, a fence of holes stretching from 2 kilometres west of the deposit to 1.5 kilometres east of the deposit was chosen, with the help of Dr. Bruce Gemmell and the geology staff at Burnie, to be sampled during the study (Table 1). A hole 900 metres to the north-east which had recorded some intense fuchsite alteration was also sampled. Several trips were made to the Hellyer mine core shed, mostly in winter, core from all the holes was laid out and a 10 centimetre half core sample was cut at intervals of approximately ten metres down the hole, with samples taken at five metre intervals for the last 15-20 metres above the contact with the underlying Hangingwall Volcaniclastic Sequence.
Due to budgetary constraints, three of the holes proposed to be used in the study were sampled only, with no further work undertaken, and one hole was not sampled. In all a total of 158 samples were cut.

Blocks for thin sections were cut from each sample by the author at the University of Tasmania and submitted to the lapidary section for preparation of polished thin sections to be used for mineral chemistry analysis using the Cameca electron microprobe at the University of Tasmania. The probe was unavailable for considerable lengths of time during the project due to: microprobe breakdowns, changes to the operating system, staff changes, and budgetary considerations, so it was not possible to carry out all the probe work originally intended. All probing completed was carried out by the author.

After thin section blocks were removed, all samples were prepared for XRF analysis by the author, including jaw crushing, milling (tungsten-carbide ring mill), pill making, disc making and ignition losses. Samples were analysed at the University of Tasmania using XRF analysis (major elements, S, As, Ba, Bi, Ce, Cr, Cu, La, Nb, Nd, Ni, Pb, Rb, Sc, Sr, Th, V, Y, Zn, and Zr) and at Analabs in Perth using ICP-MS analysis (Ag, As, Bi, Cd, Cs, Mo, Sb, Th, Tl, and U) and LECO titration analysis (C). The ICP-MS analyses for As and Th were rejected in favour of XRF analyses due to inconsistencies in repeat and standard analyses.

PIMA spectra were acquired for all samples (using powders) at the University of Tasmania using a machine borrowed from the CSIRO.
Table 1. Holes sampled for study.

<table>
<thead>
<tr>
<th>Hole number</th>
<th>No. of samples</th>
<th>Interval (metres)</th>
<th>Sample numbers</th>
<th>Metres from ore position</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC 31</td>
<td>unaltered</td>
<td>11</td>
<td>99.7 - 169.0</td>
<td>628521 - 628531</td>
</tr>
<tr>
<td>MAC 10</td>
<td>unaltered</td>
<td>14</td>
<td>117.4 - 260.7</td>
<td>628426 - 628439</td>
</tr>
<tr>
<td>HL 541</td>
<td>unaltered</td>
<td>19</td>
<td>330.7 - 458.0, 559.0 - 585.7</td>
<td>628600, 628801 - 628818</td>
</tr>
<tr>
<td>HL 246</td>
<td>unaltered</td>
<td>6</td>
<td>189.8 - 269.6</td>
<td>628440 - 628445, 628854 - 628856</td>
</tr>
<tr>
<td>HL 20</td>
<td>altered</td>
<td>15</td>
<td>79.3 - 185.0</td>
<td>628446 - 628460</td>
</tr>
<tr>
<td>HL 51</td>
<td>altered</td>
<td>17</td>
<td>76.1 - 202.4</td>
<td>628461 - 628477</td>
</tr>
<tr>
<td>HL 12</td>
<td>altered</td>
<td>21</td>
<td>83.0 - 238.5</td>
<td>628478 - 628498</td>
</tr>
<tr>
<td>HL 5</td>
<td>altered</td>
<td>21</td>
<td>82.6 - 289.25</td>
<td>628500 - 628520, 628853</td>
</tr>
<tr>
<td>MAC 19</td>
<td>some alteration</td>
<td>19</td>
<td>465.4 - 792.4</td>
<td>628819 - 628837</td>
</tr>
<tr>
<td>HL 841B</td>
<td>altered</td>
<td>15</td>
<td>500.5 - 645.8</td>
<td>628838 - 628852</td>
</tr>
<tr>
<td>HL 14</td>
<td>unaltered</td>
<td>5</td>
<td>107.0 - 198.7</td>
<td>333971 - 333975</td>
</tr>
<tr>
<td>HL 28</td>
<td>altered</td>
<td>6</td>
<td>139.6 - 265.8</td>
<td>334195 - 334196, 334201 - 334202, 334205 - 334206</td>
</tr>
<tr>
<td>HL 46</td>
<td>altered</td>
<td>19</td>
<td>53.6 - 237.3</td>
<td>628532 - 628550</td>
</tr>
<tr>
<td>HL 47</td>
<td>altered</td>
<td>23</td>
<td>46.8 - 235.3</td>
<td>628551 - 628573</td>
</tr>
<tr>
<td>HL 49</td>
<td>not sampled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HL 31</td>
<td>altered</td>
<td>26</td>
<td>102.4 - 324.2</td>
<td>628574 - 628599</td>
</tr>
</tbody>
</table>
Previous Research

Although the Hellyer deposit has been extensively studied, little research has been done on alteration within the hangingwall basalt, most work concentrating on alteration within the footwall and the latter is summarised, with references, in Gemmell and Fulton (1998). Jack (1989) undertook some research on the hangingwall as part of a MSc. project and his findings were:

- There is a green hangingwall plume which extends upwards from the deposit to the contact with the overlying Que River Shale and extends laterally below that contact.
- The plume consists of pervasive calcite-fuchsite, accessory Fe-chlorite patches, calcite veining and increased quantities of interpillow pyrite.
- Albite alteration extends out from the plume,
- Associated with hangingwall calcite-fuchsite alteration is major mass addition of S (2-4 times background S), CaO (2 times background CaO, K2O, Al2O3, Ba and depletion of Fe2O3, MgO, SiO2, with relative enrichment in As, Rb, and Mn.

Immobile elements include Zr, Ti, Y, Nb and rare-earth elements.

- Above the Hellyer hydrothermal feeder system, and possibly extruded along the same conduit, there exists a more primitive “core” lava characterised by higher Ti/Zr of ~53, higher MgO, Ni and Cr and lower SiO2, TiO2, P2O5, Y, Zr, La and Nb than the surrounding basalt.
Thesis Outline

An outline of the regional geological setting, followed by a more detailed description of the local geology is presented in Chapter 2. Chapter 3 deals with mapping of alteration within the hangingwall basalt based on core logged by Aberfoyle geologists. Chapter 4 describes the whole rock geochemistry of the hangingwall basalt and the geochemical signature of hydrothermal alteration associated with the Hellyer mineralising event. Chapter 5 presents findings in relation to mineral chemistry of the hangingwall basalt and changes in mineral chemistry associated with hydrothermal alteration for carbonates, micas, chlorites and feldspars. PIMA spectra taken from hangingwall samples are presented and analysed in Chapter 6, whilst in Chapter 7 a discussion of the extent, magnitude and vector possibilities of hydrothermal alteration and comparison with diagenetic alteration and regional metamorphic effects concludes the thesis.
CHAPTER 2
GEOLOGY

Regional Geology

The Mount Read Volcanics (MRV) are of Cambrian age and form an arcuate volcanic belt approximately 220 km long and 5-15 km wide wrapping around the western and northern margin of a block of Precambrian metamorphics, the Tyennan block (Figure 2.1). The MRV lie along the eastern margin of the Dundas Trough which is bounded to the west by another Precambrian block (Rocky Cape). The Dundas trough is occupied by quartz sandstones and mudstones of the Late Precambrian - Early Cambrian Success Creek Group (Everard et al., 1992), which are conformably overlain by volcaniclastics and intercalated basalts of the Crimson Creek Formation (Brown, 1986). Several allochthonous mafic-ultramafic complexes have been emplaced into and on to the Crimson Creek Formation during the Early or Middle Cambrian (Berry and Crawford, 1988). The MRV are considered to be younger than all these rocks. The MRV are a sequence of deformed, regionally metamorphosed (lower greenschist facies), largely submarine volcanics of Middle Cambrian age which have been moderately to highly altered in many areas.

The MRV has been divided into four main lithostratigraphic units (Corbett, 1992): the Central Volcanic Complex, the Eastern quartz-phyric sequence, the Western volcano-sedimentary sequences, and the Tyndall Group (Figure 2.2a).

The feldspar-phyric rhyolitic lavas and very thick, pumiceous volcaniclastic units of the Central Volcanic Complex interfinger with the quartz and feldspar-bearing lavas, intrusions and volcaniclastic units of the Eastern quartz-phyric sequence. These both
Figure 2.1 Regional geology of the Mount Read Volcanics. From Corbett, 1992 and Crawford et al., 1992.
interfinger with the Western volcano-sedimentary sequences of well-bedded, volcaniclastic and Precambrian basement-derived sandstone and conglomerates. Major base metal mineralisation occurs in units within the Central Volcanic Sequence, including Rosebery, Hercules and Mt. Lyell and is considered to have occurred during a short period of extensional tectonics in the middle Middle Cambrian with ore deposits occurring near the top of massive volcanic successions (Berry and Keele, 1996). The Que-Hellyer Volcanics (Komyshan, 1986), which host the Hellyer mineralisation, form the lower part of the Mt. Charter Group (Corbett, 1992), previously referred to as “Dundas Group correlates” and are now considered to be lateral equivalents of the Central Volcanic Sequence, thus placing the Hellyer and Que River mineralisation in a similar stratigraphic position to the other major base metal deposits (Pemberton and Corbett, 1992).

Cambrian granites intrude the Central Volcanic Complex and the Eastern quartzphyric sequence.

Above these are the widespread crystal- and pumice-rich mass-flow deposits of the Tyndall Group, which occur south and east of the Henty fault, and in the Rosebery - Hellyer area, the volcanioclastics, sediments and minor felsic lavas of the Southwell Subgroup, and above that, the Mt Cripps Subgroup, a correlate of the Tyndall Group.

A Late Cambrian unconformity marks the upper boundary of the MRV, above which lies the Owen Conglomerate, a thick unit of siliciclastic conglomerates and sandstones. Major deformations with regional greenschist facies metamorphism and granite intrusion occurred in the Devonian.

In the northern part of the MRV, north of Hellyer, widespread Tertiary volcanism has extensively covered the MRV.
### Figure 2.2a
Diagrammatic section showing relationships of major rock associations and stratigraphic units in the Mt. Read Volcanics. AND = andesites, BAS = basalt, C = Comstock, CK = creek, DG = Darwin Granite, H = Hellyer, Hertty, MG = Murchison Granite, ML = Mt. Lyell, PC = Precambrian, Tyennan region, QR = Que River, QRS = Que River Shale, QTZ = quartz, SEQ = sequence, THOL = tholeiite. From Crawford et al., 1992.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Average Thickness (m)</th>
<th>Schematic Section</th>
<th>Major Lithologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwell Sub-Group</td>
<td></td>
<td>NNE</td>
<td>Crystal rich volcaniclastic, shales, greywacke, minor teosic lava</td>
</tr>
<tr>
<td>Que River Shale</td>
<td>100</td>
<td>SSW</td>
<td>Black shales, minor sandstone</td>
</tr>
<tr>
<td>Hellyer Basalt</td>
<td>220</td>
<td></td>
<td>Massive to pillowed basalt, pillow breccia, hyaloclastics, Andesite lava</td>
</tr>
<tr>
<td>Mixed Sequence</td>
<td>10-100</td>
<td></td>
<td>Polymict mass flows massive / autobrecciated dacite, massive sulphide mineralisation</td>
</tr>
<tr>
<td>Lower Andesites and Basalts</td>
<td>500</td>
<td></td>
<td>Andesite + dacite + basalt lavas, hyaloclastics, minor volcaniclastics</td>
</tr>
<tr>
<td>Lower Basalt</td>
<td>100</td>
<td></td>
<td>Massive to pillowed basalt, hyaloclastics, pillow breccia</td>
</tr>
<tr>
<td>Animal Creek Greywacke</td>
<td></td>
<td></td>
<td>Micaceous Greywacke</td>
</tr>
</tbody>
</table>

### Figure 2.2b
Footwall Alteration Zone
Projected to Surface

Footwall Qebbody
Projected to Surface

Figure 2.3a  Surface geology of the Hellyer district and location of drill holes used in this study. From Gemmell and Pittion 1998.
Figure 2.3b  Schematic cross-section of Hellyer sea floor environment at time of deposition of Hellyer deposit, A-A' in Figure 3a. From Gemmell and Fulton, 1998.
Local Geology

Stratigraphy

As noted in the preceding section, the Que Hellyer Volcanics which host the Hellyer and Que River mineralisation, form the lower part of the Mt. Charter Group (Figure 2.2b). The mine surface geology and projections to surface of the ore body and footwall alteration zone are presented in Figure 2.3a and a cross-section in Figure 2.3b.

The Que-Hellyer Volcanics are a suite of mafic to felsic lavas and volcaniclastics which occur in a belt of some 20 kilometres length and 5 kilometres width, stretching northwards from a little south of Mt. Charter, and having a thickness of approximately 1 kilometre. The volcanics are covered by younger Cambrian rocks and Tertiary volcanics to the north, cropping out only in the area around the Hellyer and Que River deposits. The Que-Hellyer Volcanics lie above a micaceous greywacke unit of approximately 300 metres thickness, the Animal Creek Greywacke, and are overlain by, and near the contact, intercalated with the 100± metre thick Que River Shale - a black carbonaceous, pyritic shale unit. The Que River Shale is overlain by the crystal-rich volcaniclastics, sediments and minor felsic lavas of the Southwell Subgroup, approximately 1000 metre thick, and above this the volcaniclastics and sediments of the Mt. Cripps Subgroup, a correlate of the Tyndall Group.

Lower Basalt

The Lower Basalt is the basal unit of the Que-Hellyer Volcanics and conformably overlies, and interfingers with, the Animal Creek Greywacke. The Lower Basalt has a patchy
distribution and variable thickness, reaching a maximum of 100 metres in the area around
the Que River mine. The unit consists of porphyritic basaltic lavas, hyaloclastites and minor
volcaniclastics (Jack, 1989; Gemmell and Fulton 1998).

Lower Andesites and Basalts

This unit consists of 300 to 600 metres of auto-brecciated andesitic lavas, polymict
volcaniclastics lavas, coherent andesitic lavas and minor basaltic and rhyolitic lavas and
sediments.

In the Que-Hellyer area, andesite lavas and breccias are dominant to the east, a mixture of
andesitic lavas and breccias with rhyolitic lavas/ intrusives and minor shales and sandstones
occur to the west, whilst debris flow epiclastics and dacitic lavas/ intrusives with minor
andesitic and basaltic lavas and breccias occur to the south (Gemmell and Fulton, 1998).

Mixed Sequence (Hangingwall Volcaniclastic Sequence)

The Mixed Sequence or Hangingwall Volcaniclastic Sequence (HVS) is comprised
of a wide variety of lithologies including polymict volcaniclastic breccias, which include
fragments of massive sulphide and barite mineralisation, volcaniclastic sandstones, dacitic
lava and autobrecciated to quench fragmented and resedimented autobreccias of dacitic
composition, and minor shales. Waters and Wallace, 1992 divided the Mixed Sequence into
two subunits, the mixed sequence volcaniclastics and the mixed sequence dacites. The
volcaniclastics are best developed near mineralisation whilst away from mineralisation, the
mixed sequence dacites, which occur towards the top of the mixed sequence, are more
important. The HVS reaches a maximum thickness of 100 to 150 metres immediately adjacent to mineralisation and thins rapidly laterally to about 10 metres.

Hellyer Basalt (Pillow Lava Sequence)

The hangingwall basalt is the uppermost of four informal sub-units which make up the Que-Hellyer Volcanics (Corbett, 1992). The hangingwall basalt or Hellyer basalt (pillow lava sequence or PLS in mine terminology) has been subdivided into three major primary volcanic facies which grade into each other both vertically and laterally (Waters and Wallace, 1992). Laterally, the sequence shows complex variation and in some areas consists of andesitic lavas (Corbett and Komyshan, 1989; Waters and Wallace, 1992).

Massive basaltic lava facies:

This facies consists of massive, sheet-like flows of up to tens of metres thickness with minor sediment or lava breccias occurring between individual flow units. The basalts are mostly porphyritic and non-vesicular to weakly vesicular (5-10%). Mineralogically, the least altered of the basalts, away from the ore body, are composed of phenocrysts or glomerocrysts of augite (15-20%), plagioclase (up to 15%), and a chlorite ± calcite pseudomorph after olivine (Crawford et al., 1992). The ground mass consists of feldspar microlites, distinctive reddish-brown chromite and opaques. The massive basaltic lava facies becomes increasingly predominant to the south of 10400mN (mine grid).
Figure 2.4a  Schematic cross section of the Hellyer deposit. From Gemmell and Large, 1993.

Figure 2.4b  Schematic reconstruction of the local depositional environment for mineralisation in the Que-Hellyer Volcanics - (a) Que River (b) Hellyer. From Waters and Wallace, 1992.
Pillow lava facies:

Volumetrically, this facies is the most dominant within the hangingwall basalt. This facies consists of pillow lavas with interpillow mud- to silt-sized sediments and hyaloclastic breccias. Pillows vary in cross-sectional width from 0.25 to 2m and commonly have chilled rims. Vesicularity of the pillows increase from approximately 2% at the cores to approximately 10% at the rims, although a few rims have considerably higher vesicularity. Vesicles range in size from 2 to 5 mm at the cores, to 30 to 50 mm at the rims and are filled with chlorite, chlorite-carbonate or quartz. The interpillow hyaloclastites are fine grained and interpreted to have been derived from the margins of pillows, whilst the sediments, which can contain up to 20% authigenic (?) pyrite, are considered to be an indication of extrusion of the lavas into black shales, similar to the overlying Que River Shale. Near the contact with the Que River Shale, a characteristic peperitic texture has developed within the Hellyer basalt. The pillow lava facies becomes more predominant to the north of 10400mN.

Brecciated basaltic lava facies:

This facies consists of poorly sorted, angular fragments: porphyritic fragments of the first two basalt facies ranging in size from a few millimetres up to tens of centimetres, and aphyric, totally chloritised fragments of what are interpreted to have been chilled, juvenile, glassy fragments ranging in size from 4 cm to 6 cm. Vesicularity ranges from 0 to 20% in both fragment types. The breccias range from closed framework jigsaw-fit to open framework, with up to 50% mud matrix, and are considered to be the product of quench fragmentation. This facies occurs throughout the Hellyer basalt and represents 10 to 15% of the unit.
Andesitic lava facies:

As well as the abovementioned three facies, some portions of the hangingwall are predominantly andesitic lavas, although volumetrically very small overall. These lavas consist of plagioclase phenocrysts and glomerocrysts (10 to 15%), altered totally to albite ± carbonate, and a feldspar/glass groundmass extensively altered to chlorite, sericite, silica and carbonate.

Deformation and Metamorphism

Folding under east-west compression during the Devonian Tabberabberan Orogeny has produced open anticlines and tight, locally isoclinal synclines within the orebody (Drown and Downs, 1990), however there is little deformation or metamorphism, including recrystallisation, compared to the Que River massive sulphide deposit 3 kilometres to the south. Locally, strain has been taken up within the phyllosilicate-rich altered footwall rocks and within the galena-sphalerite rich part of the orebody. Strain partitioning into the hangingwall basalt is much less evident.

The deposit is transected by a major post-mineralisation and post-folding north-south sub-vertical sinistral wrench fault, the Jack fault, with movement of east block 130 metres north and 30 metres vertically.

In the Que-Hellyer of the MRV, regional metamorphism associated with Devonian deformation has reached prehnite-pumpellyite facies, compared with the MRV to the south where the grade has reached greenschist facies at Mt. Lyell (Walshe and Solomon, 1981) and Rosebery/Hercules (Jack, 1989).
The effects of metamorphism have been expressed within the footwall andesites at Hellyer by the formation of epidote, pumpellyite and prehnite, but only rarely are these minerals seen within the Hellyer basalt.

Mineralisation

The Hellyer deposit is a massive sulphide mound measuring 800 metres north-south, 200 metres east-west, and with an average thickness of 45 metres. A schematic cross-section through the deposit and reconstruction of the local depositional environment is presented in Figure 2.4. The deposit is well described by Jack, 1989. A small zone of silica-pyrite occurs above the centre of the deposit and surrounding this is a 10-15 metre thick barite cap. A zonation exists within the deposit with higher Cu-Fe in the hotter core and lower portion of the deposit, with the cooler outer and higher part of the deposit being elevated in Pb, Zn, Ag, As, an Au. Mineralisation averages 54% pyrite, 20% sphalerite, 8% galena, 2% arsenopyrite, 1% chalcopyrite and trace tetrahedrite, boulangerite, bouronite, and tennantite. Gangue mineralogy is dominantly calcite and quartz, with lesser barite and some ankerite and apatite.
CHAPTER 3
ALTERATION MAPPING

Alteration types from company drill core logging

The Aberfoyle Hellyer database was accessed with the help of Aberfoyle staff at the Burnie office. In total, 95,281 metres of hangingwall basalt (Aberfoyle terminology: PLS or pillow lava sequence) had been logged at the time of this study. The Aberfoyle Hellyer core logging system allows for up to four alteration types to be allocated for each core log entry, and this has led to a total of 365 different combinations of alteration assemblage appearing in the database. An entry of “CISeCOFu” indicates recognition of chlorite + sericite + carbonate + fuchsite alteration with the most dominant type appearing first and the least dominant type appearing last, whilst an entry of “Fu” would indicate recognition of fuchsite alteration alone. Intensity of alteration is indicated by a single digit form 0 to 5, 0 being unaltered and 5 intensely altered. As 365 different alteration types is too many to work with, they have been amalgamated to form 13 different types (Table 3.1), based on frequency of occurrence and on importance as determined by the experience of Aberfoyle’s senior geology staff at Burnie.

Tables 3.2 to 3.4 shows the total metres of each alteration type recorded against the 6 basalt rock types (reduced from 12) in the Hellyer database with the percentage or rock type for each alteration type in brackets, and the percentage of each alteration type recorded for each rock type.
Table 3.1. Hellyer alteration assemblages

<table>
<thead>
<tr>
<th>Type</th>
<th>Alteration assemblage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fu, FuCO, FuCO+, COFu, COFu+</td>
</tr>
<tr>
<td>2</td>
<td>FuSe, FuSe+, SeFu, SeFu+</td>
</tr>
<tr>
<td>3</td>
<td>Cl, FuCl, FuCl+, ClPy, ClPy+</td>
</tr>
<tr>
<td>4</td>
<td>ClSe, ClSe+, SeCl, SeCl+</td>
</tr>
<tr>
<td>5</td>
<td>Se</td>
</tr>
<tr>
<td>6</td>
<td>SeCO, SeCO+, COSe, COSe+</td>
</tr>
<tr>
<td>7</td>
<td>CO, COCl, COCl+, COSi, COSi+, ClCO, ClCO+</td>
</tr>
<tr>
<td>8</td>
<td>Si, SiAb, SiAb+(not Cl), AbSi, AbSi+(not Cl)</td>
</tr>
<tr>
<td>9</td>
<td>Ab, Ab+(not Si, Fu)</td>
</tr>
<tr>
<td>10</td>
<td>AbSiCl, ClAb, ClAb+, ClSi, ClSi+, SiAbCl+</td>
</tr>
<tr>
<td>11</td>
<td>FuAb, FuAb+, AbFu, AbFuCl</td>
</tr>
<tr>
<td>12</td>
<td>Si+(not Ab, Ep)</td>
</tr>
<tr>
<td>13</td>
<td>Ep, Ep+, SiEp, SiEp+</td>
</tr>
</tbody>
</table>

Explanatory note:
Al = albite, Cl = chlorite, CO = carbonate, Ep = epidote, Fu = fuchsite, Py = pyrite, Se = sericite, Si = silica. FuCO = fuchsite + carbonate alteration, FuCO+ = fuchsite + carbonate alteration + one or two other alteration types e.g. FuCOSeCl, AbSi+(not Cl) = albite + silica + one or two other alteration types but not AbSiCl or AbSiClFu etc

In order to ascertain the distribution of each alteration type within different rock types, and to determine whether any alteration assemblage is occurring preferentially within a certain rock type, the overall fraction of each alteration type has been divided by the actual logged fraction of alteration for each rock type and the results presented in Figures 3.1 to 3.13. Looking at the three clearly defined facies, pillow lava, massive lava and breccia, and using an arbitrary figure of ±20% the following observations can be made.

The pillow lava facies is preferentially altered with respect to alteration assemblages:

Fu, FuCO, FuCO+, COFu, COFu+

Cl, FuCl, FuCl+, ClPy, ClPy+
<table>
<thead>
<tr>
<th>Alteration Code</th>
<th>breccia</th>
<th>lava</th>
<th>pillow lava</th>
<th>lava + breccia</th>
<th>lava + pillow</th>
<th>pillow + breccia</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fu, FuCO, COFu</td>
<td>3353</td>
<td>3484</td>
<td>2670</td>
<td>131</td>
<td>1460</td>
<td>793</td>
<td>29891</td>
</tr>
<tr>
<td>SiAb, AbSi, Si</td>
<td>3620</td>
<td>4211</td>
<td>12568</td>
<td>1351</td>
<td>2990</td>
<td>673</td>
<td>25412</td>
</tr>
<tr>
<td>SiAbCl, SiCl, AbCl</td>
<td>1690</td>
<td>1523</td>
<td>1124</td>
<td>1764</td>
<td>308</td>
<td>623</td>
<td>7032</td>
</tr>
<tr>
<td>Cl, ClFu, ClPy</td>
<td>373</td>
<td>532</td>
<td>4930</td>
<td>261</td>
<td>7</td>
<td>376</td>
<td>6479</td>
</tr>
<tr>
<td>FuSe, SeFu</td>
<td>849</td>
<td>835</td>
<td>3733</td>
<td>87</td>
<td>438</td>
<td>379</td>
<td>6321</td>
</tr>
<tr>
<td>CO, COCl, COSi</td>
<td>939</td>
<td>1199</td>
<td>1587</td>
<td>473</td>
<td>9</td>
<td>517</td>
<td>4773</td>
</tr>
<tr>
<td>Si (not +Ab, +Ep)</td>
<td>918</td>
<td>683</td>
<td>1201</td>
<td>233</td>
<td>98</td>
<td>104</td>
<td>3236</td>
</tr>
<tr>
<td>AbFu, AbFuCl, FuAb</td>
<td>11</td>
<td>115</td>
<td>2643</td>
<td>7</td>
<td>308</td>
<td>56</td>
<td>3139</td>
</tr>
<tr>
<td>Se</td>
<td>263</td>
<td>431</td>
<td>1880</td>
<td>20</td>
<td>159</td>
<td>117</td>
<td>2970</td>
</tr>
<tr>
<td>SeCO, COSe</td>
<td>786</td>
<td>310</td>
<td>663</td>
<td>164</td>
<td>165</td>
<td>203</td>
<td>2291</td>
</tr>
<tr>
<td>ClSe, SeCl</td>
<td>465</td>
<td>327</td>
<td>928</td>
<td>103</td>
<td>115</td>
<td>113</td>
<td>2051</td>
</tr>
<tr>
<td>Ep, SiEp</td>
<td>239</td>
<td>662</td>
<td>182</td>
<td>104</td>
<td>56</td>
<td>8</td>
<td>1251</td>
</tr>
<tr>
<td>Ab (not +Si, +Fu)</td>
<td>66</td>
<td>82</td>
<td>187</td>
<td>7</td>
<td>33</td>
<td>33</td>
<td>438</td>
</tr>
<tr>
<td><strong>Total (metres)</strong></td>
<td>13669</td>
<td>14364</td>
<td>52294</td>
<td>4766</td>
<td>6194</td>
<td>3995</td>
<td>95281</td>
</tr>
</tbody>
</table>

Table 3.2 Metres of alteration type by rock type.

<table>
<thead>
<tr>
<th>Alteration Code</th>
<th>breccia</th>
<th>massive lava</th>
<th>pillow lava</th>
<th>lava + breccia</th>
<th>lava + pillow</th>
<th>pillow + breccia</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fu, FuCO, COFu (56)</td>
<td>24.5%</td>
<td>24.3%</td>
<td>39.5%</td>
<td>2.7%</td>
<td>23.6%</td>
<td>19.9%</td>
<td>31.4%</td>
</tr>
<tr>
<td>SiAb, AbSi, Si (28)</td>
<td>26.5%</td>
<td>29.3%</td>
<td>24.0%</td>
<td>28.3%</td>
<td>48.3%</td>
<td>16.8%</td>
<td>34.7%</td>
</tr>
<tr>
<td>SiAbCl, SiCl, AbCl (36)</td>
<td>12.4%</td>
<td>10.6%</td>
<td>2.1%</td>
<td>37.0%</td>
<td>5.0%</td>
<td>15.6%</td>
<td>7.4%</td>
</tr>
<tr>
<td>Cl, ClFu, ClPy (47)</td>
<td>2.7%</td>
<td>3.7%</td>
<td>9.4%</td>
<td>5.5%</td>
<td>0.1%</td>
<td>9.4%</td>
<td>6.8%</td>
</tr>
<tr>
<td>FuSe, SeFu (54)</td>
<td>6.2%</td>
<td>5.8%</td>
<td>7.1%</td>
<td>1.8%</td>
<td>7.1%</td>
<td>9.5%</td>
<td>6.6%</td>
</tr>
<tr>
<td>CO, COCl, COSi (31)</td>
<td>6.9%</td>
<td>8.1%</td>
<td>3.0%</td>
<td>9.9%</td>
<td>1.5%</td>
<td>12.9%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Si (not +Ab, +Ep) (4)</td>
<td>6.7%</td>
<td>4.8%</td>
<td>2.3%</td>
<td>4.9%</td>
<td>1.6%</td>
<td>2.6%</td>
<td>3.4%</td>
</tr>
<tr>
<td>AbFu, AbFuCl, FuAb (13)</td>
<td>0.1%</td>
<td>6.8%</td>
<td>5.1%</td>
<td>0.1%</td>
<td>5.0%</td>
<td>1.4%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Se (49)</td>
<td>2.7%</td>
<td>3.0%</td>
<td>3.6%</td>
<td>0.4%</td>
<td>2.6%</td>
<td>2.9%</td>
<td>3.1%</td>
</tr>
<tr>
<td>SeCO, COSe (50)</td>
<td>5.8%</td>
<td>2.2%</td>
<td>1.3%</td>
<td>3.4%</td>
<td>2.7%</td>
<td>5.1%</td>
<td>2.4%</td>
</tr>
<tr>
<td>ClSe, SeCl (51)</td>
<td>3.4%</td>
<td>2.3%</td>
<td>1.8%</td>
<td>2.2%</td>
<td>1.9%</td>
<td>2.8%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Ep, SiEp (8)</td>
<td>1.7%</td>
<td>4.6%</td>
<td>0.3%</td>
<td>2.2%</td>
<td>0.9%</td>
<td>0.2%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Ab (not +Si, +Fu) (29)</td>
<td>0.5%</td>
<td>0.6%</td>
<td>0.4%</td>
<td>1.5%</td>
<td>-</td>
<td>0.8%</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 3.3 Percentage of different alteration types for each rock type.
<table>
<thead>
<tr>
<th>Alteration Code</th>
<th>breccia</th>
<th>massive lava</th>
<th>pillow lava</th>
<th>lava + breccia</th>
<th>lava / pillow</th>
<th>pillow + breccia</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fu, FuCO, COFu (56)</td>
<td>11.2%</td>
<td>11.7%</td>
<td>69.2%</td>
<td>0.4%</td>
<td>4.9%</td>
<td>2.7%</td>
<td>100%</td>
</tr>
<tr>
<td>SiAb, AbSi, Si (28)</td>
<td>14.2%</td>
<td>16.6%</td>
<td>49.5%</td>
<td>5.3%</td>
<td>5.3%</td>
<td>6.9%</td>
<td>100%</td>
</tr>
<tr>
<td>SiAbCl, SiCl, AbCl (36)</td>
<td>24.0%</td>
<td>21.7%</td>
<td>16.0%</td>
<td>25.1%</td>
<td>11.8%</td>
<td>2.6%</td>
<td>100%</td>
</tr>
<tr>
<td>Cl, ClFu, ClPy (47)</td>
<td>5.7%</td>
<td>8.2%</td>
<td>76.1%</td>
<td>4.0%</td>
<td>0.1%</td>
<td>5.8%</td>
<td>100%</td>
</tr>
<tr>
<td>FuSe, SeFu (54)</td>
<td>13.4%</td>
<td>13.2%</td>
<td>59.1%</td>
<td>1.4%</td>
<td>6.9%</td>
<td>6.0%</td>
<td>100%</td>
</tr>
<tr>
<td>CO, COCl, COSi (31)</td>
<td>19.7%</td>
<td>24.5%</td>
<td>33.2%</td>
<td>9.9%</td>
<td>1.9%</td>
<td>10.8%</td>
<td>100%</td>
</tr>
<tr>
<td>Si (not +Ab, +Ep) (4)</td>
<td>28.4%</td>
<td>21.1%</td>
<td>37.1%</td>
<td>7.2%</td>
<td>3.0%</td>
<td>3.2%</td>
<td>100%</td>
</tr>
<tr>
<td>AbFu, AbFuCl, FuAb (13)</td>
<td>0.4%</td>
<td>3.7%</td>
<td>84.2%</td>
<td>0.2%</td>
<td>9.8%</td>
<td>1.8%</td>
<td>100%</td>
</tr>
<tr>
<td>Se (49)</td>
<td>12.2%</td>
<td>14.5%</td>
<td>63.3%</td>
<td>0.7%</td>
<td>5.4%</td>
<td>3.9%</td>
<td>100%</td>
</tr>
<tr>
<td>SeCO, COSe (50)</td>
<td>34.3%</td>
<td>13.5%</td>
<td>29.0%</td>
<td>7.2%</td>
<td>7.2%</td>
<td>8.9%</td>
<td>100%</td>
</tr>
<tr>
<td>ClSe, ClCl (51)</td>
<td>22.7%</td>
<td>15.9%</td>
<td>45.3%</td>
<td>5.0%</td>
<td>5.6%</td>
<td>5.5%</td>
<td>100%</td>
</tr>
<tr>
<td>Ep, SiEp (8)</td>
<td>19.1%</td>
<td>53.0%</td>
<td>14.5%</td>
<td>8.3%</td>
<td>4.5%</td>
<td>0.7%</td>
<td>100%</td>
</tr>
<tr>
<td>Ab (not +Si, + Fu) (29)</td>
<td>15.1%</td>
<td>18.8%</td>
<td>42.6%</td>
<td>15.9%</td>
<td>-</td>
<td>7.6%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>14.3%</strong></td>
<td><strong>15.1%</strong></td>
<td><strong>54.9%</strong></td>
<td><strong>5.0%</strong></td>
<td><strong>6.5%</strong></td>
<td><strong>4.2%</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Table 3.4 Percentage of different rock types for each alteration type.
FuAb, FuAb+, AbFu, AbFuCl

and is under-represented with respect to alteration assemblages:

CO, COCl, COCl+, COSi, COSi+, CICO, CICO+
Si, SiAb, SiAb+(not Cl), AbSi, AbSi+(not Cl)
SeCO, SeCO+, COSe, COSe+
Si+(not Ab, Ep)
Ep, Ep+, SiEp, SiEp+

The massive lava facies is preferentially altered with respect to alteration assemblages:

CO, COCl, COCl+, COSi, COSi+, CICO, CICO+
Ab, Ab+(not Si, Fu)
AbSiCl, ClAb, ClAb+, ClSi, ClSi+, SiAbCl, SiAbCl+
Si+(not Ab, Ep)
Ep, Ep+, SiEp, SiEp+

and is under-represented with respect to assemblages:

Fu, FuCO, FuCO+, COFu, COFu+
Cl, FuCl, FuCl+, ClPy, ClPy+
FuAb, FuAb+, AbFu, AbFuCl

The breccia lava facies is preferentially altered with respect to alteration assemblages:

ClSe, ClSe+, SeCl, SeCl+
CO, COCl, COCl+, COSi, COSi+, CICO, CICO+
AbSiCl, ClAb, ClAb+, ClSi, ClSi+, SiAbCl, SiAbCl+
SeCO, SeCO+, COSe, COSe+

Si+(not Ab, Ep)

Ep, Ep+, SiEp, SiEp+

and is under-represented with respect to alteration assemblages:

Fu, FuCO, FuCO+, COFu, COFu+

Cl, FuCl, FuCl+, ClPy, ClPy+

FuAb, FuAb+, AbFu, AbFuCl

In summary, visual logging indicates that the pillow lava facies is more amenable to Fu+ and Cl+ alteration, whilst the massive lava facies is more likely to be affected by CO+, Si/Ab+ and Ep+ alteration. The breccia facies appears to behave similarly to the massive lava facies with the addition of Se+ alteration.
Figure 3.1 Percentage variation from expected metres of alteration type Fu, FuCO, FuCO+, COFu, COFu+ for each rock type.

Figure 3.2 Percentage variation from expected metres of alteration type FuSe, FuSe+, SeFu, SeFu+ for each rock type.
Figure 3.3 Percentage variation from expected metres of alteration type Cl, FuCl, FuCl+, ClPy, ClPy+ for each rock type.

Figure 3.4 Percentage variation from expected metres of alteration type ClSe, ClSe+, SeCl, SeCl+ for each rock type.
CO, COCl, COCl+, COSi, COSi+, ClCO, ClCO+ (Total metres - 4773)

breccia
massive lava
pillow lava
lava + breccia
lava/pillow lava
pillow lava + breccia

Figure 3.5 Percentage variation from expected metres of alteration type CO, COCl, COCl+, COSi, COSi+, ClCO, ClCO+ for each rock type.

AbSi, AbSi+(not Cl), Si, SiAb, SiAb+(not Cl) (Total metres - 25412)

breccia
massive lava
pillow lava
lava + breccia
lava/pillow lava
pillow lava + breccia

Figure 3.6 Percentage variation from expected metres of alteration type AbSi, AbSi+(not Cl), Si, SiAb, SiAb+(not Cl) for each rock type.
Figure 3.7 Percentage variation from expected metres of alteration type Ab, Ab+(not Si, Fu) for each rock type.

Figure 3.8 Percentage variation from expected metres of alteration type AbSiCl, ClAb, ClAb+, ClSi, ClSi+, SiAbCl, SiAbCl+ for each rock type.
Se (Total metres - 2970)

- breccia
- massive lava
- pillow lava
- lavas + breccia
- lava/pillow lava
- pillow lava + breccia

Percent variation

Figure 3.9 Percentage variation from expected metres of alteration type Se for each rock type.

SeCO, SeCO+, COSe, COSe+ (Total metres - 2291)

- breccia
- massive lava
- pillow lava
- lavas + breccia
- lava/pillow lava
- pillow lava + breccia

Percent variation

Figure 3.10 Percentage variation from expected metres of alteration type SeCO, SeCO+, COSe, COSe+ for each rock type.
AbFu, AbFuCl, FuAb, FuAb+ (Total metres - 3139)

breccia
massive lava
pillow lava
lavas + breccia
lava/pillow lava
pillow lava + breccia

Percent variation

Figure 3.11 Percentage variation from expected metres of alteration type AbFu, AbFuCl, FuAb, FuAb+ for each rock type.

Si+(not Ab, Ep) (Total metres - 3236)

breccia
massive lava
pillow lava
lavas + breccia
lava/pillow lava
pillow lava + breccia

Percent variation

Figure 3.12 Percentage variation from expected metres of alteration type Si+(not Ab, Ep) for each rock type.
Figure 3.13 Percentage variation from expected metres of alteration type Ep, Ep+, SiEp, SiEp+ for each rock type.

Ep, Ep+, SiEp, SiEp+ (Total metres - 1251)
3-D mapping of hangingwall alteration

In order to produce a map of the hangingwall alteration at Hellyer, Datamine software was used (with the help of staff at the Burnie office) to generate twenty eight east-west cross-sections for the length of the ore body from 10150N to 11000N, using the Hellyer core log database. The cross-sections contain drill hole traces which have been annotated with lithological information and coloured according to the 13 amalgamated alteration assemblages. Initially, alteration of all intensities from 1 to 5 was plotted, however this proved somewhat cumbersome to work with on sections which contained a lot of holes, so the sections were replotted for alteration intensities of 3 to 5 which it was felt would be more likely to represent hydrothermal alteration and eliminate spurious data, and also make the sections less cluttered.

To create a three-dimensional map of the hangingwall alteration each section was divided into 25m² squares and the dominant alteration type within each square was recorded. Using Stanford Graphics software, each 25m² was made the centre of a 25m³ block and all data was plotted to shown the alteration and ore body from different orientations (Figures 3.15 - 3.17). The ore body was also plotted up without alteration (Figure 3.14) and the displacement by the Jack fault is well defined. It was found that using 13 different alteration types produced a model which was difficult to visualise, so the 13 alteration assemblages were further reduced to 5 assemblages:

- Si, SiAb, SiAbC
- FuCO, Fu
- CO, COSi, COSe
- ClSe, Cl, ClFu
Se, FuSe

In order to examine the distribution of each of the five alteration assemblages, they have been plotted up individually in Figures 10a-e. From these plots it can be seen that fuchsite dominant alteration and silica-albite dominant alteration are by far the commonest alteration assemblages with carbonate dominant alteration the least significant.

Figure 3.18 shows that silica albite dominant alteration is best developed on the flanks of the ore body and extending 200-300 metres to the south and 200 metres to the west at the southern end of the ore body. It is much better developed on the eastern flank of the orebody than on the west. Silica-albite dominant alteration does not appear to extend far above the ore body. Overall, this alteration assemblage is better developed towards the southern part of the ore body.

Fuchsite dominant alteration (Figure 3.19), in contrast to the first type, is well developed vertically above the ore body, especially above the deeper northern end of the ore body, and does not exhibit much lateral development nor is it very well developed at the southern end of the ore body. Carbonate dominant alteration (Figure 3.20) is fairly sparsely distributed about the ore body but does appear, in the main, to occur immediately adjacent, either vertically or laterally, to the ore body. The highest concentration of carbonate dominant alteration occurs above the deeper northern end of the ore body.

Chlorite dominant alteration (Figure 3.21) is best developed above the ore body but more laterally than the fuchsite dominant alteration. It is reasonably evenly distribute along the length of the ore body.
Sericite dominant alteration (Figure 3.22) occurs to the south of the ore body and is concentrated in an area above the orebody at about 10500N and adjacent to and laterally above the northern end of the orebody.

In contrast to the hangingwall alteration described above, footwall alteration is zoned symmetrically about the stringer system as illustrated in Figure 3.23.
Figure 3.14  Computer generated models of Hellyer ore body: plan section, cross section looking north and longitudinal section looking west.
Figure 3.15a  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10150N

Figure 3.15b  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10250N
Figure 3.15c  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10350N

Figure 3.15d  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10450N
Figure 3.15e  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10550N

Figure 3.15f  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10650N

- **Ore body, SiAb, Si, SiAbCl**
- **FuCO, Fu**
- **CO, COSi, COSe**
- **CISe, Cl, CIFu**
- **Se, FuSe**
Figure 3.15g  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10750N

Figure 3.15h  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10850N

- Ore body, SiAb, Si, SiAbCl
- FuCO, Fu
- CO, COSi, COSe
- ClSe, Cl, ClFu
- Se, FuSe
Figure 3.15i Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10900N

Figure 3.15j Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 10950N

Ore body, SiAb, Si, SiAbCl, FuCO, Fu, CO, COSi, COSe, ClSe, CI, ClFu, Se, FuSe
Figure 3.15k  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 11050N

Figure 3.15l  Computer generated cross-section of Hellyer hangingwall alteration - view looking north at 11100N

Legend:
- Ore body,
- SiAb, Si, SiAbCl
- FuCO, Fu
- CO, COSi, COSe
- ClSe, Cl, ClFu
- Se, FuSe
Figure 3.16a  Computer generated plan section of Hellyer hangingwall alteration - view looking down on 300RL.

Figure 3.16b  Computer generated plan section of Hellyer hangingwall alteration - view looking down on 550RL.
Figure 3.16c  Computer generated plan section of Hellyer hangingwall alteration - view looking down on 400RL.

Figure 3.16d  Computer generated plan section of Hellyer hangingwall alteration - view looking down on 450RL.

- Ore body,
- SiAb, Si, SiAbCl
- FuCO, Fu
- CO, COSi, COSe
- CISe, Cl, CIFu
- Se, FuSe
Figure 3.16e  Computer generated plan section of Hellyer hangingwall alteration - view looking down on 500RL

Figure 3.16f  Computer generated plan section of Hellyer hangingwall alteration - view looking down on 550RL
Figure 3.16g  Computer generated plan section of Hellyer hangingwall alteration - view looking down on 600RL.
Figure 3.17a  Computer generated longitudinal section of Hellyer hangingwall alteration - view looking west at 5600E

Figure 3.17b  Computer generated longitudinal section of Hellyer hangingwall alteration - view looking west at 5650E

Ore body, SiAb, Si, SiAbCl, FuCO, Fu, CO, COSi, COSe, ClSe, Cl, ClFu, Se, FuSe
Figure 3.17c  Computer generated longitudinal section of Hellyer hangingwall alteration - view looking west at 5700E

Figure 3.17d  Computer generated longitudinal section of Hellyer hangingwall alteration - view looking west at 5750E
Figure 3.17e  Computer generated longitudinal section of Hellyer hangingwall alteration - view looking west at 5800E

Figure 3.17f  Computer generated longitudinal section of Hellyer hangingwall alteration - view looking west at 5850E
Figure 3.17g  Computer generated longitudinal section of Hellyer hangingwall alteration - view looking west at 5900E
Figure 3.18 Computer generated models of silica-albite alteration in Hellyer hangingwall: plan section, cross-section looking north and longitudinal section looking west.
Figure 3.19 Computer generated models of fuchsite dominated alteration in Hellyer hanging wall: plan section, cross-section looking north and longitudinal section looking west
Figure 3.20  Computer generated models of carbonate dominated alteration in Hellyer hangingwall: plan section, cross-section looking north and longitudinal section looking west.
Figure 3.21 Computer generated models of chlorite dominated alteration in Hellyer hangingwall: plan section, cross-section looking north and longitudinal section looking west
Figure 3.22 Computer generated models of sericite dominated alteration in Hellyer hangingwall: plan section, cross-section looking north and longitudinal section looking west
Figure 3.23 Schematic reconstruction of the footwall alteration zone through the centre of the stringer system. SEZ = stringer envelope zone (quartz-sericite alteration), Si = quartz, Se + sericite, Cl = chlorite, CO = carbonate (primarily dolomite). From Gemmell and Large, 1992.
Petrography of the Hellyer Basalt

Relict primary textures

The petrography of the Hellyer basalt has been described by Jack (1989). A representative sample of unaltered basalt is pictured in Plate 3a. In hand specimen, the least altered basalt is dark grey-green, with generally narrow (2-10 mm) veining ubiquitous, as is lighter quartz/carbonate vesicle filling. Veining is thicker and more intense in places and light coloured vesicles are more intense in the upper twenty to thirty metres.

In thin section, the least altered samples of basalt contained euhedral phenocrysts or glomerocrysts of stubby augite crystals, averaging 0.4 to 0.7 mm across, but up to 3 mm across, and constituting 20 to 50% of the rock. These are set in a groundmass of albite microlaths and glass, largely altered to chlorite. In less fresh samples, the clinopyroxene is replaced by carbonate and quartz, with chlorite in some cases.

Albite is mainly distributed throughout the groundmass, intergrown with other minerals and displaying a very fine grained habit, occasionally coarsening up to small lathes. In a few samples, albite phenocrysts and glomerocrysts up to 1 mm occur.

The major accessory mineral is chrome spinel which occurs as distinctive red euhedral crystals in both the least and most altered samples. Minor sphene and apatite occur throughout the basalt with rare epidote.

Secondary or alteration textures

Carbonate, quartz, chlorite, white mica and pyrite are interpreted to occur as secondary minerals throughout the basalt and may have a diagenetic, metamorphic or hydrothermal origin. In comparison to the nearby Que River deposit, Hellyer has suffered
substantially less deformation, and textures suggestive of a metamorphic origin are rarely observed. Thus there are few samples with a strong preferred orientation, fibrous growth habits within extension fractures or pressure shadows, or annealing or dynamic recrystallisation textures (Fulton, 1996)

There are however, many examples of textures which have been outlined as indicative of hydrothermal alteration ((Offler and Whitford, 1992). These textures are:

1. Minerals occurring in a sheaf-like, spherulitic, atoll-like, botryoidal, colloform or radiating habit, similar to modern seafloor hot spring deposit mineral textures observed in the Kuroko VHMS deposits.
2. Exhibiting primary depositional features, e.g. growth banding.
3. Exhibiting non-preferred orientation and pleochroism distinctive from their metamorphic counterparts.
4. Are wrapped around by any schistosity present.
5. Are euhedral and associated with other minerals lacking a preferred orientation.
6. Displaying a void-filling habit.

Within the basalt, preservation of such textures includes spherulites, ellipsoidal or lobate structures sometimes ringed by pyrite, atoll-like structures ringed with fine grained Ti-rich opaques, growth banded mineral aggregates, colloform or botryoidal textures, and euhedral quartz and pyrite. However as these textures are distributed throughout the basalt and are not related to proximity to the basalt, it is not possible to discriminate texturally between a hydrothermal origin or diagenetic processes associated with the extrusion of the
lava onto the muddy seafloor. These textures are commonest in the breccia facies, and in peperitic and variolitic samples which tend to occur more frequently near the contact with the Que River Shale. Examples of the five alteration textures defined in the first part of this chapter, from Aberfoyle company logging, are described below.

**Silica-albite alteration**

An example of silica-albite alteration is presented in Plate 3b. In hand specimen silica-albite alteration produces a bleached look and strong induration, evidenced by sparking when core is being cut. In thin section, silica is the abundant mineral and occurs within the groundmass as very fine grained intergrowths with varying amounts of chlorite, carbonate, white mica and albite. Silica also occurs within small to large ellipsoidal, spheroidal or lobate structures, usually being coarse grained at the centre and finer grained at the rims, as euhedral crystals in carbonate filled amygdules, and as irregular aggregates. A minor amount of fibrous quartz has been observed in the pressure shadow of pyrite. Albite occurs as very fine grained intergrowths with silica, too fine to probe.

**Fuchsite (chromian muscovite) alteration**

Fuchsite-carbonate alteration in sample 628520, from immediately above the ore body, is shown in Plate 3c. An important point to note with respect to fuchsite alteration is that, based on microprobe work reported in Chapter 5, there is very little true fuchsite within the Hellyer Basalt. Most of the bright green mica is chromian muscovite, however the term fuchsite is entrenched at Hellyer. In hand specimen, fuchsite alteration gives the basalt a distinctive, bright, apple green colour. The colour is present on freshly cut surfaces but it
Sample No.: 628435
Location: Hellyer
Alteration zone: Unaltered
Formation: Hellyer Basalt
Mt Read Volcanics, Central Volcanic Complex

Description: Clinopyroxene-phyric basaltic lava. Some carbonate after glass in groundmass.

Facies interp: Massive basaltic lava.

Alteration Intensity: none ~ weak moderate strong intense
Alteration Style: patchy pervasive veined cleavage control
Alteration Mineralogy: Groundmass minor carbonate Mafics
Interpretation: diagenetic metamorphic synlctonic hydrothermal
Relict Mineralogy: clinopyroxene, plagioclase, chromite

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Plate 3a: Split core and thin section of unaltered sample. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.
Sample No. | 628453
---|---
Location | Hellyer
Alteration zone | Silica-albite
Formation | Mt Read Volcanics, Central Volcanic Complex
Description | Strongly silica-albite altered, clinopyroxene-phyric basalt.
Facies Interp | Pillowed basaltic lava.

Alteration Intensity | none weak moderate strong intense
Alteration Style | pervasive veined cleavage control
Alteration Mineralogy | Groundmass silica-albite Feldspars silica-albite Mafics silica-chlorite-carbonate
Interpretation | diagenetic metamorphic syntectonic hydrothermal
Relict Mineralogy | none

Geochemistry

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Plate 3b: Split core and thin section of silica-albite altered sample. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.
Sample No. 628516
Location Hellyer
Alteration zone Fuchsite-Carbonate
Formation Hellyer Basalt
Mt Read Volcanics, Central Volcanic Complex

Description Intensely fuchsite-carbonate altered basalt
Facies Interp Massive basaltic lava.

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Plate 3c
Split core and thin section of fuchsite-carbonate altered sample. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.
Sample No. 628475
Location Hellyer
Alteration zone Chlorite
Formation Hellyer Basalt
Mt Read Volcanics,
Central Volcanic Complex

Description
Moderately chlorite-carbonate
altered clinopyroxene-phyric basalt.

Facies Interp
Massive basaltic lava

Alteration Intensity
none weak moderate strong intense Py < 1%
Alteration Style
patchy pervasive veined cleavage control
Alteration Mineralogy
Groundmass chlorite, carbonate
Feldspars
Mafics chlorite
diagenetic metamorphic syntectonic hydrothermal

Alteration Intensity
none weak moderate strong intense Py < 1%
Alteration Style
patchy pervasive veined cleavage control
Alteration Mineralogy
Groundmass chlorite, carbonate
Feldspars
Mafics chlorite
diagenetic metamorphic syntectonic hydrothermal

Interpretation
diagenetic metamorphic syntectonic

Relict Mineralogy
plagioclase, chromite

Geochemistry

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Plate 3d
Split core and thin section of chlorite altered sample. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.
Sample No. 628520
Location Hellyer
Alteration zone Carbonate-chlorite-sericite altered clinopyroxene-phyric basalt
Formation Hellyer Basalt
Mt Read Volcanics, Central Volcanic Complex

Description
Strongly carbonate-chlorite-sericite altered clinopyroxene-phyric basalt.

Facies interp
Massive basaltic lava.

Alteration Intensity
- none
- weak
- moderate
- strong
- intense

Alteration Style
- patchy
- veined
- cleavage control

Alteration Mineralogy
- Groundmass: carbonate, chlorite, sericite
- Feldspars: carbonate, white mica
- Mafics: carbonate, chlorite
- Diagenetic metamorphic syntectonic hydrothermal

Alteration Mineralogy
Groundmass carbonate, chlorite, sericite
Feldspars carbonate, white mica
Mafics carbonate, chlorite
Diagenetic metamorphic syntectonic

Geochemistry

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Plate 3c
Split core and thin section of carbonate altered sample. Also shown are geochemical characteristics including alteration box plot, and location of sample within alteration envelope determined from alteration mapping.
appears that the colour fades with time as old core which was logged as having intense green
colour has now faded to a light green. The alteration is especially noticeable near pillow
margins. Intensely fuchsite altered samples can be easily broken apart by hand. In thin
section, fuchsite/white mica occurs mostly in very fine grained intergrowths with varying
amounts of carbonate, chlorite, quartz, and albite. In one sample (333972), much coarser
white mica occurs in a colloform intergrowth with chlorite.

Chlorite alteration

A sample of chlorite altered basalt is presented in Plate 3d. In hand specimen,
chlorite altered basalt has an almost greasy feel and a dark green colour. Chlorite alteration
is especially prevalent near the margins of pillows. Chlorite occurs in very fine grained
intergrowths with varying amounts of quartz, carbonate, white mica and albite; at the centre
of ellipsoidal, spheroidal or lobate structures and displaying a radiating habit or rimming
these structures where they contain quartz or carbonate; in colloform growth with white
mica, quartz, and carbonate. Infrequently, chlorite exhibits a preferred orientation and
fibrous growth habit.

Carbonate alteration

A carbonate altered sample is shown in Plate 3e. Carbonates occur as irregular
aggregates; in spheroidal or ellipsoidal structures rimmed by quartz and/or chlorite, or
rimming quartz and/or chlorite; in colloform growths; and in veins. It can display either a
sheaf-like habit within large spherulites or ellipsoids, or be an optically continuous clear
grains up to 10mm across. In one sample (334201) there was a strong preferred orientation
of carbonate grains and veins with fibrous growth habit. Carbonate also occurs in very fine
grounded intergrowths with varying amounts of chlorite, quartz, white mica, and albite.

**Sericite alteration**

Sericite alteration is not pictured, but its occurrence is essentially similar to fuchsite
alteration, which as noted above, is mostly chromian muscovite.

**Other alteration**

There discrete occurrences of pyrite within the Hellyer Basalt, more common in the
upper twenty or thirty metres. It occurs as discrete euhedral crystals; partially or completely
rimming spheroidal, ellipsoidal or lobate structures; in veinlets; and finely disseminated.

**Summary**

Visual logging indicates that the pillow lava facies is more likely to undergo $Fu+$ and
$Cl+$ alteration, whilst the massive lava facies is more likely to be affected by $CO+$, $SiAb+$
and $Ep+$ alteration, although $Ep+$ is a very minor occurrence alteration type. The breccia
facies appears to be similar to the massive lava facies, with the addition of $Se+$ alteration.
These results are a little surprising as it would be expected that the pillow lava facies would
be more susceptible to $CO+$ alteration that the massive lava facies, and the breccia facies
would be expected to be the most susceptible to all alteration. $Cl+$ alteration dominance in
the pillow lava facies may be due to diagenetic alteration of chilled glassy pillow margins.
Three-dimensional modelling of Hellyer’s core log database indicates alteration zonation,
with fuchsite (chromian muscovite) alteration occurring immediately above the ore deposit.
and silica-albite alteration enveloping the fuchsite alteration laterally. Carbonate and chlorite alteration are less abundant and occur in a position roughly between the fuchsite and silica-albite alteration.

Figure 3.24  General alteration zonation model. Footwall legend as for Figure 3.23. Modified from Gemmell and Fulton (1998).
CHAPTER 4
GEOCHEMISTRY OF THE HANGING WALL SEQUENCE

Previous work

Jack (1989) studied the geochemistry of both the footwall and hangingwall at the Hellyer deposit. He concluded that within the zone of hangingwall calcite-fuchsite alteration above the deposit, there is major mass addition of S (2-4 times background S), CaO (2 times background CaO, K2O, Al2O3, Ba and depletion of Fe2O3, MgO, SiO2, with relative enrichment in As, Rb, and Mn. He also suggested that above the Hellyer hydrothermal feeder system, and possibly extruded along the same conduit, there exists a more primitive “core” lava characterised by higher Ti/Zr of ~53, higher MgO, Ni and Cr and lower SiO2, TiO2, P2O5, Y, Zr, La and Nb than the surrounding basalt. Jack also suggested that Zr, Ti, Y, Nb and rare-earth elements were immobile.

Background

In order to ascertain whether or not there are any geochemical vectors to ore at Hellyer, a fence of holes (Figure 2.3a) was selected from west of the deposit (distal and unaltered) to immediately above the deposit (proximal and altered). A hole which was logged as having fuchsite alteration some 1500 metres to the east has also been included in the study, as has an altered hole some 900 metres to the north-east along strike from the mineralisation. Results of analyses are presented in Appendix 1.

Crawford et al. (1992) has defined five major geochemical suites within the Mt Read Volcanics and the Hellyer basalt has been assigned to Suite III, along with the Lynch
Creek basalts, Howards Plains intrusives, and possibly the Sock creek basalts. Suite III basalts and andesites have a distinctive and variable chemistry. They range from rocks with low TiO$_2$ (0.5%), low P$_2$O$_5$ (0.1%) and Ti/Zr values of 30-40, to rocks with low TiO$_2$ (0.4-0.8%), high P$_2$O$_5$ (0.4-1.0%, light REE enriched and Ti/Zr ranging from 19 to 25. The former have affinities with transitional medium to high K calc-alkaline lavas from modern arcs such as Sunda, whilst the latter have been described as remarkably P$_2$O$_5$ and REE-enriched shoshonites with no compositional equivalents in the Andes or modern arc systems.” (Crawford et al., 1992). Figures 4.1 shows a discrimination diagram for the Que Hellyer Volcanics, while Figures 4.2 and 4.3 show the geochemical/stratigraphic relationships within the Mt. Read Volcanics in terms of the five suites, and some geochemical discrimination diagrams.

**Element Mobility**

Various studies have found that the high-field strength elements (Ti, Zr, Nb, Y, Hf, Ta, Th) and the transition metals (Ni, Cr, V) and Sc remain immobile in VHMS alteration zones, even zones of intense alteration (Crawford, 1992; MacLean and Barrett, 1993; Barrett and Maclean, 1994). In order to ascertain whether or not this holds true for the Hellyer basalt, Zr has been plotted against a range of elements (Figures 4.4a-c). From these diagrams it can be seen that Zr, Ti, Y, Nb, La, Ce and Nd are immobile, confirming the findings of Jack (1989). He also suggested Sc is immobile, but the pattern is less clear (Figure 4.4c), similarly with V. In addition, Al and Th also appear to be immobile. Both Ni and Cr are not immobile.
Figure 4.1 Ti/Zr versus Nb/Y for all Hellyer volcanics (except highly altered rocks in stringer zone).
Figure 4.2  Summary of the stratigraphic relationships of the different geochemical suites. Legend as for Figure 2a. From Pemberton and Corbett, 1992.

Figure 4.3  
(a) P2O5/TiO2 versus SiO2 diagram for representative Mount Read Volcanics showing fields for each suite.  
(b) Ti/Zr versus SiO2 diagram for representative Mount Read Volcanics fields for each suite. From Crawford et al., 1992.
Figure 4.4a  
TiO$_2$, Al$_2$O$_3$ (wt%), La, Nd, Y, and Ce (ppm) versus Ti/Zr in hanging-wall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered) and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.4b  P2O5, MnO, MgO, Fe2O3 (wt%), Rb, and Sr (ppm) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line is average value in unaltered basalt.
Figure 4.4c  Sc, V, Cr, Ni, Th, and Nb, (ppm) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Chemostratigraphy

Based on the immobility of Ti and Zr, Ti/Zr has been plotted against other elements and parameters by basalt facies and the HVS (Figures 4.5a-h) to determine the extent and nature of the Hellyer core lava and to see whether it's occurs preferentially within a facies. The core lava has been postulated by Jack (1989) to occur above the ore deposit and is distinguished by higher Ti/Zr (~53), Ni, and Cr and lower SiO₂, TiO₂, P₂O₅, Y, Zr, La, and Nb than the surrounding lava. This study agrees with that of Jack, with the exception of MgO, which Jack claimed was elevated in the core lava but which is clearly not, and further distinguishes the core lava as having lower Ce, Nd, Th, U and possibly Fe and PIMA MgOH wavelengths, while having higher Sb. The average Ti/Zr of the core lava is lower than Jack found, at about 40-45, while the surrounding lava has a Ti/Zr of about 20-25. With respect to facies, it can be seen that the majority of pillow lava facies samples have lower Ti/Zr, whereas the massive lava and breccia facies show a relatively even distribution between the two ratios.

The data has been replotted on the basis of distal and proximal holes, and MAC 19 and HL841B to see if the core lava is present distal to the deposit as well (Figure 4.6). It can be seen that there is only one distal sample with high Ti/Zr, confirming that the core lava is not yet found away from the deposit, and there are also plenty of low Ti/Zr proximal samples suggesting that the core lava exists as discrete discontinuous flows above the deposit. The core lava can also be seen to exist in HL841B and in MAC 19. In the downhole variation diagram for Ti/Zr (Figure 4.30), it can be seen that the core lava lies immediately above the HVS and extends up to 140 metres above the HVS in HL 5, about 40 metres above in HL 20, about 50 metres above in HL 51, and about 80 metres above in
HL 12. Interestingly, the core lava occupies a similar stratigraphic position in HL 841, to the north of the deposit, but in MAC 19, occurs near the top of the hole, although the Ti/Zr is lower (~30-35) than for the rest of the core lava. The core lava extends to within about 50 metres of the Que River Shale in HL 5.
Figure 4.5a  SiO2, TiO2, Al2O3, Fe2O3, MnO, and MgO (all wt%) versus Ti/Zr in hangingwall rocks. Data plotted for Hellyer Basalt facies and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.5b  CaO, Na2O, K2O, P2O5, BaO, and log S (all wt%) versus Ti/Zr in hangingwall rocks. Data plotted for Hellyer Basalt facies and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.5e  C (wt%), Sc, V, Cr, Ni, and Cu (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for Hellyer Basalt facies and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.5d  Log Zn, log As, Rb, Sr, Y, and Zr (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for Hellyer Basalt facies and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.5e  Nb, log Mo, log Ag, log Cd, log Sb, and Cs (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for Hellyer Basalt facies and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.5f  La, Ce, Nd, log Ti, log Pb, and Bi (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for Hellyer Basalt facies and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.5g  Th, U (ppm), Th/U, Ba/Sr, CCP index, and Ishikawa alteration index versus Ti/Zr in hangingwall rocks. Data plotted by Hollyer Basalt facies and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.5h  Hellyer alteration index, PIMA FeOH peak, PIMA MgOH peak and visual alteration intensity versus Ti/Zr in hangingwall rocks. Data plotted by Hellyer Basalt and HVS. Dotted line marks average value in unaltered basalt.
Figure 4.6a  SiO2, TiO2, Al2O3, Fe2O3, MnO, and MgO (all wt%) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.6b  CaO, Na2O, K2O, P2O5, BaO, and log S (all wt%) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 10 (distal and altered), and HL841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.6c  C (wt%), Sc, V, Cr, Ni, and Cu (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.6d: Log Zn, log As, Rb, Sr, Y, and Zr (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.6e  Nb, log Mo, log Ag, log Cd, log Sb, and Cs (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line is average value in unaltered basalt.
Figure 4.6f  
La, Ce, Nd, log Tl, log Pb, and Bi (all ppm) versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), HL 841B (distal and altered). Dotted line is average value in unaltered basalt.
Figure 4.6g  Th, U (ppm), Th/U, Ba/Sr, CCP index, and Ishikawa alteration index versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.6h  Hellyer alteration index, PIMA FeOH peak, PIMA MgOH peak and visual alteration intensity versus Ti/Zr in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Alteration Indices

The Ishikawa alteration index (Ishikawa et al. (1976) was developed to define the intensity of alteration associated with VHMS deposits:

\[
\text{Ishikawa alteration index} = \frac{100(K_2O + MgO)}{(K_2O + MgO + Na_2O + CaO)}
\]

This index is correlates positively with sericitisation, chloritisation and sodium depletion, and correlates negatively with carbonate alteration. Unaltered rocks fall within the range 20 to 50, whilst altered rocks fall within the ranges of 50 to 100 (Large et al. 1996). The index is useful for alteration systems which are limited to a few alteration types, e.g. sericite replacing albite, but in more complex alteration regimes, carbonate alteration which occurs spatially with sericite or chlorite alteration may produce a value indicating an unaltered rock. The index also does not measure silicification, which may be very important. A way of making the index more useful in the Mt. Read Volcanics has been to plot the Ishikawa alteration index against another index, the Chlorite-Carbonate-Pyrite index or CCPI (Large et al., 1996) to produce a box plot (Large et al., 1997).

The CCPI is defined as:

\[
\frac{100(MgO + FeO)}{(MgO + FeO + Na_2O + K_2O)}
\]

Unaltered rocks thus plot within in a small box and altered rocks define trends away from the box towards the boundaries. In Figure 4.7, the Hellyer data from this study has been plotted on such a diagram, with the unaltered box based on samples from Stanley and Gemmell (1997). In Figure 4.7a samples have been divided into distal and proximal and it can be seen that most fall within the unaltered box although proximal (unaltered) samples trend away from the unaltered box more than the distal (unaltered) samples, as would be
expected. In Figure 4.7b, the proximal (altered) samples have been classified into alteration type based on visual (Aberfoyle) logging and in Figure 4.7c, only samples with alteration intensity of 3 (maximum of 5) have been plotted. It can be seen that samples do not trend very well towards the end member compositions on the box edge. This may reflect limitations in the ability of the Alteration Index to discriminate between alteration types or may indicate inconsistent logging practice in the core shed. Some Hellyer cross-sections show holes drilled very close together, but logged by different people, as having substantially different alteration types and intensities.

In order to better quantify the extent and intensity of alteration at Hellyer, a local index based on the deviation from an average composition of unaltered Hellyer basalt has been devised. The Hellyer alteration index takes the form:

\[
Y_I = \left( \frac{Y_1 + Y_2 + Y_3 + Y_4 + Y_5}{5} \right) \times 100 \\
\text{where}
\]

\[
Y_1 = \frac{\text{wt}\% X_1 \text{ in unaltered basalt} - \text{wt}\% X_1 \text{ in sample}}{\text{wt}\% X_1 \text{ in unaltered basalt}}
\]

for \( X_1 = 8.51 \) (CaO), \( X_2 = 9.08 \) (MgO), \( X_3 = 8.52 \) (Fe₂O₃), \( X_4 = 0.94 \) (K₂O), and \( X_5 = 2.70 \) (Na₂O).

A comparison of the Ishikawa and Hellyer alteration indices versus various geochemical parameters is presented in Figures 4.8-4.15. To at least some degree, and mostly clearly, the Hellyer alteration index shows the same trends, which are:
Increasing Hellyer alteration index

- decreasing $\text{SiO}_2$, $\text{Fe}_2\text{O}_3$, $\text{MgO}$, $\text{Na}_2\text{O}$, $\text{Sr}$, $\text{P}_2\text{O}_5$
- increasing $\text{CaO}$, $\text{K}_2\text{O}$, $\text{Rb}$, $\text{S}$, $\text{As}$, $\text{Mo}$, $\text{Cs}$, $\text{Tl}$

In contrast, the Ishikawa alteration index

- decreasing $\text{CaO}$, $\text{Na}_2\text{O}$, $\text{Sr}$,
- increasing $\text{SiO}_2$, $\text{Fe}_2\text{O}_3$, $\text{MgO}$, $\text{Rb}$, $\text{K}_2\text{O}$, $\text{Cs}$, $\text{Tl}$

which gives a false picture with respect to some elements.

In order to determine which elements are involved in carbonate veining/alteration, $C$ has been plotted against various elements in Figure 4.16. It can be seen that $\text{Ca}$ correlates very positively with $C$, but $\text{Mg}$ correlates well negatively, suggesting that $\text{Mg}$ is not present as dolomite in any abundance. $C$ also appears to correlate positively with $\text{Mn}$ and $\text{Sr}$, while it appears to correlate with $\text{K}$. 
Figure 4.7a  Plot of Ishikawa alteration index versus chlorite-carbonate-pyrite index for distal (unaltered) and proximal (altered) samples. The unaltered box is based on samples from Stanley and Gemmell (1997).
Figure 4.7b  Plot of Ishikawa alteration index versus chlorite-carbonate-pyrite index for distal (unaltered) and proximal (altered) samples. Proximal samples are broken down into the five main alteration types determined from visual logging. The unaltered box is based on samples from Stanley and Gemmell (1997).
Figure 4.7c  Plot of Ishikawa alteration index versus chlorite-carbonate-pyrite index for samples with alteration intensity of 3 or above, broken down into the five main alteration types determined from visual logging. The unaltered box is based on samples from Stanley and Gemmell (1997).
Figure 4.8a Scatter plots showing relationship between Hellyer alteration index and SiO2, TiO2, Al2O3, Fe2O3, MnO, and MgO. Dotted line marks average value in unaltered basalt.
Figure 4.8b  Scatter plots showing relationship between Ishikawa alteration index and SiO2, TiO2, Al2O3, Fe2O3, MnO, and MgO. Dotted line marks average value in unaltered basalt.
Figure 4.9a Scatter plots showing relationship between Hellyer alteration index and CaO, Na2O, K2O, P2O5, BaO, and S. Dotted line marks average value in unaltered basalt.
Figure 4.9b  Scatter plots showing relationship between Ishikawa alteration index and CaO, Na2O, K2O, P2O5, BaO, and S. Dotted line marks average value in unaltered basalt.
Figure 4.10a  Scatter plots showing relationship between Hellyer alteration index and C, Sc, V, Cr, Ni, and Cu. Dotted line marks average value in unaltered basalt.
Figure 4.10b Scatter plots showing relationship between Ishikawa alteration index and C, Sc, V, Cr, Ni, and Cu. Dotted line marks average value in unaltered basalt.
Figure 4.11a Scatter plots showing relationship between Hellyer alteration index and Zn, As, Rb, Sr, Y, and Zr. Dotted line marks average value in unaltered basalt.
Figure 4.11b Scatter plots showing relationship between Ishikawa alteration index and Zn, As, Rb, Sr, Y, and Zr. Dotted line marks average value in unaltered basalt.
Figure 4.12a  Scatter plots showing relationship between Hellyer alteration index and Sb, Cs, Nb, Mo, Ag, and Cd. Dotted line marks average value in unaltered basalt.
Figure 4.12b  Scatter plots showing relationship between Ishikawa alteration index and Sb, Cs, Nb, Mo, Ag, and Cd. Dotted line marks average value in unaltered basalt.
Figure 4.13a Scatter plots showing relationship between Hellyer alteration index and La, Ce, Nd, Tl, Pb, and Bi. Dotted line marks average value in unaltered basalt.
Figure 4.13b  Scatter plots showing relationship between Ishikawa alteration index and La, Ce, Nd, Tl, Pb, and Bi. Dotted line marks average value in unaltered basalt.
Figure 4.14a  Scatter plots showing relationship between Hellyer alteration index and Th, U, Th/U, Ba/Sr, CCP index and Ti/Zr. Dotted line marks average value in unaltered basalt.
Figure 4.14b Scatter plots showing relationship between Ishikawa alteration index and Th, U, Th/U, Ba/Sr, CCP index and Ti/Zr. Dotted line marks average value in unaltered basalt.
Figure 4.15a  Scatter plots showing relationship between Hellyer alteration index and PIMA MgOH peak, PIMA FeOH peak, visual alteration intensity, and Ishikawa alteration index. Dotted line marks average value in unaltered basalt.
Figure 4.15b Scatter plots showing relationship between Ishikawa alteration index and PIMA MgOH peak, PIMA FeOH peak, and visual alteration intensity.
Figure 4.16a SiO2, TiO2, Al2O3, Fe2O3, MnO, and MgO (all wt%) versus C(wt%) in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.16b  CaO, Na2O, K2O, P2O5, BaO, and log S (all wt%) versus C (wt%) in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 10 (distal and altered), and HL841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.16c  Ti/Zr, Sc, V, Cr, Ni, and Cu (all ppm) versus C (wt%) in hanging-wall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.16d  Log Zn, log As, Rb, Sr, Y, and Zr (all ppm) versus C (wt%) in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.16e  Nb, log Mo, log Ag, log Cd, log Sb, and Cs (all ppm) versus C (wt%) in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line is average value in unaltered basalt.
Figure 4.16f  La, Ce, Nd, log Tl, log Pb, and Bi (all ppm) versus C (wt%) in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), HL 841B (distal and altered). Dotted line is average value in unaltered basalt.
Figure 4.16g  Th, U (ppm), Th/U, Ba/Sr, CCP index, and Ishikawa alteration index versus C (wt%) in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.
Figure 4.16h  Hellyer alteration index, PIMA FeOH peak, PIMA MgOH peak and visual alteration intensity versus C (wt%) in hangingwall rocks. Data plotted for HVS, distal (unaltered), proximal (altered), MAC 19 (distal and altered), and HL 841B (distal and altered). Dotted line marks average value in unaltered basalt.