Chapter 4
Stratigraphy, structure and geochemistry of the northern Central Volcanic Complex

4.1 Introduction

Despite the enormous amount of exploration and research in the Mount Read Volcanics, the northern Central Volcanic Complex has previously been treated as “undifferentiated volcanics”. Poor exposure, complex facies relationships, strong alteration and structural reorganisation of the volcanic succession make subdivision difficult.

In this study, the integration of geological mapping, detailed facies analysis and structural interpretation allows subdivision of the northern Central Volcanic Complex into four formations (Table 4.1): the Hercules Pumice Formation (previously the Footwall Pyroclastics and Host Rocks), the Kershaw Pumice Formation (previously part of the Mount Black Volcanics), the Mount Black Formation (previously part of the Mount Black Volcanics), and the Sterling Valley Volcanics (unchanged). The distribution of these subdivisions and structure of the northern Central Volcanic Complex are described below. The primary compositions of least-altered lavas, sills and syn-eruptive pumice breccia in the northern Central Volcanic Complex, which support this subdivision, are presented and their magmatic and tectonic affinities considered. Primary compositions and facies characteristics are compared within the Central Volcanic Complex and with other parts of the Mount Read Volcanics.

This new stratigraphic and structural interpretation of the northern Central Volcanic Complex has important implications for models of the tectono-magmatic evolution of the Mount Read Volcanics.

Table 4.1: Proposed nomenclature and previous terminology for stratigraphic subdivisions in the northern Central Volcanic Complex. This table depicts changes in nomenclature for the rocks in the northern Central Volcanic Complex and is not equivalent to a stratigraphic column.
and for regional VHMS exploration. In particular, the new interpretation implies that the highly prospective host rocks to the Rosebery and Hercules ore deposits are repeated in the Mount Black and Mount Read areas.

4.2 Stratigraphic problems in the northern Central Volcanic Complex revisited

The northern Central Volcanic Complex has previously been divided into four informally named units: the Rosebery-Hercules host sequence, Mount Black Volcanics, Sterling Valley Volcanics, and the Holway andesite (Campana and King, 1963, Brathwaite, 1974; McNeill and Corbett, 1989; Corbett and Solomon, 1989; Allen, 1995 unpub.). The most recent published subdivision of the Rosebery-Hercules host sequence is: Footwall Pyroclastics, Host Rocks, black mudstone and Hangingwall Volcaniclastics (Corbett, 1981; Green et al., 1981; Corbett and Lees, 1987). However, Allen (1991 unpub., 1994a unpub., 1995 unpub.) proposed that the Hangingwall Volcaniclastics correlate with the White Spur Formation at the base of the Dundas Group, and that the Mount Black Volcanics were similar to the Footwall Pyroclastics (Table 4.1). The nature of contacts and correlations between these units have previously been confusing, with considerable doubt about the stratigraphic position of the Mount Black Volcanics (Chapter 2).

In this section, correlations between part of the Mount Black Volcanics and the Footwall Pyroclastics, and between the Hangingwall Volcaniclastics and the White Spur Formation are considered based on detailed facies (Chapter 3) and structural analysis (section 4.4) and lithogeochemical comparisons (section 4.6).

4.2.1 Mount Black Volcanics and the Footwall Pyroclastics

Most previous workers have assumed that the Mount Black Volcanics are younger than the Footwall Pyroclastics because they structurally overlie the Rosebery-Hercules host sequence (Brathwaite, 1969; Lees, 1987). However, detailed facies analysis (Chapter 3), and lithogeochemical comparisons (section 4.6) suggest that the pumice breccias in the Mount Black Volcanics and Footwall Pyroclastics may be stratigraphic equivalents as proposed by Allen (1991 unpub., 1994a unpub., 1995 unpub.).

This correlation is supported by:

(1) The Footwall Pyroclastics and the Mount Black Volcanics both contain texturally and compositionally similar facies associations including: pumice-rich facies associations, feldspar-phyric rhyolitic and dacitic sills and quartz-feldspar-phyric rhyolitic sills.

(2) The pumice-rich facies associations in the Footwall Pyroclastics and the Mount Black Volcanics contain similar facies with identical components, lithofacies characteristics and textures. Pumice breccia, pumice-rich sandstone and shard-rich siltstone contain juvenile pumice clasts, shards, plagioclase crystal fragments and sparse lithic clasts consistent with pyroclasts produced by felsic explosive eruptions. Pumice breccia units are typically massive or normally graded with lithic clast- and crystal-rich bases and stratified shard-rich siltstone tops. These lithofacies characteristics are consistent with syn-eruptive facies deposited by water-supported gravity flows in a below-wave-base submarine environment (Chapter 3).
In both the Footwall Pyroclastics and the Mount Black Volcanics, there is a change from rhyolitic to dacitic composition towards the top of the pumice-rich facies association (section 4.6.2).

The pumice-rich facies associations in Footwall Pyroclastics and the Mount Black Volcanics, are conformably overlain by laminated feldspar-quartz-phyric pumice-rich sandstone and shard-rich siltstone of the Host Rocks and the texturally and mineralogically similar Jones Creek sediments (part of the Mount Black Volcanics west of Mount Read).

Both the Footwall Pyroclastics and the Mount Black Volcanics are conformably, at least in part, overlain by quartz-phyric volcaniclastic facies of the Hangingwall Volcaniclastics and the White Spur Formation (Dundas Group) respectively.

Lithological and compositional similarities between pumice-rich facies association in the Mount Black Volcanics and the Footwall Pyroclastics suggest that they may be correlates. This implies that the pumice-rich facies association in the Mount Black Volcanics is a structural repetition of the Footwall Pyroclastics. This is supported by the structural interpretation that the Mount Black Fault and other thrust faults repeat major facies associations in a series of north-striking fault-bounded slices (section 4.4).

4.2.2 Hangingwall Volcaniclastics and the White Spur Formation

The Hangingwall Volcaniclastics and White Spur Formation both comprise thick successions of massive to stratified, feldspar-quartz-phyric rhyolitic volcaniclastic facies intercalated with feldspar-phyric lava and black mudstone (Chapter 2). Clasts in the volcaniclastic facies include: pumice, quartz-phyric and/or feldspar-phyric rhyolite, granite, siltstone, sandstone, schist, black mudstone and sparse massive sulfide clasts (Lees, 1987; Corbett and Solomon, 1989; Pemberton and Corbett, 1992).

Lithological similarities between the Hangingwall Volcaniclastics and the White Spur Formation at the base of the Dundas Group, which disconformably overlies the northern Central Volcanic Complex south of Hercules, led Allen (1994a unpub.) to suggest that the Hangingwall Volcaniclastics are correlates of the White Spur Formation. The Hangingwall Volcaniclastics conformably to disconformably overlies the Footwall Pyroclastics. Between Hercules and Mount Read, this relationship is repeated by a series of east-dipping thrust faults, suggesting that the Hangingwall Volcaniclastics are the youngest exposed portion of the Rosebery-Hercules host sequence stratigraphy. This is consistent with the interpretation that the Hangingwall Volcaniclastics are correlates of the White Spur Formation.

As a result of these correlations, it is proposed that the Hangingwall Volcaniclastics should not be included in the Central Volcanic Complex, but rather, are part of the Dundas Group.

4.3 Revised stratigraphy of the northern Central Volcanic Complex

The lack of regional stratigraphic subdivisions, inconsistent use of informal local names, and recognition of regionally mappable compositionally distinct lithologies have prompted an attempt to define the internal stratigraphy of the northern Central Volcanic Complex (Table 4.1). No formal stratigraphic subdivision of the entire northern Central Volcanic Complex has previously been attempted.
The true stratigraphic thickness of the northern Central Volcanic Complex varies from greater than 3 km east of Rosebery to more than 1.5 km at Mount Read. The northern Central Volcanics Complex is conformably and disconformably overlain by and in fault contact with the Dundas and Mount Charter Groups, which are part of the Western volcano-sedimentary sequences. The lower contact of the northern Central Volcanic Complex has not been recognised.

It is clear from this study that four regionally mappable, lithologically and compositionally distinctive formations occur within the northern Central Volcanic Complex: the Sterling Valley Volcanics, Mount Black Formation, Kershaw Pumice Formation, and Hercules Pumice Formation (Figs. 4.1 and 4.2). The Sterling Valley Volcanics are essentially unchanged from the informal unit of the same name. The Mount Black Formation refers to the rhyolitic to dacitic lava- and sill-dominated part of the informal Mount Black Volcanics. The Kershaw Pumice Formation consists of pumice-rich facies associations and associated rhyolitic and dacitic sills that were previously assigned to the Mount Black Volcanics. The Hercules Pumice Formation refers to the Footwall Pyroclastics and Host Rocks in the Rosebery-Hercules host sequence. It is proposed that the Kershaw Pumice Formation and the Hercules Pumice Formation are equivalent. Formal definitions of these four formations follow.

### 4.3.1 Sterling Valley Volcanics

The Sterling Valley Volcanics are the oldest exposed part of the northern Central Volcanic Complex, occurring at the eastern margin of the northern Central Volcanic Complex in the core of a regional anticline. The base of the Sterling Valley Volcanics has been removed by the Henty Fault and is not exposed. This formation consists of polymictic mafic breccia, mafic sandstone and siltstone, and dacitic to basaltic lavas and sills that have a gradational upper contact with felsic (dacitic to rhyolitic) units of the Mount Black Formation (Fig. 4.1). This gradational and conformable contact is exposed on the Murchison Highway east of Rosebery (Fig. 4.2; 5373 000 mN, 382 800 mE). The Sterling Valley Volcanics have a minimum lateral extent of 7 km and true stratigraphic thickness of 1.5 km.

The Sterling Valley Volcanics comprise ten facies interpreted to be lavas, sills and resedimented syn-eruptive volcanic breccias of basaltic to dacitic composition (Chapter 3). The Sterling Valley Volcanics are interpreted to represent the medial to proximal facies of a submarine basaltic volcanic centre.

Tholeiitic andesites and basalts dominate the Sterling Valley Volcanics but calc-alkaline dacites are locally present (section 4.5.4). This indicates that tholeiitic and calc-alkaline volcanism were coeval during early stages of formation of the northern Central Volcanic Complex.

The Sterling Valley Volcanics is exposed on the Murchison Highway between the Henty Fault and the summit of Mount Black (Fig. 4.2; 5373 000 mN, 382 800 mE to 5374 000, 384050 mE). The outcrop is strongly weathered and overgrown, and drill hole intersections (e.g. drill holes STP 218 and STP 234; Figs. 3.11 and 3.12) provide much better sections through the formation.

### 4.3.2 Mount Black Formation

The Mount Black Formation (previously part of the Mount Black Volcanics) is exposed in a N-striking belt from Mount Read to Mount Block (Fig. 4.2). It is conformably overlain by pumice breccia
White Spur Formation and correlates
interbedded quartz-feldspar crystal-rich volcanic and non volcanic sandstone and breccia, pumice breccia and black mudstone. Feldspar-phyric sills.

Hercules and Kershaw Pumice Formations
Host-rock member
interbedded pumice breccia, pumice-rich sandstone, shard-rich siltstone, crystal-lithic-rich siltstone and black mudstone. Quartz-feldspar-phyric rhyolitic/dacitic sills. Massive sulfide.

Footwall member

Mount Black Formation
Feldspar-phyric rhyolitic and dacitic lavas, domes, cryptodomes and sills. Quartz-feldspar-phyric rhyolite sills and feldspar-hornblende-phyric dacites. Reesedimented hyaloclastite and autobreccia. Sparse intercalated crystal-rich sandstone and black mudstone.

Sterling Valley Volcanics
intercalated polymictic mafic breccia, mafic volcanic sandstone and siltstone with dacitic to basaltic lavas and sills.

Legend
- Coherent rhyolite
- Quartz-feldspar-phyric rhyolite
- Coherent feldspar-phyric dacite
- Massive basalt and dolerite
- Monomictic rhyolite breccia
- Monomictic dacite breccia
- Polymictic mafic breccia, mafic volcanic sandstone and siltstone
- Pumice breccia
- Dacitic pumice breccia
- Pumice-lithic clast-rich breccia
- Interbedded volcanic and non-volcanic sandstone and black mudstone
- Quartz-feldspar crystal-rich volcanic sandstone and breccia
- Crystal-rich sandstone
- Mudstone clast
- Flammé
- Massive sulfide

Figure 4.1: Schematic diagram depicting the stratigraphy and facies architecture of the northern Central Volcanic Complex in the Mount Read-Pieman area.
Figure 4.2: Geological interpretation of the northern Central Volcanic Complex. Geology east of the Mount Black Fault from this study, west of the Mount Black Fault from Allen (1991 unpub.) and in the Pinnacles area north of Chester from Corbett and McNeill (1986). The proposed Hercules Pumice Formation, Kershaw Pumice Formation, Mount Black Formation and Sterling Valley Volcanics are overlayed on the geology in colour. Units correlated with the White Spur Formation are white.
and pumice-lithic clast-rich breccia units of the Kershaw Pumice Formation (Fig. 4.1). This contact is exposed between Mount Read and Dallwitz (Fig. 4.2; 5367 200 mN, 377 700 mE). The Mount Black Formation has a minimum lateral extent of 20 km and a minimum stratigraphic thickness of 1.6 km.

The Mount Black Formation is dominated by massive, flow-banded and autobrecciated lavas, domes, cryptodomes and syn-volcanic sills that are interpreted to represent the proximal facies of a dacitic to rhyolitic, mainly effusive and intrusive volcanic complex (Chapter 3).

The calc-alkaline affinity and crustal isotopic signature of the Mount Black Formation contrasts with the underlying tholeiitic Sterling Valley Volcanics (section 4.5.4). The Mount Black Formation may reflect a change in magma source from mantle-derived, back-arc-type, tholeiitic melt to calc-alkaline magma produced by melting of lower crustal rocks.

A possible type section for the Mount Black Formation is on the summit and eastern flank of Mount Read (Fig. 4.2; 5366 325 mN, 378 675 to 379 600 mE), where there are good exposures of both intrusive and extrusive rhyolites and dacites.

4.3.3 Kershaw Pumice Formation
The Kershaw Pumice Formation includes pumice-rich facies associations previously assigned to the Mount Black Volcanics (including the Jones Creek sediments, Fig. 4.2). It occurs in a narrow (>800 m) N-striking belt from Jones Creek to Mount Kershaw and then in NE-striking fault slices from Mount Kershaw to north of Mount Block (Fig. 4.2). The Kershaw Pumice Formation has a minimum lateral extent of 16 km and a maximum measured stratigraphic thickness of 800 m.

The lower contact is commonly the Mount Black Fault (section 4.6.3, Fig. 4.2), but where exposed or intersected in drill core, pumice breccia or pumice-lithic clast-rich breccia of the Kershaw Pumice Formation conformably overlies rhyolitic lavas of the Mount Black Formation. The top of the Kershaw Pumice Formation comprises a complex arrangement of laterally extensive and discontinuous volcaniclastic facies and rhyolitic and dacitic lavas and sills (Fig 4.1). These include dacitic pumice breccia or pumice-rich sandstone (drill holes EHP319, JCP211 and 118R), pumiceous hyaloclastite (drill holes 78R and 80R) or pumiceous rhyolite (drill hole 120R). Quartz-feldspar-phyric rhyolite sills (exposed on Mount Read and in drill holes 56R and 113R) and dacitic sills (east of Rosebery) commonly intrude the top of the Kershaw Pumice Formation. At Jones Creek and Dallwitz the upper contact is conformable with overlying stratified quartz-phyric sandstone, siltstone and black mudstone. At Pinnacles and Burns Peak, the top of the Kershaw Pumice Formation is defined as the base of the quartz-phyric volcaniclastic facies of the Dundas Group.

The Kershaw Pumice Formation is mainly composed of pumice breccia, pumice-rich sandstone, shard-rich siltstone, with lesser proportions of pumice-lithic clast-rich breccia and sandstone, massive, flow-banded and brecciated rhyolitic and dacitic lavas, cryptodomes and sills. The pumice breccias are laterally extensive and interpreted to be sourced from an explosive eruption. Compositional similarities between the pumice breccia and rhyolites in the Kershaw Pumice Formation are consistent with the explosive and effusive products of a single calc-alkaline felsic volcanic centre (section 4.5).
There is a general decrease in FeO total and Ti/Zr with increasing SiO₂ towards the top of the Kershaw Pumice Formation stratigraphy (section 4.5). However, dacitic pumice breccia near the top of the formation reverses this trend.

Immobile element variation in facies of the Mount Black Formation and the Kershaw Pumice Formation are consistent with fractionation from a single parent magma. Rhyolitic and dacitic sills in the Kershaw Pumice Formation are texturally and compositionally similar to those in the Mount Black Formation (section 4.5.4).

A thick dacitic sill with peperitic contacts in the Kershaw Formation east of Rosebery has been dated at 494.9±4.3 Ma using U-Pb in zircon (Perkins and Walshe, 1993). Peperitic contacts imply that the sill was intruded into unconsolidated pumice breccia. This date is thus a good approximation of the age of the Kershaw Pumice Formation. This date and another U-Pb in zircon date for the Comstock Formation at the base of the Tyndall Group south of the Henty Fault (494.4±3.8 Ma), are younger than other U-Pb in zircon and ⁴₀Ar/³⁹Ar in hornblende ages in the Mount Read Volcanics, the older ages have a mean of 500 Ma (Chapter 2) (Perkins and Walshe, 1993; Everard and Villa, 1994). Although the errors in these dates suggest that the Kershaw Pumice Formation, Comstock Formation and other Mount Read rocks could all be contemporaneous, this study suggests that the Kershaw Pumice Formation is the youngest part of the northern Central Volcanic Complex, not inconsistent with a younger age than other parts of the Mount Read Volcanics. However, this date is inconsistent with stratigraphic relationships south and east of the Henty Fault where the southern Central Volcanic Complex is intruded by the Cambrian Darwin granite and is unconformably overlain by the Tyndall Group.

A well exposed type section for the Kershaw Pumice Formation occurs on the flank of Mount Kershaw along the Pieman Road (Fig. 4.2; 5378 800 mN, 377 750 mE to 5379 550 mN, 378 250 mE). Excellent intersections also occur in drill hole 120R (Fig. 4.17).

4.3.4 Hercules Pumice Formation
The Hercules Pumice Formation refers to the Footwall Pyroclastics and Host Rocks in the Rosebery-Hercules host sequence. The Hercules Pumice Formation has a minimum stratigraphic thickness of 550 m (Allen, 1992b unpub.) and 12 km lateral extent. The base of the Hercules Pumice Formation is the Rosebery Fault (Fig. 4.2). The Hercules Pumice Formation is disconformably overlain by the White Spur Formation (formerly the Hangingwall Volcaniclastics) (R.L. Allen, written communication, 2000). It comprises two informal members: the Footwall member (Footwall Pyroclastics) and the Host-rock member (Host Rocks).

The Footwall member is a thick (up to 500 m), poorly stratified succession of pumice breccia and rhyolitic and dacitic sills (Lees, 1987; Allen, 1990b unpub., 1994b unpub.). The Host-rock member is a 5-60 m-thick, discontinuous layer of interbedded pumice-rich sandstone and siltstone at the top of the Footwall member (Figs. 2.6 and 4.1) (Corbett and Solomon, 1989; Allen, 1991 unpub., 1994b unpub.). The contact between the Footwall member and the Host-rock member is gradational from massive, monomictic juvenile pumice breccia to stratified polymictic crystal-lithic clast-rich sandstone and siltstone (Allen, 1993 unpub.). At Rosebery, a quartz-feldspar-phyric rhyolite sill intrudes the
contact between the Footwall member and the Host-rock member.

The Hercules Pumice Formation is interpreted to be the product of large felsic explosive eruptions, with the Host-rock member reflecting local redeposition at the top of the Footwall member and the influx of quartz-bearing sediments (Allen, 1990b unpub., 1991 unpub.; Large et al., in press b).

4.4 Structure of the northern Central Volcanic Complex

In the northern Central Volcanic Complex, structures are difficult to identify because of the massive and unbedded nature of the volcanic succession and the paucity of extensive marker beds. Structural information includes sparse bedding, flow-banding, the S1 compaction foliation and the regional tectonic foliation (S2). Open, shallowly plunging, N- to NNE-trending folds and brittle-ductile faults dominate the structure and are parallel to folds and faults in the Dundas Group and equivalents (cf. McNell, 1986) (Fig. 2.5). The northern Central Volcanic Complex is segmented into a number of N-striking thrust slices (Figs. 4.2 and 4.3).

In the Rosebery and Tullah area, 7 km total displacement is inferred to have occurred on the major thrust faults causing thickening of the Central Volcanic Complex (Fig. 4.3).

4.4.1 Regional foliations

Three major regional planar fabrics are recognised in the northern Central Volcanic Complex, bedding (S0), the compaction foliation (S1) and regional tectonic cleavage (S2).

Bedding: Sparse bedding (S0) in the northern Central Volcanic Complex generally strikes north; however changes in strike, dip and younging direction define folds and faults.

Compaction foliation: The earliest foliation (S1) is a bedding-parallel spaced stylolitic foliation defined by the alignment of sericite or chlorite-sericite fiamme and chlorite-sericite-hematite stylolites in the pumice-rich facies and in originally glassy flow-banded rhyolites, and by hematite stylolites in the carbonate facies (Fig. 4.4). The sericite or chlorite-sericite fiamme are elongate and ragged with delicate feathery terminations and locally preserve flattened tube pumice textures, indicating that they are altered compacted pumice clasts (Chapter 6). The high proportion of fiamme in pumice-rich facies commonly results in a foliation which resembles eutaxitic texture in welded pyroclastic deposits (Allen, 1988). This eutaxitic texture is particularly prominent in pumice breccias and the pumiceous margins of rhyolite lavas in the Hercules and Kershaw Pumice Formations at Rosebery and Hercules (Fig. 4.4).

S1 is crenulated by the dominant pervasive axial planar cleavage (S2) that is associated with regional folds and shear zones (Fig. 4.4). In areas of strong deformation, fiamme are stretched and transposed into the steeply dipping axial planar cleavage (S2) and stylolites are crenulated by S2 (Fig. 4.4). S1 is interpreted as a pre-tectonic, diagenetic compaction and dissolution fabric (Chapter 6) (Allen, 1990a; Allen and Cas, 1990 unpub.). Mapping of the compaction foliation by Allen (1991 unpub., 1994a unpub.) in the Rosebery and Hercules areas, and mapping in this study, has shown that S1 is bedding-parallel and that it can be used to define the orientation of bedding in otherwise massive
Figure 4.3: Interpretive cross sections through the northern Central Volcanic Complex showing major facies associations, structures and the proposed formations for the northern Central Volcanic Complex. Geology west of the Mount Black Fault after Allen (1991 unpub.).
Figure 4.4: Foliations and structures in the northern Central Volcanic Complex. A. $S_1$ defined by a chlorite-sericite-hematite stylolitic foliation and parallel chlorite-rich fiamme in pumice-lithic breccia (128R 141.3 m). Non-vesicular lithic clasts and pumice clasts are variably altered to assemblages of feldspar-quartz-sericite and chlorite-sericite. B. Photomicrograph (85R 848m ppl) of $S_1$ foliation defined by chlorite-sericite-hematite stylolites in pumice breccia. C. Photomicrograph (ppl) of $S_1$ defined by a chlorite-sericite-hematite stylolitic fabric in feldspar-phycite pumice-lithic breccia (120R, 723 m). $S_1$ is crenulated by the regional cleavage ($S_2$). D. Photomicrograph (120R, 727 m xn) of the two fabrics in pumice-rich breccias. $S_1$ is a compaction foliation defined by chlorite-sericite-rich lenses (fiamme) which are enclosed in feldspar-quartz-sericite-rich domains. The feldspar-rich domains preserve uncompacted shards. $S_2$ is the regional cleavage defined by the alignment of sericite. E. Folded fiamme with an axial planar regional cleavage ($S_2$) exposed on the eastern flank of Mount Read. F. The east-dipping Rosebery Fault exposed between the Pieman Road and Bastyan Dam north of Rosebery.
pumice breccia. Mapping of $S_1$ has been crucial in the identification of folds and faults in the northern Central Volcanic Complex (Fig. 4.5).

Regional tectonic cleavage: Two regional tectonic cleavages have been recognised in strongly deformed parts of the Central Volcanic Complex (Corbett and Lees, 1987; Aerden, 1993). The dominant cleavage ($S_2$) is present throughout the Central Volcanic Complex. $S_2$ is axial planar to the main folds ($F_2$), and is parallel with the stretching lineation in rocks at Rosebery. $S_2$ strikes north, dips steeply (easterly to sub-vertical dips) and varies from a moderately intense, spaced cleavage to an intense, pervasive anastomosing cleavage in the most strongly deformed rocks (Figs. 4.4 and 4.5). $S_2$ becomes shallower adjacent to major brittle-ductile faults (Rosebery Fault, Mount Black Fault and Henty Fault) and grades with increasing intensity into shear zones. $S_2$ is interpreted to be associated with regional Devonian deformation (Brathwaite, 1974; Corbett and Lees, 1987; McNeill and Corbett, 1989).

**Figure 4.5:** Stereographic projections of the poles to foliations in the northern Central Volcanic Complex. A. Poles to bedding ($S_0$), compaction foliation ($S_1$) and flow-banding lie on a fan which suggests that the compaction foliation and to a lesser extent the flow-banding, is parallel to bedding and that they have been folded by N-plunging open folds. The fold axis plunges 31° toward 353°. B. Poles to regional cleavage ($S_2$) indicate steep, mainly easterly, dips.

### 4.4.2 Folds

One generation of folds ($F_2$) is recognised in the northern Central Volcanic Complex. It comprises open, NNE-trending, upright folds with axial-planar, regionally pervasive $S_2$ cleavage and steeply E-dipping axial surfaces (Fig. 4.5). Parasitic folds defined by rapid changes in younging directions in the volcaniclastic units are associated with the limbs of $F_2$ folds. $F_2$ folds are disrupted by E-W-striking, steeply dipping, strike-slip faults ($F_3$).

The Hercules Pumice Formation and White Spur Formation (formerly Hangingwall Pyroclastics) occupy a 800 to 1700 m wide block between the Rosebery and Mount Black Faults. They strike north,
and young and dip steeply east (Fig. 4.2). The Kershaw Pumice Formation and Mount Black Formation also dip and young east at their western margin; however towards the east they dip and young west. The Sterling Valley Volcanics dip and young west. These changes in structural orientation are interpreted to indicate that the Hercules Pumice Formation, White Spar Formation, Kershaw Pumice Formation and western portion of the Mount Black Formation form the eastern limb of an $F_2$ anticline. This NNE-trending, N-plunging regional anticline extends for 20 km from Hercules in the south, to Pinnacles in the north (Fig. 4.2).

Open folds are present in the northern Central Volcanic Complex. In the Rosebery-Tullah area, the Mount Black Formation is exposed in a regional syncline (Figs. 4.2 and 4.3). Changes in dip define a number of N-plunging parasitic folds related to this regional syncline. Across the 6 km-width of the northern Central Volcanic Complex at Pieman Road and in the Rosebery-Tullah area, folds and faults repeat units in the Kershaw Pumice Formation and the Mount Black Formation at a similar stratigraphic level (Fig. 4.3).

To the east, the Mount Black Formation and Sterling Valley Volcanics are exposed in the core and on the western limb of a regional N-plunging anticline (Figs. 4.2 and 4.3). This anticline extends from north of Mount Black to south of Tullah and is truncated by the Henry Fault (Corbett and Solomon, 1989). The position of the Sterling Valley Volcanics in the core of the anticline implies that they are the lowest exposed part of the northern Central Volcanic Complex, underlying the Mount Black Formation.

### 4.4.3 Faults and shear zones

Faults and shear zones are common in the northern Central Volcanic Complex, and several generations of movement have been recognised along major faults (Berry, 1989; Allen, 1991 unpub.).

Faults include N- and NNE-striking, steeply dipping faults, and E-W-striking faults (Fig. 4.2). Three N-striking faults dominate the northern Central Volcanic Complex: these are the E-dipping Rosebery Fault and Mount Black Fault, and the W-dipping Henry Fault. A NNE-striking fault is also exposed along the Murchison Highway towards the top of Mount Black. E-W-striking faults ($F_3$) offset the Rosebery and Mount Black Faults (Fig. 4.2).

N-striking shear zones within the Mount Black Formation along the Pieman Road and Murchison Highway are accompanied by intense hydrothermal alteration to assemblages of sericite-pyrite ± chlorite. These steeply E-dipping shear zones have a reverse sense of movement and are parallel with the regional $S_2$ cleavage.

**Rosebery Fault:** The Rosebery Fault separates the Dundas Group from the Central Volcanic Complex north of Hercules and cuts across the Dundas Group south of Williamsford (Corbett, 1986). At Rosebery, the Rosebery Fault dips 40° to the east (Fig. 4.4) (Corbett and Lees, 1987). This thrust fault has a minimum down-dip displacement of 1.5 km, a 1 m thick gouge-filled zone and a zone, tens of metres thick, of strongly developed slaty cleavage (Corbett and Lees, 1987). North of Williamsford most displacement at the western margin of the Central Volcanic Complex is taken up by one main fault, the Rosebery Fault. South of Williamsford the Rosebery Fault bifurcates into a
series of fault splays (R.L. Allen, written communication, 2000). The fault is marked by quartz-
tourmaline veins, minor fluorite, pyrite, galena, chalcopyrite, calcite, gold and silver at Rosebery (Corbett,
1986; Corbett and Lees, 1987). The overlying Hercules Pumice Formation have been silicified adjacent
to the fault (Corbett and Lees, 1987). The paragenesis of veins and hydrothermal alteration in the
fault zone implies that the Rosebery Fault had at least two phases of movement, one in the Middle to
Late Cambrian and a second during the Devonian (Corbett and Lees, 1987, Corbett and Turner,
1989).

**Henty Fault**: The Henty Fault obliquely bisects the Mount Read Volcanics. It extends for 30 km
from the Henty mine to Tullah and further north to Mount Cripps where it steps east on a transfer
fault (Corbett and Komyshan, 1989; Berry, 1989). The Henty Fault separates the northern Central
Volcanic Complex from the Farrell Slates (Mount Charter Group) to the east. It is a major brittle-
ductile reverse fault that dips west under the Sterling Valley Volcanics (Berry, 1993 unpub.). The fault
is slightly oblique to bedding in both map view and cross section (Figs. 4.2 and 4.3). In map view, this
discordance is reflected in the southward truncation of both the Farrell Slates and Sterling Valley
Volcanics (Fig 4.2). This structural discordance and change in facies either side of the fault indicate
major displacement along the Henty Fault.

The Henty Fault has a deformation zone of up to 1 km wide (Corbett and Lees, 1987). Near
Tullah, the fault zone comprises intensely broken, sheared, quartz-veined rock within a strong zone
of silicification (Allen, 1995 unpub.). Adjacent to the Henty Fault cleavage steepens to near vertical
and trends NNE, parallel to the fault (McNeill and Corbett, 1989; Berry, 1993 unpub.).

The Henty Fault has a complex history with at least five fault movement generations: two early
phases of reverse movement, sinistral wrench faulting, wrench faulting and normal faulting (Berry,
1989). The major movement on the fault post-dates Devonian folding (F3) (Berry, 1989).

**Mount Black Fault**: The Mount Black Fault was first recognised by Purvis, (1989 unpub.) and
Allen (1990) and defined by Allen (1991 unpub.; 1992b unpub.). It is a thrust fault that juxtaposes the
quartz-phyric units of the White Spur Formation at Rosebery with the feldspar-phyric Kershaw Pumice
Formation. The Mount Black Fault has been intersected in drill core between Bastyan Dam and
Hercules. At the surface, south of Rosebery Lodes, the Mount Black Fault juxtaposes the Kershaw
Pumice Formation and the Hercules Pumice Formation.

The Mount Black Fault is sub-parallel to the Rosebery Fault, dipping 28-40° to the east beneath
the Kershaw Pumice Formation and the Mount Black Formation. It strikes and dips at a low angle to
bedding and truncates units in the White Spur Formation, the Kershaw Pumice Formation and basaltic
dykes of the Henry Dyke Swarm. At depth, in the south end of the Rosebery mine, the Mount Black
Fault splays into a lower and upper fault (Fig. 4.6). The lower ductile fault occurs at the White Spur
Formation-Kershaw Pumice Formation contact and is defined by a rapid change in lithofacies and a 1
m wide zone of intense shearing and fault gouge. A 1 m thick zone of fault breccia and abundant
quartz-tourmaline-calcite veins in a 3-10 m wide zone marks the upper fault. These two splays of the
Mount Black Fault enclose a wedge of plagioclase-phyric pumice breccia identical to pumice breccia
in both the Hercules and Kershaw Pumice Formations (Fig. 4.5). South of Rosebery, the Mount Black
Table 4.2: Number of whole-rock geochemistry samples analysed for the main facies in the Sterling Valley Volcanics, the Mount Black Formation and the Kershaw Pumice Formation.

<table>
<thead>
<tr>
<th>Volcanic facies</th>
<th>Interpretation</th>
<th>Total number of samples</th>
<th>Number of least-altered samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent rhyolite</td>
<td>coherent facies of lavas and sills</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>Monomictic rhyolite breccia</td>
<td>autobreccia and hyaloclastite</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Coherent feldspar-phyric dacite</td>
<td>coherent facies of lavas and sills</td>
<td>47</td>
<td>27</td>
</tr>
<tr>
<td>Coherent feldspar-hornblende-phyric dacite</td>
<td>coherent facies of lava domes and cryptodomes</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Feldspar-phyric andesite and basalt</td>
<td>coherent facies of lavas and sills</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Aphric andesite and basalt</td>
<td>coherent facies of lavas and sills</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Monomictic mafic breccia</td>
<td>autobreccia and hyaloclastite</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pumice breccia</td>
<td>syn-eruptive, juvenile, pyroclastic</td>
<td>22</td>
<td>16</td>
</tr>
<tr>
<td>Pumice-clast-rich breccia</td>
<td>resedimented autobreccia, hyaloclastite ± pyroclastic</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>Crystal-rich sandstone</td>
<td>post-eruptive, resedimented sediment</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Polymictic mafic breccia</td>
<td>resedimented syn-eruptive autobreccia, hyaloclastite ± pyroclastic</td>
<td>6</td>
<td>6</td>
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<tr>
<td>Quartz-feldspar-phyric rhyolite</td>
<td>syn-volcanic sills or dykes</td>
<td>10</td>
<td>7</td>
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<tr>
<td>Massive basalt and dolerite</td>
<td>post-lithification dykes</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

used. Detection limits are listed in Appendix C.

Complete whole-rock analyses are presented in Appendix D according to facies designation based on hand specimen and thin section descriptions.

4.5.2 Element mobility

The chemical compositions of volcanic rocks in the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation vary widely, reflecting primary magmatic variation, and the combined effects of diagenesis, metamorphism and hydrothermal alteration. Although, the major oxide and trace element contents, including Na₂O, of the least-altered samples are consistent with those of fresh, unaltered modern calc-alkaline and tholeiitic volcanics (Na₂O 3-5 wt %, Barrett et al., 1993; Stolz et al., 1996a unpub.), altered samples have a much greater range, particularly in Na₂O content (0-7.24 wt %, Appendix D). Typically major elements used for the classification of fresh, modern volcanic rocks are mobile during diagenesis, metamorphism and hydrothermal alteration (MacLean and Krandidiotis, 1987; Whitford et al., 1989; Rollinson, 1993; McNeill and Corbett, 1989; Lipman, 1965). Classification of ancient volcanic rocks relies on the comparison of their immobile element concentrations with those of modern examples from known tectonic settings (eg. Pearce and Cann, 1973; Winchester and Floyd, 1977; Rollinson, 1993; Barrett and MacLean, 1997).

Elements that are generally considered to be immobile during greenschist facies metamorphism and hydrothermal alteration associated with VHMS mineralisation are the high field strength (ie, Ti, Zr, Hf, Y, Nb, Ta, Th, U) and rare earth elements (REE) (Winchester and Floyd, 1977; Barrett and MacLean, 1994). However, some of these elements, particularly the REE may be mobile under certain conditions (Finlay-Bates and Stumpfl, 1981; Larson, 1984; Wynne and Strong, 1984).
Figure 4.7: Geology of the northern Central Volcanic Complex east of the Mount Black Fault. This map shows the distribution of the samples used for whole-rock geochemistry.
The immobility of elements in the Central Volcanic Complex samples was tested on a texturally homogenous pumice breccia unit from the Hercules Pumice Formation, for which there are a relatively large number (85) of analyses. This pumice breccia unit can be traced laterally through the Rosebery VHMS alteration zone. Analyses used in this test were carefully selected from the MRCEM database (produced on CD-ROM in conjunction with AMIRA project P439 final report, Blake, 1998 unpub), and are partly reproduced in Large and Allen (1997 unpub.). Scatter plots of TiO₂, Al₂O₃, P₂O₅, Zr, Nb, V Sc and Y element pairs for least-altered and altered Hercules Pumice Formation pumice breccia show linear trends, which regress to the origin (Fig. 4.8). This strong correlation of element pairs implies that there has been no fractionation of these elements relative to each other during emplacement of the pumice breccia facies or during alteration (cf. MacGeehan and MacLean, 1980). It does not preclude the small possibility that they have been jointly and equally mobilised. The linear distribution of points can be attributed to mass gains and losses of the mobile elements during alteration (cf. Barrett and MacLean, 1994). Ratios between Ti, Zr, Nb, Sc, V, Al₂O₃ and P₂O₅ are constant which suggests that they were all relatively immobile during alteration and metamorphism. Y shows more variation (Fig. 4.8) which may be due in part to primary variations in Y (Ewart, 1979), mobility of Y in strongly altered rocks, or due to analytical precision of Y.

4.5.3 Immobile element geochemistry

In the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation, immobile element compositions of least-altered samples can be used to identify compositional groups. In this section, only texturally homogeneous volcanic facies, such as the coherent facies of lavas and intrusions, and syn-eruptive pumice breccias are considered, because these facies have undergone minimal compositional changes during emplacement.

In the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation, least-altered samples show a negative correlation between SiO₂ contents and Ti/Zr, indicating that SiO₂ in these samples has been relatively immobile during metamorphism (Fig. 4.9a). However, altered samples have considerably more variation in SiO₂ relative to Ti/Zr, which precludes the use SiO₂ content to classify altered rocks (Fig. 4.9b). For these, the fractionation-dependent compatible-incompatible immobile ratio, Ti/Zr, was used to estimate the primary magmatic composition (cf. Berry et al., 1992; MacLean and Barrett, 1993; Stolz, 1995). This ratio is dependent on the initial Ti/Zr ratio in the source (ie. protolith) and the degree of fractionation. Ranges in Ti/Zr for rhyolitic, dacitic, andesitic and basaltic compositions for the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation were determined using the SiO₂ values of the least-altered samples compared with values for samples from unaltered modern volcanics (Fig. 4.9a and Table 4.3). Altered and least-altered rocks have been classified primarily on the basis of their mineralogy and Ti/Zr values (Table 4.3).

Compositions in the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation range from rhyolitic to basaltic (Table 4.4). The least-altered samples can be divided into three broad compositional groups using plots of immobile elements (TiO₂-Zr, TiO₂-Nb, Al₂O₃-Zr, Al₂O₃-Nb, P₂O₅-SiO₂, TiO₂-SiO₂ and Zr/Sc-SiO₂, Fig. 4.10).

Group 1

Group 1 samples are rhyolites with very low TiO₂ (<0.4 wt %), low Ti/Zr (4-9), low Al₂O₃ (10-16 wt
Figure 4.8: Plots of immobile element concentrations in altered and least-altered samples from a homogeneous pumice breccia in the Hercules Pumice Formation (Footwall Pyroclastics). A. Zr versus TiO\textsubscript{2}. B. Zr versus Y, Nb, V and Sc. C. Zr versus Al\textsubscript{2}O\textsubscript{3} and P\textsubscript{2}O\textsubscript{5}. D. TiO\textsubscript{2} versus Y, Nb, V and Sc. E. TiO\textsubscript{2} versus Al\textsubscript{2}O\textsubscript{3} and P\textsubscript{2}O\textsubscript{5}. F. Al\textsubscript{2}O\textsubscript{3} versus Y, V and Sc. G. Al\textsubscript{2}O\textsubscript{3} versus Nb and P\textsubscript{2}O\textsubscript{5}. Linear trends are due to mass gains and losses of mobile elements (cf. MacLean and Barrett, 1993) and imply that Zr, TiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}, Nb and Sc were relatively immobile. The Y distribution is more scattered possibly due to mobility during alteration, inherent primary variations or analytical precision.
Figure 4.9: Plots of SiO$_2$ versus Ti/Zr for A. least-altered and B. altered and least-altered Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation. Compositions of least-altered rocks in the northern Central Volcanic Complex range from rhyolitic to basaltic. The negative correlation between SiO$_2$ and Ti/Zr suggests that SiO$_2$ was relatively immobile in most samples, however some altered samples are depleted or enriched in SiO$_2$ compared to the least-altered samples. The plot of least-altered samples was used to determine Ti/Zr ratio ranges that correspond to rhyolitic, dacitic, andesitic and basaltic compositions.

Group 1

Group 1 samples are plagioclase-phyric rhyolitic sills, lavas, pumice breccias and some quartz-feldspar-phyric rhyolitic sills of the Mount Black Formation and the Kershaw Pumice Formation.

Group 2

Group 2 samples are dacites characterised by moderate TiO$_2$ (0.4-0.8 wt %), moderate Ti/Zr (10-19), moderate Al$_2$O$_3$ (14-17 wt %), moderate P$_2$O$_5$ (0.07-0.16 wt %), moderate Nb (8-14 ppm) and high SiO$_2$ (64-72 wt %). Group 2 includes plagioclase-phyric dacitic lavas and sills, plagioclase-hornblende-phyric dacitic lavas, some quartz-feldspar-phyric rhyolitic sills and sparse dacitic pumice breccias of the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation.

Group 3

Group 3 samples are andesites and basalts and are characterised by generally high TiO$_2$ (0.4-2 wt %), variable but high Ti/Zr (26-158), moderate Al$_2$O$_3$ (8-23 wt %), moderate P$_2$O$_5$ (0.05-0.25 wt %), low Nb (<6 ppm) and low SiO$_2$ (42-59 wt %). These samples are predominantly basalt or dolerite dykes of the Henry Dyke Swarm, but also include aphyric and feldspar-phyric basaltic lavas and sills in the Sterling Valley Volcanics.
Table 4.3: A. Phenocryst mineralogy and Ti/Zr for different compositions in the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation, including altered and least-altered samples. These compositional ranges are consistent with the values of Large et al. (1986 unpub.) for the Central Volcanic Complex. B. SiO₂ contents for different compositions of least-altered samples in the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation. These compositional ranges are consistent with the values of Crawford et al. (1992) for the Central Volcanic Complex and for modern subduction-related volcanics (Ewart, 1979 and 1982).

A

<table>
<thead>
<tr>
<th>Phenocryst mineralogy</th>
<th>Ti/Zr (this study)</th>
<th>Ti/Zr (Large et al., 1986 unpub.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhyolite</td>
<td>plagioclase ± quartz</td>
<td>4-10</td>
</tr>
<tr>
<td>Dacite</td>
<td>plagioclase ± hornblende</td>
<td>10-20</td>
</tr>
<tr>
<td>Andesite</td>
<td>plagioclase</td>
<td>20-60</td>
</tr>
<tr>
<td>Basalt</td>
<td>plagioclase ± pyroxene ± hornblende</td>
<td>60-157</td>
</tr>
</tbody>
</table>

B

<table>
<thead>
<tr>
<th>SiO₂ (this study)</th>
<th>SiO₂ (Crawford et al., 1992)</th>
<th>SiO₂ (Ewart 1982)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhyolite</td>
<td>&gt;69 wt %</td>
<td>&gt;68 wt %</td>
</tr>
<tr>
<td>Dacite</td>
<td>64-72 wt %</td>
<td>64-68 wt %</td>
</tr>
<tr>
<td>Andesite</td>
<td>52-59 wt %</td>
<td>53-64 wt %</td>
</tr>
<tr>
<td>Basalt</td>
<td>&lt;52 wt %</td>
<td>&lt;53 wt %</td>
</tr>
</tbody>
</table>

Group 3 can be subdivided into two compositional subgroups (a and b) based on Ti/Zr and Nb content (Fig. 4.11). Group 3a samples are andesites and basalts and are characterised by generally high TiO₂ (0.5-2 wt %), Ti/Zr from 26 to 101, high Al₂O₃ (15-23 wt %), moderate P₂O₅ (0.05-0.25 wt %), low Nb (1-6 ppm) and low SiO₂ (49-59 wt %). Group 3a is compositionally diverse and includes two petrographically and texturally distinctive facies: (i) aphyric or weakly plagioclase-phric basalts and dolerites, and (ii) coarsely porphyritic, plagioclase ± clinopyroxene ± hornblende-phric andesites and basalts. The coarsely porphyritic rocks plot as a discrete field within Group 3a and have low MgO values (3.5-5 wt %), low SiO₂ (51-52.5 wt %) and high Cr (60-107 ppm) and Ni (31-53 ppm) contents compared with other Group 3a rocks (Fig. 4.11).

Group 3b samples are dolerite dykes characterised by high TiO₂ (0.4-1 wt %), Ti/Zr from 96 to 158, moderate Al₂O₃ (12-19 wt %), moderate P₂O₅ (0.06-0.15 wt %), very low Nb (< 0.5 ppm) and low SiO₂ (42-50 wt %). The Nb abundances are below the detection limit (1 ppm), and although inaccurate appear to be distinct from the less depleted Group 3a. Group 3b is also characterised by high Cr (53-1326 ppm), Ni (52-266 ppm) and low V (195-245 ppm).

4.5.4 Magmatic affinities and tectonic implications

A plot of Zr/TiO₂ versus Nb/Y (Fig. 4.12) distinguishes subduction-related magmas from intraplate or rift-related alkaline magmas (Winchester and Floyd, 1977). It also distinguishes the various rock groups within these associations that would normally be determined on SiO₂ and alkali contents in the absence of alteration. For the northern Central Volcanic Complex, this plot shows that the samples are dominantly rhyolites and dacites that define a group with a restricted range in Nb/Y and a broad range in Zr/TiO₂ (Fig. 4.12). There is a good correlation between the compositional fields in Figure 4.12 and compositions based on mineralogy and Ti/Zr (Fig. 4.9 and Table 4.3). Feldspar-phric rhyolites and quartz-feldspar-
Table 4.4: Average composition of least-altered volcanic facies in the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation. Averages determined from analyses recalculated to 100% on an anhydrous basis (Appendix D).

<table>
<thead>
<tr>
<th></th>
<th>Coherent feldspar dacite</th>
<th>Coherent feldspar hornblende dacite</th>
<th>Feldspar-basalt</th>
<th>Massive basalt and dolerite</th>
<th>Polymictic breccia</th>
<th>Crystal-rich sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=11</td>
<td>n=12</td>
<td>n=9</td>
<td>n=6</td>
<td>n=7</td>
<td>n=8</td>
</tr>
<tr>
<td><strong>Major elements (wt %)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>74.47</td>
<td>73.99</td>
<td>73.39</td>
<td>74.21</td>
<td>67.62</td>
<td>65.08</td>
</tr>
<tr>
<td>TiO₂</td>
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<td>0.24</td>
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</tr>
<tr>
<td>Al₂O₃</td>
<td>2.83</td>
<td>2.19</td>
<td>2.19</td>
<td>2.42</td>
<td>2.87</td>
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</tr>
<tr>
<td>Fe₂O₃{total}</td>
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<td>1.89</td>
<td>1.89</td>
<td>2.18</td>
<td>3.50</td>
<td>4.25</td>
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<tr>
<td>MgO</td>
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<td>0.67</td>
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<tr>
<td>CaO</td>
<td>3.43</td>
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<td>3.60</td>
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<tr>
<td>Sr</td>
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<td>10.03</td>
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<td><strong>Trace elements (ppm)</strong></td>
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</tr>
<tr>
<td>Ba</td>
<td>687</td>
<td>669</td>
<td>944</td>
<td>965</td>
<td>711</td>
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<tr>
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<td>0.84</td>
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</tr>
<tr>
<td>Cr</td>
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<tr>
<td>La</td>
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<tr>
<td>Ba</td>
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<tr>
<td>Cr</td>
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<tr>
<td>La</td>
<td>0.72</td>
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<td>0.72</td>
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<tr>
<td>Ti</td>
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<td>1.38</td>
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<tr>
<td>Zr</td>
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<td>800</td>
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<td>800</td>
</tr>
</tbody>
</table>

**Notes:**
- Data recalculated to 100% on an anhydrous basis.
- Major elements and trace elements are provided in wt % and ppm, respectively.
phyric rhyolites plot as rhyolites and rhyodacites. Aphyric and feldspar-phyric andesites and basalts plot as basaltic andesites. The northern Central Volcanic Complex has low Nb/Y values characteristic of subduction-related subalkaline volcanic suites (cf. Winchester and Floyd, 1977).

Groups 1 and 2 rhyolites and dacites are volumetrically abundant (~89 vol %) within the Central Volcanic Complex. These rhyolites and dacites have similar incompatible element ratios (Zr-Y and Zr-Nb) and negative correlations between compatible elements, incompatible-compatible ratios and SiO2 (Figs. 4.10, 4.11 and 4.13). This is consistent with Groups 1 and 2 resulting from fractionation of a single parent magma or separate essentially compositionally identical parent magmas. Petrographically, the least-evolved rocks in these groups are the feldspar-hornblende-phyric dacites.
Figure 4.11: Discrimination diagrams for subgroups 3a and 3b of least-altered andesitic and basaltic lavas, sills, dykes and polymictic mafic breccias in Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation. A. $P_{2}O_{5}$/Zr versus $P_{2}O_{5}$/Y. B. Zr versus Nb. C. MgO versus Ti/Zr. D. SiO$_2$ versus MgO. Polymictic mafic breccia (in red) plot along a trend from Group 3 tholeiitic basalts to Group 2 calc-alkaline dacites. See Figure 4.9 for key to symbols.

Figure 4.12: Discrimination diagram of Nb/Y versus Zr/TiO$_2$ (after Winchester and Floyd, 1977) for least-altered samples from the Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation. Variations in immobile element ratios reflect primary compositional variations of the main lithofacies.
Subalkaline volcanic suites can be divided into tholeiitic and calc-alkaline associations (Irvine and Baragar, 1971). Calc-alkaline affinity is commonly defined by a progressive decrease in $\text{FeO}_{\text{tot}}$ and $\text{TiO}_2$ with increasing fractionation (increasing $\text{SiO}_2$ and decreasing $\text{MgO}$), whereas tholeiitic suites show increases in $\text{FeO}_{\text{tot}}$ and $\text{TiO}_2$ at the mafic end of the spectrum. Tholeiitic and calc-alkaline associations can also be distinguished using the incompatible element pair Zr-Y (Lesher et al., 1986; MacLean and Barrett, 1993). On a Zr-Y scatter plot, samples from different parental magmas plot as separate linear fractionation trends that regress to the origin. MacLean and Barrett (1993) assigned samples with Zr/Y <5 as tholeiitic, Zr/Y = 7-30 as calc-alkaline, and values between 5-7 as transitional. The higher Zr/Y of calc-alkaline magmas is interpreted to reflect the compatible behaviour of Y in calc-alkaline magmas and decreasing Y concentration in the magma during fractionation of hornblendes (Pearce, 1982). Groups 1 and 2 are calc-alkaline and transitional, with decreasing $\text{FeO}_{\text{tot}}$ as $\text{SiO}_2$ increases and Zr/Y values between 6-30 (Fig. 4.13). They typically have 2-5 wt % $\text{K}_2\text{O}$, suggesting affinities with medium to high-K calc-alkaline series (Fig. 4.13).

Group 3 andesites and basalts are compositionally distinct from Groups 1 and 2, having different Zr/Y and Zr/Nb values and plotting on separate trends on $\text{P}_2\text{O}_5$/Y-$\text{P}_2\text{O}_5$/Zr and $\text{Al}_2\text{O}_3$/TiO$_2$-$\text{Al}_2\text{O}_3$/Zr diagrams (Figs. 4.11 and 4.13). This indicates that Group 3 samples were derived from different parental magmas than Groups 1 and 2. The considerable variation in TiO$_2$ and Zr over a limited $\text{SiO}_2$ range within Group 3 suggests that although Group 3 samples were probably derived from similar parental magmas they were not all identical. Group 3 is tholeiitic, with increasing FeO$_{\text{tot}}$ as MgO decreases and Zr/Y values less than 5 (Fig. 4.13).

A variety of discrimination diagrams using high-field-strength elements (HFSE, such as, Ti, Zr, Y, Nb, P and Th) have been used to constrain the tectonic setting of Group 3 basalts (Fig. 4.14; Pearce and Cann, 1973; Pearce and Norray, 1975; Rollinson, 1993). Group 3 samples are similar to island arc or back-arc tholeiites, with the exception of the high-Ti dykes (Group 3b) which plot in the MORB or back-arc basin tholeiitic field (Fig. 4.14). Group 3 tholeiites are compositionally similar to basalts erupted during rifting of a volcanic arc and embryonic development of a back-arc basin (cf. Weaver et al., 1979; Thy, 1992; Shinjo, 1998).

The petrology and tectono-magmatic evolution of the Mount Read Volcanics were examined on a regional scale by Crawford et al. (1992) using whole-rock geochemistry, and REE. Crawford et al. (1992) defined three calc-alkaline and two tholeiitic compositional suites to improve chemostratigraphic correlation within the succession, identify prospective volcanic associations, and characterise the tectonic setting. Suite I is a transitional and medium to high-K calc-alkaline suite which includes rhyolites and dacites of the Eastern quartz-phyric sequence, Central Volcanic Complex, Tyndall Group, quartz-phyric intrusions, Cambrian granites, and andesites of the Que-Hellyer footwall (Mount Charter Group). Suite II comprises dacies and andesites of high-K calc-alkaline affinity. Suite III includes calc-alkaline to shoshonitic andesites and basalts from the Que-Hellyer hangingwall, Lynch Creek and Howard’s Plain (Yolande River sequence). Suite IV comprises tholeiitic andesites and basalts from the Henty Fault Wedge and basaltic dykes of the Henry Dyke Swarm. Suite V comprises the tholeiitic Miners Creek Basalt.

Groups 1 and 2 rhyolite and dacites of the Sterling Valley Volcanics, Mount Black Formation.
Figure 4.13: Diagrams discriminating magmatic affinity and tectonic setting of least-altered lavas, sills, dykes and pumice breccias in Sterling Valley Volcanics, Mount Black Formation and Kershaw Pumice Formation. See Figure 4.9 for key to symbols. A. TiO$_2$ versus SiO$_2$ shows a decrease in TiO$_2$ for Groups 1 and 2 rhyolites and dacites with increasing SiO$_2$, whereas Group 3 andesites and basalts increase SiO$_2$. B. FeO$_{total}$ versus SiO$_2$. Groups 1 and 2 lie on a trend of decreasing FeO$_{total}$ with increasing SiO$_2$ consistent with fractionation of a calc-alkaline magma. C. Ti/Zr versus SiO$_2$. Groups 1 and 2 rhyolites and dacites plot on a single trend consistent with fractionation. D. Y versus Zr. This shows the tholeiitic and calc-alkaline fields as defined by MacLean and Barrett (1993). Groups 1 and 2 plot in the calc-alkaline field, whereas Group 3 is tholeiitic. E. K$_2$O versus SiO$_2$. The high-, medium- and low-K boundaries from Ewart (1982) indicate that the K$_2$O contents of Groups 1 and 2 are medium to high-K, although some spread in the data is due to the mobility of K$_2$O during alteration and metamorphism. F. FeO$_{total}$ versus MgO. Increasing FeO$_{total}$ with decreasing MgO for Group 3 consistent with tholeiitic affinities. G. Al$_2$O$_3$/Zr versus Al$_2$O$_3$/TiO$_2$ indicates that Groups 1 and 2 have a different magmatic source from Group 3. H. P$_2$O$_5$/TiO$_2$ versus SiO$_2$. Fields for Suite I, III, IV and V from Crawford et al. (1992). Groups 1 and 2 are Suite I and Group 3 is Suite IV of Crawford et al. (1992).
Figure 4.14: Tectonic discrimination diagrams for least-altered basalts, andesites and polymictic mafic breccias of the Sterling Valley Volcanics and basaltic dykes. See Figure 4.9 for key to symbols. A. Ti-Zr-Y discrimination diagram (after Pearce and Cann, 1973). The fields are: A, island arc tholeiites; B, MORB, island arc tholeiites and calc-alkaline basalts; C, calc-alkaline basalts; and D, intraplate basalts.

B. Ti-Zr discrimination diagram for basalts (after Pearce and Cann, 1973). The fields are: A, island-arc tholeiites; B, MORE, island arc tholeiites and calc-alkaline basalts; C, calc-alkaline basalts; and D, MORB.

C. Zr/Y-Zr discrimination diagram (after Pearce and Norray, 1979). The fields are: A, volcanic-arc basalts; B, MORB; C, intraplate basalts; D, MORB and volcanic-arc basalts; and E, MORB and intraplate basalts.

D. Ti-V discrimination diagram for basalts (after Rollinson, 1993). Samples of andesitic and basaltic lavas and sills of the Sterling Valley Volcanics and dykes from northern Central Volcanic Complex plot in fields consistent with arc tholeiites.

and Kershaw Pumice Formation match Suite I of Crawford et al. (1992), with high SiO₂ (>63 wt %) and low P₂O₅/TiO₂ (<0.35) (Fig. 4.13). Group 1 feldspar-phyric rhyolites are the most evolved Central Volcanic Complex rocks. Rhyolites and dacites of the northern Central Volcanic Complex have La/Yb ratios, Sm-Nd isotopic values and εNd values typical of rocks derived largely from crustal melts (Crawford et al., 1992, 2000 unpub.; Hollings et al., 2000 unpub.).

Group 3 andesites and basalts of the Sterling Valley Volcanics and the basalt and dolerite dykes of the Henty Dyke Swarm plot within Crawford et al. (1992) Suite IV. They have relatively high TiO₂ (0.4-2 wt %) and very low Nb (<6 ppm) contents and low P₂O₅/TiO₂ (<0.25). In the Sterling Valley Volcanics, dacitic, andesitic and basaltic lavas and sills are intercalated with regraded andesitic breccia, hyaloclastite, polymictic mafic breccia, mafic volcanic sandstone and siltstone. The interpretation of lavas, sills and dykes is based on the distribution of coherent and autoclastic facies and the nature of the contacts (Chapter 3). Polymictic mafic breccia facies contains a wide variety of clast types and
shows a compositional range, plotting both within the field for Group 3 tholeiitic, feldspar-phyric lavas of the Sterling Valley Volcanics and along a trend towards Group 2 calc-alkaline, feldspar-phyric dacites (Fig. 4.11). This compositional trend and the intercalation of calc-alkaline feldspar-phyric dacitic lavas with the tholeiitic andesitic and basaltic lavas suggests that tholeiitic and calc-alkaline volcanism were coeval during formation of at least part of the Sterling Valley Volcanics.

The presence of intrusions and lavas in the Sterling Valley Volcanics with compositional affinities with the Henry Dyke Swarm has significant implications for regional stratigraphic correlation and tectonic interpretations of the Mount Read Volcanics (section 4.7).

4.6 Lithogeochemical comparisons for the Central Volcanic Complex

Three facies associations in the northern Central Volcanic Complex are useful for local and regional lithogeochemical comparisons: (1) calc-alkaline, rhyolitic and dacitic lavas and intrusions; (2) calc-alkaline pumice breccia; (3) tholeiitic andesites and basalts.

4.6.1 Calc-alkaline, rhyolitic and dacitic lavas and intrusions

The northern Central Volcanic Complex contains abundant feldspar-phyric and quartz-feldspar-phyric rhyolitic and dacitic lavas, domes and sills. They occur predominantly in the Mount Black Formation, but also in the Kershaw Pumice Formation, the Sterling Valley Volcanics and Hercules Pumice Formation. The identical textures, lithofacies characteristics and compositions of feldspar-phyric dacites in the Kershaw, Pumice Formation, Mount Black Formation and the Sterling Valley Volcanics have been described in Chapter 3 and section 4.5.3. Rhyolites and dacites in the Hercules Pumice Formation also have similar textures, lithofacies characteristics and compositions to those in the Kershaw Pumice Formation and the Mount Black Formation (Allen, 1991 unpub.). Unlike the rhyolites and dacites in the Mount Black Formation, those in the Hercules and Kershaw Pumice Formations are dominantly syn-volcanic sills with peperitic margins (Allen, 1991 unpub.).

Coherent feldspar-phyric rhyolites in the Kershaw Pumice Formation, Mount Black Formation and Hercules Pumice Formation are compositionally very similar (Fig. 4.15). They typically have high SiO₂ (70-78 wt %), low Ti/Zr (4-10), low TiO₂ (0.16-0.44 wt %), moderate Al₂O₃ (11-15 wt %), low P₂O₅ (0.01-0.07 wt %) and high Nb (7-18 ppm). Analyses for feldspar-phyric rhyolites and dacites and quartz-feldspar-phyric rhyolites in the Hercules Pumice Formation are from the MRCHEM database (Blake, 1998 unpub.), Large and Allen (1997 unpub.) and Large et al. (in press b).

Feldspar-phyric dacites in the Kershaw Pumice Formation, Mount Black Formation and Hercules Pumice Formation are characterised by moderately high SiO₂ (63-78 wt %), moderate Ti/Zr (10-19), low TiO₂ (0.2-0.81 wt %), moderate Al₂O₃ (8-22 wt %), moderate P₂O₅ (0.07-0.25 wt %) and high Nb (5-16 ppm).

Quartz-feldspar-phyric rhyolites in the Kershaw Pumice Formation, Mount Black Formation and Hercules Pumice Formation are characterised by high SiO₂ (67-78 wt %), low Ti/Zr (6-14), low TiO₂ (0.25-0.5 wt %), moderate Al₂O₃ (12-19 wt %), moderate P₂O₅ (0.04-0.14 wt %) and high Nb (9-16 ppm).
Figure 4.15: Comparison diagrams for rhyolites and dacites in the Mount Black Formation, Kershaw Pumice Formation and Hercules Pumice Formation. A. Ti/Zr versus SiO₂. B. TiO₂ versus Al₂O₃. C. TiO₂/P₂O₅ versus SiO₂. D Nb versus Al₂O₃. These comparison plots suggest that the feldspar-phyric rhyolites and dacites and quartz-feldspar-phyric rhyolites in the Mount Black Formation, Kershaw Pumice Formation and Hercules Pumice Formation have compositional similarities.

The similarities in mineralogy and whole-rock chemistry among the rhyolites and dacites in the Kershaw Pumice and Mount Black Formations, and the rhyolitic and dacitic sills in the Hercules Pumice Formation suggests that they probably had a similar parental magma and source.

4.6.2 Calc-alkaline pumice breccia
Feldspar-phyric pumice breccias are also common in the northern Central Volcanic Complex. They occur in a thick (>550 m, Allen, 1992b unpub.) unit, the Hercules Pumice Formation, along the eastern side of the Rosebery Fault. They also occur in a thick (>800 m) unit, the Kershaw Pumice Formation, along the eastern side of the Mount Black Fault from south of Mount Read to north of Mount Block (Fig. 4.2).

The pumice-rich facies association in both the Kershaw and Hercules Pumice Formations are generally thick (up to 550 m) and laterally extensive (> 16 km), although commonly disrupted by faulting, folding and the intrusion of syn-volcanic rhyolitic and dacitic sills. They have similar
components, textures and lithofacies characteristics (sections 2.6.1 and 3.8)

Pumice breccia in the Kershaw Pumice Formation is composed of plagioclase-phyric tube pumice clasts (60-90 %), fiamme, shards (5-20%), plagioclase crystal fragments (5-20 %), and non-vesicular volcanic lithic clasts (1-5 %) (Chapter 3). Pumice breccia in the Hercules Pumice Formation is also composed of plagioclase-phyric tube pumice clasts (70-90 %), fiamme, shards (5-10%), plagioclase crystal fragments (10-20 %), and weakly or non-vesicular volcanic lithic clasts (1-3 %) which include sparse chlorite-altered, subrounded mafic clasts (Lees, 1987; Allen, 1991 unpub.).

Least-altered pumice breccias in the Kershaw and Hercules Pumice Formations have similar ranges of immobile element concentrations (Table 4.5, Fig. 4.16). Large and Allen (1997 unpub.) showed that the Hercules Pumice Formation contains a lower rhyolitic part and an upper dacitic part. Based on plots of immobile element ratios, the pumice breccias in the Kershaw Pumice Formation can be divided into the same rhyolitic and dacitic groups (Fig. 4.16). Geochemical data for Hercules Pumice Formation pumice breccia units are from the MRCHEM database (produced on CD-ROM in conjunction with AMIRA project P439 final report, Blake, 1998 unpub.) and are partly reproduced in Large and Allen (1997 unpub.) and Stolz et al. (1996a unpub.).

Least-altered rhyolitic pumice breccias in both the Kershaw and Hercules Pumice Formations have 68 to 80 wt % SiO₂ and low Ti/Zr (6.3 to 8.3). They have low TiO₂ (<0.4 wt %), low Al₂O₃ (10-16 wt %), low P₂O₅ (0.01-0.07 wt %), low Sc (2-6 ppm) and low V (2-21 ppm) characteristic of Group 1.

In the Kershaw Pumice Formation, rhyolitic pumice breccia, pumice-rich sandstone and shard-rich siltstone facies show some compositional variations (Fig. 4.16). The more diverse compositions occur in the stratified pumice-rich sandstone and shard-rich siltstone facies. Between beds rapid changes in incompatible immobile element concentrations correspond with observed alternating zircon crystal-poor and crystal-rich beds. Less dramatic variations in composition occur within single pumice breccia beds. Typically, Ti/Zr is lower in the crystal- and lithic clast-rich base than in the well sorted, normally graded or stratified tops of beds (Fig. 4.17). These variations may reflect the behaviour of Zr and Ti during fractionation and subsequent deposition. In pumice-rich sandstone, low Ti/Zr (e. 5.4, sample 120R 614 m) correspond with higher than average modal % zircon crystals. This is consistent with the concentration of largely incompatible Zr into either the original glass or into zircons during fractionation. In contrast, Ti is compatible and is partitioned into Fe-Ti-rich oxides. Variations in the abundance of Fe-Ti-oxides and hematite, which may reflect low temperature replacement of titanomagnetite (Henneberger and Browne, 1988), in the pumice breccia and pumice-rich sandstone facies are generally consistent with the immobile element concentrations. Alternatively, low Ti/Zr at the base of graded beds of pumice breccia may reflect the presence of lithic clasts with lower Ti/Zr values than the pyroclasts.

Least-altered dacitic pumice breccias have 67 to 74 wt % SiO₂ and moderate Ti/Zr (11 to 16). They have low TiO₂ (0.4-0.6 wt %), moderate Al₂O₃ (13-17 wt %), moderate P₂O₅ (0.1-0.12 wt %), high Sc (9-13 ppm) and high V (31-84 ppm) characteristic of Group 2.
Table 4.5: Comparison of characteristics of least-altered pumice breccia from Kershaw and Hercules Pumice Formations. Hercules Pumice Formation pumice breccia lithofacies characteristics from Allen (1991 unpub., 1993 unpub. and 1994a unpub.). Av. = average composition

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<th>Hercules Pumice Formation</th>
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<td>dacitic pumice breccia</td>
<td>dacitic pumice breccia</td>
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<td>massive to normally graded or diffusely stratified breccia or sandstone</td>
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<td>Components</td>
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<td>tube pumice clasts, plagioclase crystal fragments, shards, rhyolitic lithic clasts, mudstone intraclasts, fiamme</td>
<td>tube pumice clasts, feldspar crystal fragments, shards, fiamme</td>
<td>tube pumice clasts, plagioclase crystal fragments, shards, fiamme, very rare quartz crystals (&lt;1%)</td>
</tr>
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<td>8</td>
<td>2</td>
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<td>68.80 (Av. 73)</td>
<td>67.74 (Av. 74)</td>
<td>67.70 (Av. 68)</td>
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<td>11.6-13 (Av. 12.3)</td>
<td>11.2-16 (Av. 13)</td>
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<td>Al2O3 (wt %)</td>
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<td>13.7-16.6 (Av. 15)</td>
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<td>9-12 (Av. 11)</td>
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<td>222-311 (Av. 249)</td>
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In the Kershaw Pumice Formation near Rosebery, drill hole 118R intersected a thin (60 cm) interval of dacitic pumice-rich sandstone that overlies rhyolitic pumice breccia, pumice-rich sandstone and shard-rich siltstone. This dacitic pumice-rich sandstone is composed of pumice clasts (85%, 3 mm), lithic clasts (5%, 1-2 mm), plagioclase crystal fragments (10%, 0.5-2.5 mm), and very sparse quartz crystal fragments (<1%, 0.5 mm).

Further south between Mount Read and Dallwitz, pumice breccia units and rhyolitic lavas are conformably overlain by a thick (45-100 m) unit of interbedded pumice breccia, pumice-rich sandstone and siltstone (the Jones Creek sediments). The upper part of the Jones Creek sediments contains quartz-phyric sandstone and siltstone (2-20%, 0.5-2 mm), whereas the lower units are feldspar-phyric (without quartz) pumice breccia or pumice-rich sandstone. One of the lower pumice breccia beds is dacitic in composition and similar to the dacitic pumice-rich sandstone in drill hole 118R. It is composed of aphyric or plagioclase-phyric tube pumice clasts (80%, 3 cm), shards (10%, <0.2 mm), lithic clasts (5%, 1 cm), plagioclase crystal fragments (5%, 1 mm), and very rare quartz crystal fragments (<1%, 0.5 mm).

In the Hercules Pumice Formation at Rosebery and Hercules, dacitic pumice breccia occurs at the top of the Footwall member and is overlain by the Host-rock member (Large, 1996 unpub.; Large and Allen, 1997 unpub.). The Host-rock member is similar to the Jones Creek sediments comprising interbedded sandstone and siltstone, which are composed of pumice clasts, shards, plagioclase and
Figure 4.16: Comparison diagrams for pumice-rich facies association in the Kershaw and Hercules Pumice Formations. A. Ti/Zr versus SiO₂. B. Zr versus TiO₂. C. Al₂O₃ versus TiO₂. D. Sc versus TiO₂. E. Zr versus Al₂O₃. F. Nb versus Al₂O₃. G. TiO₂/P₂O₅ versus V. A, B, C, D and G define two compositional groups for the pumice-rich facies association: (i) rhyolitic pumice breccias and (ii) dacitic pumice breccias. In plots D, E and F, the rhyolitic and dacitic pumice breccias plot on a single trend consistent with a similar source. G suggests that the two compositional groups could be related by means of fractionation.
Figure 4.17: Graphic lithological log and Ti/Zr and V contents for part of drill hole 120R east of Rosebery, through a pumice-rich facies association in the Kershaw Pumice Formation. The pumice-rich facies association has been intruded by flow-banded, massive and autobrecciated rhyolitic and dacitic sills with peperitic contacts. Variations in Ti/Zr and V contents are consistent with changes in the distribution and proportion of zircon crystals and Fe-Ti-oxides. Typically the diffusely stratified pumice-rich sandstone facies also contain higher amounts (10-20%) of plagioclase crystal fragments than the underlying massive pumice breccia (3-5%).
quartz crystal fragments (cf. Lees, 1987; Allen, 1991 unpub.; Allen and Large, 1996 unpub.).

The magma from which the dacitic pumice breccia and pumice-rich sandstone facies in the Kershaw and Hercules Pumice Formations were derived was slightly less fractionated than that for the rhyolitic pumice breccia, pumice-rich sandstone and shard-rich siltstone facies. The dacitic pumice breccia was either derived from a different magma body, or from deeper within a zoned magma chamber (Large and Allen, 1997 unpub.).

4.6.3 Tholeiitic andesites and basalts

The Sterling Valley Volcanics comprise dacitic to basaltic lavas and sills and intercalated resedimented autobreccia, hyaloclastite, polymictic mafic breccia, mafic volcanic sandstone and siltstone, and sparse black mudstone (Chapter 3). The Henry Dyke Swarm comprises basalt and dolerite dykes (Chapter 3).

Feldspar (± clinopyroxene ± hornblende)-phyric andesites in the Sterling Valley Volcanics are mineralogically and geochemically distinct from the calc-alkaline feldspar-hornblende-phyric andesites in the Central Volcanic Complex. However, Group 3 tholeiitic lavas, sills and dykes in the Sterling Valley Volcanics and Henry Dyke Swarm are comparable with other tholeiites in the Mount Read Volcanics (Fig. 4.18).

Tholeiitic rocks in the Sterling Valley Volcanics are aphyric or plagioclase ± clinopyroxene ± hornblende porphyritic and are compositionally characterised by high Ti/Zr (26-158), high TiO$_2$ (0.4-2 wt %), very low Nb (<6 ppm), high Zr (63-131 ppm) and high P$_2$O$_5$/TiO$_2$ (0.09-0.23). This is both mineralogically and compositionally identical to the Henry Dyke Swarm basalts (Fig. 4.19) which have

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high Ti/Zr (88-107), TiO₂ (1-1.6 wt %), very low Nb (<3 ppm), high Zr (61-194) and low P₂O₅/TiO₂ (~0.2) (Crawford et al., 1992).

Other tholeiitic rocks in western Tasmania include: the Henty Fault Wedge, the Sock Creek basalts, Miners Ridge Basalt, and the Howards Plain basalt breccias (Corbett, 1979; Corbett and Solomon, 1989; Crawford et al., 1992).

McClenaghan and Corbett (1985 unpub.), Corbett and Lees (1987), and Crawford et al. (1992) suggested that the Henry Dyke Swarm was co-magmatic with the western Henty Fault Wedge tholeiitic basalts. The Henry Fault Wedge occurs between the North Henry and South Henty Faults (Figs. 2.2 and 2.5). It comprises both calc-alkaline and tholeiitic rocks (Corbett and Solomon, 1989; Crawford et al., 1992). The tholeiitic rocks have been informally divided into the Ewart Creek Track sequence in the west and Henty Valley sequence at the eastern margin of the Henty Fault Wedge (Poltock, 1992).

The Ewart Creek Track sequence includes: plagioclase-pyroxene-phyric pillow basalt, basaltic and andesitic autobreccia, felsic volcanic breccia, coarse quartz-rich volcanic sandstone, tuffaceous siltstone and basaltic and dolerite intrusions (Corbett, 1985 unpub.; Corbett and Solomon, 1989; Poltock, 1992). The felsic volcanic breccia includes intervals of massive feldspar-phyric pumice breccia which is mineralogically and texturally similar to pumice breccia in the Central Volcanic Complex (Poltock, 1992).

The Ewart Creek Track sequence basalts are characterised by moderately high Ti/Zr (30-96), moderate TiO₂ (0.34-1.3 wt %), very low Nb (<7 ppm), high Zr (60-131 ppm) and low P₂O₅/TiO₂ (0.13-0.26) (data from Poltock, 1992). They are compositionally similar to tholeiites of the Henry Dyke Swarm and Sterling Valley Volcanics (Fig. 4.19). Their association with pumice breccia and quartz-rich volcanic sandstone is also similar to that in the northern Central Volcanic Complex (cf. Poltock, 1992).

The Henry Valley sequence comprises quartz-rich sandstone, chert, hemiatic siltstone, polymictic volcanic breccia and tholeiitic basaltic andesite lavas (Corbett, 1985 unpub.; Poltock, 1992). The tholeiitic basaltic andesites are characterised by high Ti/Zr (82-99), very high TiO₂ (1.09-3.62 wt %), high Nb (4-25 ppm), very high Zr (68-264 ppm), low Ni (32-47 ppm) and low P₂O₅/TiO₂ (0.12-0.22) (data from Poltock, 1992). In contrast to tholeiites in the Sterling Valley Volcanics, Henry Dyke Swarm and Ewart Creek Track sequences, the Henry Valley sequence tholeiites have significantly higher TiO₂ and P₂O₅ for equivalent MgO content, Ti/Zr and P₂O₅/TiO₂ (Fig. 4.19). This suggests that they had different parent magmas. These high-Ti Henry Valley sequence tholeiites are unique in the Mount Read Volcanics.

The Miners Ridge Basalt includes aphyric or olivine-phyric basaltic lavas and intrusions which occur in the core of an anticline at Miners Ridge south of Queenstown (Corbett, 1979). It is characterised by a wide range of Ti/Zr (25-150), high MgO (6.9-12.7 wt %), low TiO₂ (0.4-0.71 wt %), moderate Nb (<3-11 ppm), high Zr (105-151 ppm), high Cr (239-830 ppm) and average P₂O₅/TiO₂ (0.12-0.22) (data from Dover, 1991, and Crawford et al., 1992). The Miners Ridge Basalt has higher MgO, Cr and Nb, and lower TiO₂ and P₂O₅ than the Henry Dyke Swarm and Sterling Valley Volcanic tholeiites.
Figure 4.19: Correlation diagrams for tholeiitic rocks in the Mount Read Volcanics. A. Ti versus Zr. B. P2O5 versus TiO2. C. Nb versus Cr. D. P2O5 versus Zr. E. P2O5/Y versus V/Zr. F. P2O5/Y versus P2O5/Zr. G. TiO2 versus MgO. Data for Henty Dyke Swarm samples from Crawford et al. (1992) and Howards Plain basalt breccia from Herrmann and MacDonald (1996 unpub.), Henry Fault Wedge Ewarts Track sequence and Henty Valley sequence from PoltOck (1992), Sock Creek Basalts from Crawford et al. (1992) and Miners Ridge Basalt from Dower (1991). Group 3 basaltic lavas, sills, polymictic mafic breccias and dykes have similar compositional fields to Henty Dyke Swarm and Ewart Creek Track sequence and some affinities with the Howards Plain basalt breccia.
The Miners Ridge Basalt is apparently unrelated to other tholeiitic rocks in the Mount Read Volcanics. It has been tentatively correlated with the Late Proterozoic-Early Cambrian basement succession (Crimson Creek Formation) onto which the Mount Read Volcanics were emplaced (Dower, 1991; Crawford et al., 1992).

The tholeiitic Howards Plain basalt breccias are plagioclase-phyric and characterised by moderate Ti/Zr (39-54), moderate TiO₂ (0.7-1.1 wt %), low MgO (2.6-6.5 wt %) and high Zr (93-103 ppm) (Herrmann and MacDonald, 1996 unpub.). These basalts have lower Ti/Zr, TiO₂ and P₂O₅ at any Zr value than tholeiites of the Henty Dyke Swarm, Sterling Valley Volcanics and western Henry Fault Wedge (Fig. 4.19).

The Sock Creek basalts are mineralogically different from tholeiites of the Sterling Valley Volcanics and Henry Dyke Swarm, being olivine-chromite-clinopyroxene porphyritic. The Sock Creek basalts are characterised by high Ti/Zr (84-88), high MgO (8-9.5 wt %), low TiO₂ (0.41-0.44 wt %), low P₂O₅ (0.06-0.08 wt %), low Nb (<3 ppm), very low Zr (28-30 ppm), high Cr (370-500 ppm), high Ni (120-137 ppm) and average P₂O₅/TiO₂ (0.12-0.22) (data from Crawford et al., 1992). Discrimination diagrams (Fig. 4.19) suggest that Sock Creek basalts have some compositional similarities with the tholeiites of the Sterling Valley Volcanics, Henry Dyke Swarm and Ewart Creek Track sequence. However, at similar MgO contents, the Sock Creek basalts have less than half the TiO₂ and Zr contents (Fig. 4.19) and were probably derived from a more depleted mantle source than the Sterling Valley Volcanics, Henty Dyke Swarm and Ewart Creek Track sequence basalts.

The similarities in mineralogy and whole-rock chemistry among the aphyric and feldspar-phyric andesites and basalts of the Sterling Valley Volcanics, massive basalts and dolerites of the Henry Dyke Swarm and the western Henry Fault Wedge basalts (Ewart Creek Track sequence basalts and dolerites) strongly suggests these tholeiites are compositionally related and probably had a similar parental magma and source.

4.7 Implications for the tectono-magmatic reconstruction of the Mount Read Volcanics

Crawford and Berry (1992) (Chapter 2) proposed that the Mount Read Volcanics represent a phase of post-collisional volcanism. This is characterised by high-K calc-alkaline andesites and shoshonitic basalts that were generated by partial melting of subduction-modified, underthrust passive margin crust. They attributed the tholeiitic basalts of the Henty Dyke Swarm, Hellyer Basalt and Henry Fault Wedge rocks to extension late in the volcanic history of the Mount Read Volcanics.

Geochemical data presented here, for the northern Central Volcanic Complex, are generally consistent with the tectono-magmatic setting for the Mount Read Volcanics proposed by Crawford and Berry (1992). However, tholeiitic volcanism, represented by the Sterling Valley Volcanics at the base of the Central Volcanic Complex, clearly occurred early in the development of the Mount Read Volcanics, and was partly coeval with felsic volcanism.

The Sterling Valley Volcanics are compositionally similar to tholeiitic basalts erupted during the
early stages of rifting of a magmatic arc and back-arc basin development (cf. Weaver et al., 1979; Thy, 1992; Shinjo, 1998). They may represent a period of crustal extension preceding the post-collisional magmatism that generated shoshonitic and high-K basalts and andesites in younger parts of the Mount Read Volcanics (cf. Crawford and Berry, 1992). However the gradational contact between the tholeiitic Sterling Valley Volcanics and the calc-alkaline Mount Black Formation precludes a significant time gap between extension-related tholeiitic magmatism and crustal-modified calc-alkaline volcanism. In addition, compositional similarities between the tholeiitic Sterling Valley Volcanics and the Henry Dyke Swarm suggest that mantle-derived magmatism associated with extension was reactivated at the end of the Central Volcanic Complex time. This implies that the northern Central Volcanic Complex formed either during repeated periods of extension and relaxation, or that rifting and emplacement of the tholeiites was simultaneous with the accumulation of crustal-modified calc-alkaline rhyolites and dacites during extension (cf. Munker and Crawford, 2000; Einsele, 1982). Extension-related coeval tholeiitic and calc-alkaline magmatism may have occurred in a back-arc basin either during volcanic arc-related subduction or during the transition between subduction-related volcanism and post-collisional volcanism (cf. Tatsumi et al., 1989; Thy, 1992; Munker and Crawford, 2000).

4.8 Implications for VHMS exploration

This new stratigraphy for the northern Central Volcanic Complex has significant implications for VHMS exploration in the Mount Read Volcanics.

The Rosebery, Hercules and South Hercules ore deposits are hosted in the same stratigraphic sequence, the Rosebery-Hercules host sequence (Green et al., 1981; Allen, 1990b unpub.; Allen and Hunns, 1990 unpub.). Over the last 15 years, mineral exploration in the Central Volcanic Complex has involved the search for the Host Rocks or equivalent horizon. In the 1980's, the discovery of massive sulfide clasts in the base of the White Spur Formation and the interpretation that the Hangingwall Volcanioclastics are correlates of the White Spur Formation concentrated exploration along the contact between the Central Volcanic Complex and the White Spur Formation (Corbett and Lees, 1987; Corbett and Solomon, 1989; Corbett, 1992; McPhie and Allen, 1992b).

In the new stratigraphic subdivision, the Host Rocks (Host-rock member) occur in the top of the Hercules Pumice Formation, which is correlated with the Kershaw Pumice Formation. Dacitic pumice breccia occurs immediately below the Host-rock member in the Hercules Pumice Formation. Dacitic pumice breccia could be useful for determining the stratigraphic position and exploration potential of pumice-rich facies associations in the northern Central Volcanic Complex. The discovery during this study (section 4.6.2) of dacitic pumice breccia both in the Jones Creek sediments, east of the Mount Black Fault near Rosebery, and at the Dallwitz VHMS prospect further supports this.

The correlation of the Hercules Pumice Formation and the Kershaw Pumice Formation suggests that there is potential for the Host-rock member to be repeated east of the Mount Black Fault. The Kershaw Pumice Formation is interpreted to include feldspar-phyric pumice breccias that extend NE towards Mount Block. This suggests the Host-rock member could be exposed north of Pieman Road in the poorly-explored area between Mount Block and Pinnacles.
4.9 Conclusions

The northern Central Volcanic Complex can be divided into four formations, from base to top: the Sterling Valley Volcanics, Mount Black Formation, Kershaw Pumice Formation, and the Hercules Pumice Formation. The Kershaw and Hercules Pumice Formations have been correlated based on detailed facies and structural analysis and lithogeochemical comparisons. The Hangingwall Volcaniclastics, previously part of the northern Central Volcanic Complex, have been correlated with the White Spur Formation and hence this unit is included in the Dundas Group.

The Sterling Valley Volcanics are composed of dacitic to basaltic lavas, sills, dykes and volcaniclastic facies (Chapter 3). They have a gradational upper contact with dacitic and rhyolitic units of the Mount Black Formation. Basaltic and andesitic lavas and sills have compositions similar to those of back-arc rift tholeiites. Dacitic lavas and sills have calc-alkaline affinities and attest to coeval tholeiitic and calc-alkaline volcanism during formation of the Sterling Valley Volcanics. The Sterling Valley Volcanics are interpreted to have formed during a period of extension and back-arc basin development.

The Mount Black Formation (previously part of the Mount Black Volcanics) includes rhyolitic and dacitic lavas and sills, and autoclastic facies (Chapter 3). It is conformably overlain by pumice breccia or pumice-lithic clast-rich breccia units of the Kershaw Pumice Formation. Least-altered lavas and sills in the Mount Black Formation are calc-alkaline rhyolites and dacites. Variations in immobile element composition are consistent with fractionation of a single parent magma.

The Kershaw Pumice Formation (previously part of the Mount Black Volcanics) and Hercules Pumice Formation (including the Footwall Pyroclastics and Host Rocks) comprise regionally extensive pumice-rich facies association, pumice-lithic clast-rich facies association and rhyolitic and dacitic sills (Chapters 2 and 3). Pumice breccias and sills in these formations are calc-alkaline rhyolites and dacites with identical compositions to rhyolites and dacites in the Mount Black Formation. The pumice-rich facies association and lavas and sills of the Kershaw and Hercules Pumice Formations and Mount Black Formation are interpreted to be the explosive and effusive products of a single volcanic centre.

Massive, fine-grained feldspar-phyric basalts of the Henry Dyke Swarm intrude the northern Central Volcanic Complex. These are compositionally similar to rift tholeiites erupted during back-arc basin development. They are interpreted to have been emplaced during a period of extension after formation of the Central Volcanic Complex.

The stratigraphy of the northern Central Volcanic Complex is disrupted and repeated by folds and faults resulting in substantial thickening of the Central Volcanic Complex between Rosebery and Tullah. The Sterling Valley Volcanics are exposed at the base of the Central Volcanic Complex in the core of a N-trending anticline. The Hercules and Kershaw Pumice Formations and the Mount Black Formation are exposed in a series of N-striking thrust slices and open folds. Folding and faulting are interpreted to have occurred mainly during the Devonian deformation and folding is associated with the regional north-striking, steeply dipping axial planar cleavage ($S_2$). $S_2$ overprints an earlier foliation ($S_1$), which is a bedding-parallel, spaced stylolitic foliation, interpreted as a diagenetic compaction and dissolution fabric (Allen, 1990a unpub.; Allen and Cas, 1990 unpub.). Late (post-$S_2$) E-W faults offset earlier structures.
Chapter 5
Pumiceous hyaloclastite and peperite in ancient submarine volcanic successions

5.1 Introduction

Although pumiceous lavas are common in both subaerial (Fink and Manley, 1987; Fink, 1983; Kano et al., 1991) and submarine settings (Pichler, 1965; Furnes et al., 1980; De Rosen-Spence et al., 1980; Yamagishi, 1987; Cas et al., 1990; Kurokawa, 1991; Yamagishi, 1991; Scutter et al., 1998), clastic pumice is more typically associated with explosive eruptions. In ancient submarine volcanic successions, deposits of pumice clasts are commonly interpreted as mass-flow deposits, pyroclastic-flow deposits and deposits of water-settled fall derived from submarine pyroclastic eruptions, dome-related explosions, or their resedimented equivalents (Fiske and Matsuda, 1964; Reynolds et al., 1980; Allen and Cas, 1990 unpub.; Cas et al., 1990; Kano, 1990; Allen et al., 1996; Kano, 1996; Kano et al., 1996; Fiske et al., 1998). In addition, pumiceous hyaloclastite associated with pumiceous lavas has been recognised (Pichler, 1965; Furnes et al., 1980; De Rosen-Spence et al., 1980; Yamagishi, 1987; Scutter and Cas, 1998 unpub.; Scutter et al., 1998). It is clear that both explosive and effusive eruptions generate deposits of coarse pumice clasts (pumice breccia). In this chapter, two varieties of non-explosive pumice breccia, pumiceous hyaloclastite and peperite, are identified. Pumiceous hyaloclastite and peperite are spatially associated with pumiceous lavas and intrusions. The potential for shallow intrusions to be pumiceous is not widely appreciated.

Hyaloclastite is produced by in situ quench fragmentation of hot lava or magma on contact with water, ice or water-saturated sediment (Rittman, 1962; Pichler, 1965; Yamagishi, 1987). Quenching involves rapid cooling and the formation of contraction fractures in response to anisotropic thermal stress (Pichler, 1965; Yamagishi and Dimroth, 1985; Yamagishi, 1987, 1991). The propagation and interconnection of second and third order contraction fractures produces in situ breccia of glassy, blocky and splintery shaped clasts, with planar and curvilinear surfaces (Pichler, 1965; Yamagishi, 1987). In situ hyaloclastite consists of clasts that fit together like a completed jigsaw puzzle and implies that there has been no relative movement of the clasts after fragmentation. In clast-rotated hyaloclastite, clasts have undergone minor rotation and separation, perhaps during continued flow and/or intrusion. Resedimented hyaloclastite shows evidence of transport, such as bedding, stratification, mixing of clasts from texturally different parts of the lava and a lack of jigsaw-fit texture. Resedimented hyaloclastite is typically produced by en masse down slope resedimentation by high-concentration density currents.

Peperite is a texturally complex mixture of disrupted magma and sediment (Schmincke, 1967; Kokelaar, 1982). It may comprise any magma composition and a wide range of sediments (Schmincke, 1967; Busby-Spera and Whine, 1987; Branney and Suthren, 1988; Hanson and Wilson, 1993; Hunns and McPhie, 1999). The igneous component is commonly weakly or non-vesicular, glassy or crystalline
and clasts vary in shape from fluidal to blocky (Busby-Spera and White, 1987; Branney and Suthren, 1988). Peperite is especially difficult to recognise in cases where the igneous component is pumiceous because pumiceous peperite may resemble other pumice-rich facies common in submarine volcanic successions and the pumice clasts may be indistinguishable from pumice produced by other mechanisms.

Peperite forms by in situ disintegration of hot magma intruding into or mingling with unconsolidated sediment (Fisher, 1960; Williams and McBirney, 1979; White et al., 2000). In peperite, fragmentation of the magma is due to one or more mechanisms that involve quenching, dynamic stressing and steam explosions (Kokelaar, 1986). Heating of pore fluid in the sediment may cause fluidisation that promotes mingling of the sediment and magma (Fisher, 1960; Williams and McBirney, 1979; Kokelaar, 1982, 1986). Sediment can be injected into fractures produced by quenching or steam explosions (Kokelaar, 1986). This promotes further propagation of the fractures and disintegration of the igneous component into clasts. The magma may also be insulated from contact with the wet unconsolidated sediment by an envelope of steam, suppressing quenching and steam explosions (Kokelaar, 1982; Busby-Spera and White, 1987).

In this chapter, three examples of pumiceous hyaloclastite and three examples of pumiceous peperite associated with felsic lavas and syn-volcanic intrusions are described. These examples occur at two locations: the Cambrian Mount Read Volcanics, Australia, and the Miocene Green Tuff Belt in the Hokuroku Basin, Japan. The examples of pumiceous hyaloclastite involve non-vesicular to pumiceous rhyolite (or dacite) surrounded by in situ and clast-rotated pumiceous hyaloclastite. The examples of pumiceous peperite involve non-vesicular to pumiceous rhyolite enveloped by in situ pumiceous hyaloclastite and pumiceous peperite. The textures, facies and the distribution of the rhyolite (or dacite), hyaloclastite, peperite and the host sediment are described for each of the examples.

Identification of pumiceous hyaloclastite and peperite is of critical importance in volcanic facies architecture and stratigraphic research, providing constraints on the age relationships and timing of intrusive episodes. Specific criteria that distinguish pumiceous hyaloclastite and peperite from other pumice-rich facies are considered. Examples of hyaloclastite are identified based on evidence that the igneous component was quenched and that fragmentation was in situ. The positive identification of peperite requires evidence that the igneous component was hot, that the sediment was unconsolidated at the time of mingling, and that mingling occurred in situ at the margins of intrusions or lavas. Pumiceous hyaloclastite and peperite can be especially difficult to recognise because the igneous component (pumice) is typically almost entirely glassy and porous, and undergoes dramatic textural changes during diagenesis.

5.2 Pumiceous hyaloclastite associated with dacitic lava in the Mount Read Volcanics

5.2.1 Geological setting
Pumiceous hyaloclastite is associated with felsic lavas and sills in the Hercules and Kershaw Pumice Formations (Fig. 5.1). The Hercules and Kershaw Pumice Formations are dominated by feldspar-phryic rhyolitic and dacitic lavas, syn-volcanic intrusions and syn-eruptive pumiceous volcaniclastic facies (Chapter 4). Bedforms and textures within the volcaniclastic units are consistent with deposition
While Spur Formation and correlates interbedded quartz-feldspar crystal-rich volcanic and non-volcanic sandstone and breccia, pumice breccia and black mudstone. Feldspar-phyric sills.

Hercules and Kershaw Pumice Formations
Host-rock member
Interbedded pumice breccia, pumice-rich sandstone, shard-rich siltstone, crystal-lithic-rich siltstone and black mudstone. Quartzfeldspar-phyric rhyolitic/dacitic sills. Massive sulfide.

Footwall member

Mount Black Formation
Feldspar-phyric rhyolitic and dacitic lavas, domes, cryptodomes and sills. Quartzfeldspar-phyric rhyolite sills and feldspar-hornblende-phyric dacites. Resedimented hyaloclastite and autobrecia. Sparse intercalated crystal-rich sandstone and black mudstone.

Sterling Valley Volcanics
Interbedded polymictic mafic breccia, mafic volcanic sandstone and siltstone with dacitic to basaltic lavas and sills.

Legend

Figure 5.1: Schematic diagram depicting the stratigraphy and facies architecture of the Central Volcanic Complex in the Rosebery-Hercules area. 1. Pumiceous hyaloclastite associated with a dacite in the Kershaw Pumice Formation in drill hole 112R near Rosebery. 2. Pumiceous hyaloclastite associated with a rhyolitic lava in the Kershaw Pumice Formation, drill hole 120R. 3. Massive sulfide. 4. Pumiceous peperite associated with a pumiceous rhyolitic sill in the Hercules Pumice Formation, drill hole KP303 near Koonya. Fiamme refers to altered, lenticular, juvenile volcanic fragments that define a bedding-parallel foliation.
from turbidity currents, debris flows and suspension in a below-wave-base submarine environment.

The lavas and intrusions are commonly highly vesicular or pumiceous at the margins and include pumiceous autobreccia, hyaloclastite and peperite. This example of pumiceous hyaloclastite is associated with the upper margin of a thick dacite in the Kershaw Pumice Formation (previously the Mount Black Volcanics), near Rosebery (Figs. 5.1 and 5.2). Facies relationships and the stratigraphic context of the pumiceous hyaloclastite are well constrained by detailed core logging of closely spaced drill holes in the Rosebery-Mount Black area.

Pumiceous dacite and pumiceous hyaloclastite at the margin of a thick (> 138 m) coherent dacite unit are preserved in drill hole 112R (Figs. 3.1, 5.1 and 5.2). The upper contact of the dacite facies association is a fault and the lower contact is marked by intervals of peperite (dacite-siltstone breccia) (Fig. 5.2). The dacite facies association overlies shard-rich siltstone at the top of thick (5-20 m), normally graded beds of feldspar-phyric pumice breccia.

5.2.2 Dacite facies association

The dacite facies association includes four facies: from base to top, monomictic dacite breccia grades into coherent dacite, vesicular dacite and monomictic pumiceous dacite breccia. The dacite facies association has a total thickness of 138 m (Fig. 5.2).

The coherent dacite facies is massive and 108 m thick (Fig. 5.2). It contains albite-sericite-altered plagioclase phenocrysts (3%, 2 mm) in a feldspar-quartz-sericite groundmass. Sparse vesicles (<5%) in the coherent dacite are filled with chlorite, feldspar and quartz.

The vesicular dacite facies occurs in a 10 m-thick interval at the top of the coherent dacite (Fig. 5.2). Vesicular dacite is flow-banded with alternating flow-bands defined by highly (40-50%) and weakly vesicular (5-10%) bands. Highly vesicular flow-bands resemble tube pumice with feldspar-, sericite- and less commonly chlorite-filled vesicles. The groundmass is composed of domains of fine feldspar-quartz-sericite and chlorite-sericite and contains albite-plagioclase phenocrysts (3%, 1 mm).

Monomictic pumiceous dacite breccia facies is 17 m thick, massive, poorly sorted and clast-supported (Fig. 5.2A). It comprises blocky, angular, jigsaw-fit, tube pumice clasts (90%, 0.1-3 cm) and angular uncompacted shards (10%, 0.1-1 mm). Pumice clasts are feldspar-phyric (2%, 1 mm) and altered to quartz-sericite and calcite. Originally glassy shards have been replaced by calcite and albite.

Monomictic dacite breccia facies occurs in two intervals, 3 m and 8 m thick (Fig. 5.2). Monomictic dacite breccia is massive, poorly sorted, clast-supported and composed of jigsaw-fit blocky, polyhedral dacite clasts. The dacite clasts are weakly plagioclase-phyric (2%, 1 mm) and angular with planar and curvilinear margins (Fig. 5.2C). Clasts have been altered to quartz-sericite and are separated by sericite-filled fractures.

5.2.3 Interpretation

The dacite facies association comprises four mineralogically identical facies (2-3%, 1-2 mm plagioclase
Figure 5.2: Graphic log of diamond drill hole 112R, from east of Rosebery in the Kershaw Pumice Formation, where it intersects intervals of pumiceous hyaloclastite (monomictic pumiceous dacite breccia), dacitic hyaloclastite (monomictic dacite breccia) and coherent dacite facies. A. Jigsaw-fit monomictic pumiceous dacite breccia with tube vesicles in adjacent pumice clasts oriented in the same direction and sericite-calcite-filled fractures between clasts. Dark lines show orientation of tube vesicles. B. Vesicular dacite containing elongated feldspar-sericite- and chlorite-filled tube vesicles. C. Jigsaw-fit monomictic dacite breccia composed of blocky, angular dacite clasts with curviplanar surfaces.
phenocrysts) which have gradational contacts and are interpreted to be genetically related.

The gradational contact between coherent dacite and vesicular dacite facies suggests that pumiceous domains occur at the margin of the dacite (cf. De Rosen-Spence, 1980; Furnes et al., 1980; Kurokawa, 1991; Scutter et al., 1998). Tube vesicles and vesicular flow-bands in the vesicular dacite facies reflect continued flow and stretching after vesiculation.

The abundance of jigsaw-fit textures in the monomictic dacite breccia indicates that clasts were produced by in situ fragmentation of the coherent dacite. The blocky, polyhedral shapes and curviplanar surfaces of dacite clasts are consistent with brittle fragmentation by the propagation and interconnection of contraction cracks during quenching of the dacite (cf. Pichler, 1965; Heiken, 1972). This is consistent with the interpretation of the monomictic dacite breccia as in situ hyaloclastite.

Similarly, clasts in the monomictic pumiceous dacite breccia were derived from the disintegration of the vesicular dacite. Blocky and angular clasts, jigsaw-fit textures and the paucity of matrix in the monomictic pumiceous dacite breccia are typical of quench fragmentation (cf. Pichler, 1965; Yamagishi, 1987). This is consistent with the interpretation that the monomictic pumiceous dacite breccia is in situ pumiceous hyaloclastite. Although the upper contact of the dacite facies association is not preserved, the occurrence of pumiceous hyaloclastite supports the interpretation that this facies association was extrusive (cf. Pichler, 1965).

5.3 Pumiceous hyaloclastite associated with rhyolitic lava in the Mount Read Volcanics

5.3.1 Geological setting
Pumiceous hyaloclastite associated with rhyolitic lava(s) in the Kershaw Pumice Formation, near Rosebery, is preserved in drill hole 120R (Fig. 5.1). Here, the Kershaw Pumice Formation comprises intercalated pumice-lithic clast-rich breccia, rhyolitic lavas and intrusions.

5.3.2 Pumice-lithic clast-rich breccia facies
Pumice-lithic clast-rich breccia facies (113-130 m, Fig. 5.3) occurs in massive to normally graded beds up to 125 m thick. These clast-supported, moderately poorly sorted beds have coarse bases (5 cm clasts), thick massive interiors and diffusely stratified, shard-rich siltstone tops. They are composed of tube pumice clasts (50-60%, 0.2-2 cm), shards (10%, 0.1-1 mm), fiamme (10%, <6 cm), plagioclase crystal fragments (10%, 1-2 mm) and non-vesicular rhyolite clasts (10-20%, 1-5 cm). The pumice clasts are plagioclase-phyric (10%, 2 mm), blocky to ragged, variably altered and compacted (Fig. 5.3C). Vesicles in the pumice clasts are feldspar-filled and originally glassy vesicle walls have been replaced by feldspar-quartz-sericite and chlorite-sericite. Originally glassy shards have been altered to albite or a fine mosaic of feldspar and quartz. Plagioclase crystal fragments and phenocrysts are altered to albite, calcite and sericite. The non-vesicular rhyolite clasts include flow-banded and massive perlitic plagioclase-phyric rhyolite. They are typically blocky and angular with planar and curviplanar surfaces and have been altered to feldspar-quartz-sericite and chlorite-sericite.

5.3.3 Rhyolite facies association
The rhyolite facies association consists of five facies: coherent rhyolite, pumiceous rhyolite, monomictic
Figure 5.3: Graphic log of diamond drill hole 120R, from the Kershaw Pumice Formation near Rosebery. This shows the distribution of coherent rhyolite, pumiceous rhyolite, monomictic rhyolite breccia, monomictic pumiceous rhyolite breccia, poorly sorted rhyolite breccia and pumice-lithic clast-rich breccia facies. A. Photomicrograph (Ppl) of blocky tube pumice clasts and shards in pumice-lithic clast-rich breccia. B. Photomicrograph (Ppl) of a sericite- and feldspar-altered pumice clast in poorly sorted rhyolite breccia. The clast has cuspate or curviplanar surfaces. C. Photomicrograph (Ppl) of clast-supported monomictic pumiceous rhyolite breccia, tube vesicles have different orientations in adjacent pumice clasts. Clast margins are highlighted by the dashed white line.
rhyolite breccia, monomictic pumiceous rhyolite breccia, and poorly sorted rhyolite breccia. The rhyolite facies association has a minimum total thickness of 113 m (Fig. 5.3).

Coherent rhyolite facies occurs in 10- to 20 m-thick massive to flow-banded intervals (Fig. 5.3). It contains plagioclase phenocrysts (5%, 2 mm) in a fine mosaic of feldspar-quartz-sericite- or feldspar-quartz-sericite-altered spherulites. Flow-bands are defined by alternating chlorite-sericite-calcite and feldspar-quartz-sericite bands. Perlitic fractures in the feldspar-quartz-sericite-altered flow-bands are quartz-sericite filled. Plagioclase phenocrysts have been altered to calcite.

Units of pumiceous rhyolite facies are approximately 1 to 5 m thick (Fig. 5.3). Elongate vesicles are weakly compacted and feldspar-sericite-filled. Rare chlorite-altered flow-bands resemble fiamme. The originally glassy groundmass has been replaced by feldspar-quartz-sericite, whereas plagioclase phenocrysts (5%, 1-2 mm) have been partially altered to albite, sericite and calcite.

Monomictic rhyolite breccia is massive, clast-supported, poorly sorted and dominated by jigsaw-fit textures. The clasts are perlitic, non-vesicular rhyolite with albite-calcite-sericite-altered plagioclase phenocrysts (5%, 1-2 mm). The clasts are blocky and angular with planar and curved surfaces. They vary in size from 2 mm to 8 cm and have been altered to feldspar-quartz-sericite.

Monomictic pumiceous rhyolite breccia facies occurs in massive, poorly sorted, clast-supported intervals, approximately 2 m thick (Fig. 5.3). This facies varies from jigsaw-fit to clast-rotated texture (Fig. 5.3A). It is composed of blocky, highly vesicular and pumiceous rhyolite clasts (90%, 0.1 - 2 cm) and shards (10%, <1 mm). Clasts contain albite-sericite-altered plagioclase phenocrysts (3%, 1.5 mm). Vesicles in the rhyolite clasts are filled with albite. Clasts and shards have been altered to quartz-sericite and feldspar-quartz-sericite.

Poorly sorted rhyolite breccia facies occurs in two thick (12-35 m), massive intervals, which are clast-supported. Clast arrangements are dominated by disorganised, clast-rotated textures with groups of clasts locally preserving jigsaw-fit textures. This facies contains pumice clasts (30%, 0.2-15 cm), flow-banded or perlitic rhyolite clasts (60%, 1-10 cm), fiamme (5%, 2-6 cm) and a matrix of originally glassy shards (5%, 0.1-1 mm). The pumice and rhyolite clasts are all weakly plagioclase-phyric, blocky and angular to sub-angular and typically have curviplanar surfaces (Fig. 5.3B). They have been altered to feldspar-quartz-sericite, chlorite-sericite, chlorite-sericite-hematite and calcite.

5.3.4 Facies geometry and relationships
The rhyolite facies association can be divided into two units: A and B (Fig. 5.3). Facies in Rhyolite A and B have similar distributions and contacts.

The character of the lower contact of Rhyolite A is unknown. Coherent rhyolite, grades up into pumiceous rhyolite. Pumiceous rhyolite grades into jigsaw-fit monomictic rhyolite breccia, and then into jigsaw-fit and clast-rotated monomictic pumiceous rhyolite breccia. Monomictic pumiceous rhyolite breccia is overlain by poorly sorted rhyolite breccia.

Rhyolite A is overlain by coherent rhyolite at the base of Rhyolite B (Fig. 5.3). This grades into
jigsaw-fit monomictic rhyolite breccia and monomictic pumiceous rhyolite breccia and then into poorly sorted rhyolite breccia. Poorly sorted rhyolite breccia is overlain by monomictic rhyolite breccia and normally graded pumice-lithic clast-rich breccia (Fig. 5.3).

### 5.3.5 Interpretation

The rhyolite facies association comprises five compositionally and mineralogically identical facies that have gradational contacts and are inferred to be genetically related. Clasts in the monomictic rhyolite breccia and monomictic pumiceous rhyolite breccia have been derived from the disintegration of the coherent rhyolite and pumiceous rhyolite, respectively. Clast shapes, jigsaw-fit arrangements, abundant perlite and gradational contacts in these facies are typical of hyaloclastite (cf. Pichler, 1965).

Gradational contacts, local jigsaw-fit textures, the paucity of matrix and textural and mineralogical similarity between clasts in the poorly sorted rhyolite breccia and other facies in the rhyolite association are consistent with the clasts being derived from fragmentation of coherent rhyolite and pumiceous rhyolite. Polyhedral, blocky, angular pumice clasts and blocky rhyolite clasts with curvilinear margins suggest that fragmentation was the result of quenching (cf. Pichler, 1965). Poorly sorted rhyolite breccia is interpreted to be clast-rotated hyaloclastite in which texturally different clasts were derived from texturally distinct parts of the rhyolite facies association (cf. De Rosen-Sperre et al., 1980; Furnes et al., 1980; Yamagishi and Dimroth, 1985). Mixing of the different clast types may have been aided by down slope rolling or resedimentation. However, the poorly sorted rhyolite breccia facies lacks stratification and is proximal to source suggesting that any resedimentation was minimal.

### 5.4 Pumiceous hyaloclastite associated with rhyolitic lava in the Green Tuff Belt

#### 5.4.1 Geological setting

Pumiceous hyaloclastite is associated with the base of a rhyolitic lava dome emplaced onto pumice breccias at the top of the Nishikurosawa Formation in the Hokuroku District of the Green Tuff Belt, northern Honshu, Japan (Fig. 5.4). The middle Miocene Nishikurosawa Formation hosts Kuroko mineralisation within the Hokuroku Basin and is conformably overlain by the Onnagawa Formation (Figs. 5.4 and 5.5) (Nakajima, 1988). The Nishikurosawa and Onnagawa Formations comprise interbedded volcanic and sedimentary rocks (Nakajima, 1988). Volcanic facies in the Nishikurosawa and Onnagawa Formations are bimodal and consist of tholeiitic basalt and calc-alkaline rhyolite (Dudas et al., 1983; Urabe, 1987). Rhyolites are commonly referred to as dacites in the Kuroko literature (Ohmoto and Takahashi, 1983; Nakajima, 1988). The Green Tuff Belt has undergone extensive diagenetic alteration, local hydrothermal alteration and minor deformation (Utada, 1970, Tanimura et al., 1983). Generally bedding has a gentle dip with open, N-S-trending folds (Tanimura et al., 1983).

Depositional structures (graded beds, planar laminae and cross bedding) in pumiceous sandstone and siltstone, and the presence of thick intervals of mudstone and foraminifers, constrain the depositional setting for the Nishikurosawa and Onnagawa Formations to 2000-3000 m below sea level (Guber and Merrill, 1983).

Pumiceous hyaloclastite is associated with non-vesicular and pumiceous rhyolite in drill hole
Figure 5.4: Geology of Hokuroku Basin, Japan, showing the distribution of the major lithostratigraphic units including the Nishikurosawa and Onnagawa Formations. An example of pumiceous hyalodastite is described from drill hole HO65 near Hanoka in the western part of the Hokuroku Basin. Examples of pumiceous peperite were recognised in diamond drill holes HO20 and J6 near the Fukazawa VHMS deposit. Geology of the Hokuroku Basin after Tanimura et al. (1993) and the distribution of the Green Tuff Belt in Japan (striped area on inset map) after Sato (1974).

HO65, east of Hanoka in the western Hokuroku Basin (Figs. 5.4 and 5.5). Here, the Nishikurosawa Formation comprises intercalated pumice-rich facies associations, pumice and rhyolite breccia, rhyolitic lavas and minor mudstone (Fig. 5.5) (Tanimura et al., 1983).

5.4.2 Pumice-rich facies association

The pumice-rich facies association is composed of pumice breccia, sandstone and siltstone facies. Thick (up to 15 m) pumice breccia units are normally graded with bioturbated, stratified siltstone tops (455 m, Fig. 5.6). Sandstone and siltstone occur in upward fining sequences composed of normally graded, thick (2 m) beds of sandstone and laminated siltstone (single laminations up to 7 mm thick).

These facies comprise tube pumice clasts (60%, <2 cm), shards (20%, 0.5 mm), fiamme (10%, 1-4 cm), plagioclase crystal fragments (7%, 1 mm) and sparse rhyolite clasts (3%, 2-5 mm). Pumice clasts are blocky or ragged in shape and contain 3-5%, 1 mm plagioclase phenocrysts. They are variably altered to mordenite, chlorite, muscovite and smectite. Fiamme are green, feldspar-phyric, chlorite-sericite-altered lenses interpreted to be compacted pumice clasts. The rhyolite clasts are blocky, angular, flow-banded, peltitic, and weakly plagioclase-phyric.
5.4.3 Pumice and rhyolite breccia facies

Pumice and rhyolite breccia occurs in thin (2-5 m thick), normally graded beds with sandstone tops (115 m and 240 m, Fig. 5.6). The components are tube pumice clasts (50%, 0.2-4 cm), non-vesicular rhyolite clasts (30%, 0.1-2 cm), fiamme (5%, ~2 cm), plagioclase crystal fragments (3%, 1-2 mm), mudstone clasts (5%, 0.5-2 cm) and andesite clasts (3-5%, ~5 mm). The matrix comprises fine non-vesicular rhyolite and pumice clasts and shards. Pumice clasts have 3%, 1 mm plagioclase phenocrysts,
Figure 5.6: Graphic log of diamond drill hole H065 showing the distribution of interbedded pumice-rich facies, pumice and rhyolite breccia facies and the rhyolite facies association (coherent rhyolite, pumiceous rhyolite, monomictic rhyolite breccia, monomictic pumiceous rhyolite breccia and poorly sorted rhyolite breccia). A. Photomicrograph (ppl) of pumiceous rhyolite. Mordenite- and chlorite-filled vesicles and originally glassy, chlorite-, muscovite- and smectite-altered tube walls. B. Photomicrograph (ppl) of jigsaw-fit monomictic pumiceous rhyolite breccia with elongate vesicles in adjacent clasts aligned in the same orientation. Mordenite-filled vesicles and chlorite-, muscovite-, smectite- and mordenite-altered vesicle walls. Clast edges are highlighted by the dashed white line. C. Photomicrograph (ppl) of blocky tube pumice clasts in the monomictic pumiceous rhyolite breccia. Pumice clasts display clast-rotated texture. D. Photomicrograph (ppl) of blocky and platy tube pumice clasts at high angles to one another in poorly sorted rhyolite breccia.
irregular shapes, and are variably compacted. Sub-angular, non-vesicular rhyolite clasts are plagioclase-phyric and included flow-banded and perlite groundmass textures. Mudstone and fine-grained andesite clasts are sub-rounded.

5.4.4 Mudstone
Dark grey-brown, laminated and bioturbated mudstone is interbedded with the pumice-rich facies association. It occurs in intervals of between 2 and 3 m thick, with single laminae approximately 2 mm thick.

5.4.5 Rhyolite facies association
The rhyolite facies association consists of five facies: coherent rhyolite, monomictic rhyolite breccia, pumiceous rhyolite, monomictic pumiceous rhyolite breccia and poorly sorted rhyolite breccia. The rhyolite facies association has a total thickness of 360 m (Fig. 5.6).

The coherent rhyolite facies occurs in 2- to 112 m-thick intervals (Fig. 5.6). Coherent rhyolite generally has fine-grained, originally glassy margins that have been replaced by cristobalite or smectite. It is massive to flow-banded, with plagioclase phenocrysts (3-5%, 1 mm) and chlorite-filled perlite fractures.

The pumiceous rhyolite facies occurs in a thin interval (6 m at 300 m, Fig. 5.6). It is plagioclase-phyric (3%, 1 mm) and contains tube vesicles filled with mordenite. Vesicle walls comprise chlorite, muscovite and smectite (Fig. 5.6A).

Monomictic rhyolite breccia facies occurs in massive, poorly sorted, clast-supported intervals between 5 and 20 m thick (Fig. 5.6). This facies is composed of angular perlite and flow-banded, plagioclase-phyric rhyolite clasts that range in size from 0.2 mm to 4 cm. They are blocky with curviplanar margins and have jigsaw-fit texture.

Monomictic pumiceous rhyolite breccia facies occurs in two intervals, 2 m and 40 m thick (at 300 m and 340 m, Fig. 5.6). They are massive, poorly sorted and clast-supported, with clast sizes varying from 0.1 mm to tens of cm. Down-hole, textures in the monomictic pumiceous rhyolite breccia grade from jigsaw-fit clasts to disorganised rotated clasts (Fig. 5.6B and C). The monomictic pumiceous rhyolite breccia is composed of blocky, polyhedral, angular and plagioclase-phyric (2%, 1 mm) tube pumice clasts (Figs. 5.6C and 5.7A). The degree of vesiculation in the clasts varies from 45 modal % vesiculation at 324 m to 70 modal % at 367 m (Fig. 5.6B and C). Pumice clasts are uncompacted to moderately compacted (Fig. 5.7C). Round vesicles filled with mordenite are commonly preserved adjacent to plagioclase phenocrysts. Vesicle walls have been variably altered to chlorite, muscovite, smectite and mordenite. A thin cristobalite-altered matrix of sub-millimetre pumice clasts occurs between jigsaw-fit pumice clasts (Fig. 5.6B).

Poorly sorted rhyolite breccia facies occurs in a 40 m-thick interval (378-408 m, Fig. 5.6). At the base, poorly sorted rhyolite breccia is composed of plagioclase-phyric tube pumice clasts (80%, 0.1-10 cm), banded perlite rhyolite clasts (20%, 0.5-4 cm) and sparse grey andesitic lithic clasts (1%, <2 cm). Some pumice clasts are folded or have fractures perpendicular to the tube vesicles (Fig. 5.7B). The
matrix comprises cristobalite- and illite-altered pumice shards. Up-hole, the proportion of tube pumice clasts to perlitic rhyolite clasts increases until the perlitic clasts are absent and groups of pumice clasts locally preserve jigsaw-fit textures. The pumice clasts vary from uncompacted, with round vesicles preserved adjacent to plagioclase phenocrysts, to moderately compacted where the tube vesicles are defined by alternating thin bands of chlorite and illite. Perlitic rhyolite clasts are blocky with curviplanar surfaces (Fig. 5.7D). Andesitic lithic clasts are fine-grained, weakly plagioclase-phyritic (2%, 0.5 mm) and subrounded.

5.4.6 Facies geometry and relationships
The rhyolite facies association includes several intervals comprising variable proportions of coherent rhyolite, pumiceous rhyolite, monomictic rhyolite breccia, monomictic pumiceous rhyolite breccia and poorly sorted rhyolite breccia. These intervals are interpreted as separate rhyolite units (lavas, lava lobes or intrusions) (A to E, Fig. 5.6).

Rhyolite A occurs at the base of the rhyolite facies association (459-587 m, Fig. 5.6). It is a 28 m-thick interval of jigsaw-fit monomictic rhyolite that grades into flow-banded coherent rhyolite. Rhyolite A has intrusive upper and lower contacts.
Rhyolite B is a 43 m-thick interval of massive, perlitic coherent rhyolite, which has fine-grained glassy margins.

Rhyolite C, the thickest (162 m) of the rhyolite intervals has planar upper and lower contacts and is overlain by pumice and rhyolite breccia. At the base of Rhyolite C is a 30 m-thick interval of poorly sorted rhyolite breccia which grades vertically into clast-rotated and then jigsaw-fit monomictic pumiceous rhyolite breccia. Monomictic pumiceous rhyolite breccia grades into pumiceous rhyolite and then coherent rhyolite.

Rhyolite D is a 127 m-thick interval of massive and flow-banded coherent rhyolite with 10- to 20 m-thick intervals of jigsaw-fit monomictic rhyolite breccia. The upper contact is planar and marked by jigsaw-fit monomictic rhyolite breccia. The lower margin is fine-grained and contains abundant chlorite-filled perlitic fractures.

Rhyolite E encompasses two thin (3-5 m) intervals of coherent rhyolite separated by pumice and rhyolite breccia. The coherent rhyolite has irregular intrusive contacts and clasts of silicified mudstone are incorporated in the lower contact.

5.4.7 Interpretation

The close spatial association, gradational contacts and similar mineralogies (2-5%, 1 mm plagioclase phenocrysts) of the five facies in the rhyolite facies association suggest that they are genetically related. The genetic relationship between the coherent rhyolite, pumiceous rhyolite and monomictic pumiceous rhyolite breccia is also supported by the gradual increase in the degree of vesiculation away from the coherent rhyolite (up to 70 modal %).

Mineralogies, textures, clast shapes and arrangements suggest that the monomictic rhyolite breccia and monomictic pumiceous rhyolite breccia were derived from quenching of the coherent rhyolite and pumiceous rhyolite, respectively. This is consistent with the interpretation that the monomictic rhyolite breccia and the monomictic pumiceous rhyolite breccia are in situ and clast-rotated hyaloclastite (cf. Pichler, 1965; Yamagishi, 1987).

The poorly sorted rhyolite breccia consists of clasts that are texturally and mineralogically similar to the spatially associated coherent rhyolite facies and pumiceous rhyolite facies. This suggests that clasts in the poorly sorted rhyolite breccia were derived from different textural facies within the rhyolite facies association. The gradational contact between monomictic pumiceous rhyolite breccia and poorly sorted rhyolite breccia suggests that clasts in the poorly sorted rhyolite breccia have not been transported any significant distance. The poorly sorted rhyolite breccia was probably derived from the disintegration of different textural facies during the emplacement of the rhyolite (cf. Furnes et al., 1980; Yamagishi and Dimroth, 1985). Although poorly sorted rhyolite breccia grades into hyaloclastite, folded and fractured pumice clasts are more consistent with fragmentation resulting from autobrecciation than quenching (cf. Heiken, 1978; Cas, 1992). Clasts are interpreted to be the product of quench brecciation and autobrecciation at the margins of the rhyolite facies association. Rare andesite clasts were probably incorporated into the base of the rhyolite as it flowed over the substrate.
The pumice and rhyolite breccia that overlies Rhyolite C contains pumice clasts and non-vesicular rhyolite clasts, which are mineralogically and texturally similar to those in the monomictic pumiceous rhyolite breccia and monomictic rhyolite breccia facies. This is consistent with the interpretation that Rhyolite C was extrusive and that unconsolidated hyalodastite (monomictic pumiceous rhyolite breccia and monomictic rhyolite breccia) associated with Rhyolite C was exposed on the seafloor and resedimented. Mudstone and andesite lithic clasts may have been derived from pre-existing deposits.

The thickness (360 m), distribution of facies, contact relationships and textures in the rhyolite facies association are typical of a rhyolitic lava dome that comprises several lobes of coherent rhyolite with variable proportions of in situ and clast-rotated hyaloclastite and autobreccia (Fig. 5.8). Rhyolite C and D have planar upper contacts that may be consistent with lavas, whereas Rhyolites A and B have intrusive contacts and are enclosed in pumice breccia or between pumice breccia and pumiceous hyaloclastite. Rhyolite E is interpreted to have intruded into interbedded mudstone and pumice-rich sandstone.

The intrusive and extrusive contact relationships and complex facies distribution within the rhyolite facies association are consistent with many subaerial and subaqueous lavas and domes (cf. Fink, 1980; Heiken and Wohletz, 1987; De Rosen-Spencer et al., 1980; Rose, 1972). Subaerial and subaqueous lavas commonly comprise multiple lobes of which the internal structure is a zoned sequence

![Figure 5.8: Schematic diagram of the distribution of facies in the rhyolite facies association from near Hanoka in the Green Tuff Belt. The rhyolite facies association comprises several lobes of rhyolite and includes coherent rhyolite, pumiceous rhyolite, monomictic pumiceous rhyolite breccia (interpreted to be pumiceous hyaloclastite), monomictic rhyolite breccia (interpreted to be hyaloclastite) and poorly sorted rhyolite breccia (interpreted to be a mixture of hyaloclastite and autobreccia). These facies associations are interpreted to represent a lava dome complex that has been emplaced onto pumice breccia.](image-url)
of autobreccia, hyaloclastite, vesicular obsidian and massive obsidian (Fig. 5.8). Rhyolites A and B are consistent with lobes of lava that have locally intruded into the hyaloclastite or autobreccia carapace (Fig. 5.8) (cf. Christiansen and Lipman, 1966; De Rosen-Spence et al., 1980; Kano et al., 1991; Scutter et al., 1998). Multiple lobes suggest that the growth of the lava dome did not involve simple inflation from the interior but repeated emplacement of small lobes at the same locality (cf. De Rosen-Spence et al., 1980). This is similar to the exogenous growth of subaerial lava domes involving the concurrent intrusion and extrusion of short lava lobes, each of which includes a carapace of autobreccia (cf. Fink, 1983; Swanson et al., 1987).

5.5 Pumiceous peperite associated with a syn-volcanic sill in the Mount Read Volcanics

5.5.1 Geological setting
Pumiceous peperite is associated with felsic intrusions in the Hercules and Kershaw Pumice Formations (Fig. 5.1). The example of pumiceous peperite presented here comes from drill core through the Footwall member of the Hercules Pumice Formation, near Koonya (Fig. 3.1). Facies relationships and the stratigraphic context of the pumiceous peperite are well constrained by detailed core logging of closely-spaced drill holes in the area.

The volcanic facies at Koonya are dominated by 60 m-thick, normally graded and stratified pumice breccia intruded by pumiceous and weakly vesicular rhyolite. Pumiceous peperite at the margin of a rhyolitic sill is preserved in drill hole KP303 (Figs. 5.1 and 5.9). Pumiceous rhyolite varies laterally from being a single 150 m-thick unit of coherent rhyolite with a pumiceous upper contact (in KP304) to several thin (< 5 m) intervals of coherent pumiceous rhyolite separated by polymictic pumice breccia (interpreted to be pumiceous peperite) and stratified pumice breccia (in KP303) (Fig. 5.9). Pumiceous rhyolite clasts derived from the pumiceous rhyolite are texturally very similar to pumice.

![Figure 5.9: Schematic diagram of the distribution of coherent poorly vesicular, coherent pumiceous rhyolite and polymictic pumice breccia (interpreted to be pumiceous peperite) in stratified pumice breccia from the Hercules Pumice Formation, near Koonya. These facies associations are interpreted to represent a syn-volcanic sill that has intruded unconsolidated pumice breccia.](image-url)
clasts in the stratified pumice breccia, making it difficult to distinguish the two types.

5.5.2 Stratified pumice breccia

Stratified pumice breccia (562-570 m, Fig. 5.10) occurs in beds up to 60 m thick. Pumice clasts are moderately well sorted, and beds are normally graded with coarse bases (6 cm clasts) and laminated sandstone-siltstone tops.

Stratified pumice breccia is composed of plagioclase-phyric pumice clasts (70%, 1 mm to 3 cm), plagioclase crystals (15%, 1 mm), shards (15%, 0.5 mm) and non-vesicular lithic clasts (approximately 1%, averaging 5 mm). Plagioclase crystals have been variably altered to albite, sericite and calcite. Vesicles in the pumice clasts are dominantly tube vesicles although round vesicles are also preserved. Clasts are both blocky and ragged in shape and show varying degrees of compaction. Uncompacted clasts are typically altered to albite and disseminated hematite. Strongly compacted clasts (fiamme) are intensely sericite or chlorite-sericite altered, elongate parallel to bedding (S₀) and have feathery terminations (Fig. 5.10A). Rare lithic clasts include feldspar-phyric spherulitic, perlitic and amygdaloidal rhyolite and dacite. The siltstone tops comprise originally glassy shards, pumice clasts and plagioclase crystals. Laminae are planar, even thickness and continuous with sharp boundaries and internal grading.

5.5.3 Pumiceous rhyolite

Intervals of rhyolite in the Koonya area vary from 150 m to 3 m in thickness, extend laterally for a minimum of 100 m (Fig. 5.9) and are conformable with bedding in the stratified pumice breccia. The rhyolite facies is feldspar-phyric containing 3%, 2 mm plagioclase phenocrysts in a fine-grained groundmass of feldspar-quartz-sericite. The plagioclase phenocrysts are partially altered to albite and sericite. The groundmass varies texturally from non-vesicular to vesicular with round and tube vesicles (pumiceous rhyolite). The vesicles are outlined by thin films of sericite or hematite and filled with albite.

5.5.4 Polymictic pumice breccia

Intervals of the polymictic pumice breccia facies are up to 15 m thick and have gradational contacts with pumiceous rhyolite and stratified pumice breccia (533 to 559 m, Fig. 5.10). The polymictic pumice breccia is composed of plagioclase-phyric pumice clasts, green plagioclase-phyric clasts in a matrix of plagioclase crystal fragments and undeformed bubble wall shards. There are two different plagioclase-phyric pumice clast populations: pumice-A and pumice-B.

Pumice-A clasts are uncompacted, plagioclase-phyric (3%, 1.5-2 mm) tube pumice. They are commonly pale pink or white with a pink rim. Clasts of pumice-A vary from <1 mm to 5 cm in length and in shape from blocky to fluidal. The blocky clasts are equant or elongate parallel to the tube vesicles. They have delicate feathery edges perpendicular to the tubes and delicately scalloped surfaces parallel to the tubes (Figs. 5.11B and D). The plagioclase crystals occur in glomerocrysts surrounded by round vesicles (Fig. 5.11C), and have been altered to albite, sericite, carbonate or microcrystalline quartz. The originally glassy vesicle walls are also altered to albite and sericite. Thin films of sericite and/or hematite line the vesicle walls and the vesicles are filled with albite (Fig. 5.11C). Many clasts contain fine fractures parallel to the tube vesicles that are filled with sub-millimetre quartz and feldspar (Fig. 5.11B).
Figure 5.10: Graphic log of diamond drill hole KP303 where it intersects intervals of pumiceous peperite (polymictic pumice breccia) and coherent pumiceous rhyolite. Refer to Figure 5.9 for legend. A. Stratified pumice breccia with chlorite-altered fiamme. B. Polymictic pumice breccia containing irregular green feldspar-phyric clasts (g) and deformed laminae. C. Large green feldspar-phyric clast (g) with feathery terminations, surrounded by pale grey, silicified, laminated siltstone. D. Interconnected green feldspar-phyric clasts (g) dispersed among pumice-B clasts and fiamme.
Figure 5.11: A. Photomicrograph (KP303 406 m ppl) of stratified pumice breccia. Sericite fiamme are transposed into the regional cleavage (S2). B, C and D are photomicrographs (ppl) of pumice-A clasts in polymictic pumice breccia. B. Uncompacted plagioclase-phyric pumice-A clast with feathery edges perpendicular to the tube vesicles (KP303 533 m). Fractures in the pumice-A clast are filled with fine quartz and feldspar and the clast is surrounded by fine silicified matrix. C. Round vesicles preserved in a pumice-A clast contain thin films of sericite and are feldspar-filled (KP303 533 m). D. Uncompacted silicified shards are preserved in the matrix adjacent to a pumice-A clast (KP303 541 m). Further from the clast, shards are variably compacted and altered to feldspar, sericite and chlorite. The pumice-A clast has scalloped margins parallel to the tube vesicles.

Pumice-B clasts are phenocryst-rich, containing 10-20%, 1 mm plagioclase phenocrysts. Clasts of pumice-B are green, elongate with ragged edges, and are between 0.5 mm and 6 cm in length. Pumice-B clasts are variably compacted and aligned parallel to bedding in the adjacent stratified pumice breccia. Albite, sericite and carbonate have replaced the original plagioclase phenocrysts. The originally glassy vesicle walls are composed of albite. Compacted pumice clasts are commonly altered to sericite and/or chlorite.

Green feldspar-phyric clasts contain 3-5%, 1.5 mm plagioclase phenocrysts in a groundmass of fine-grained massive chlorite and sericite. The green feldspar-phyric clasts are up to 6 cm in length and have a variety of shapes: blocky and equant; delicately fluidal; wispy and elongate. The blocky clasts have feathery margins (Fig. 5.10C) and some preserve tube vesicles that are filled with albite. The fluidal clasts are commonly interconnected and have random orientations (Fig. 5.10D). The elongate clasts are aligned parallel to bedding in the stratified pumice breccia.

The polymictic pumice breccia is poorly sorted, varying from clast-supported to matrix-supported.
Intervals of polymictic pumice breccia are massive, however locally discontinuous domains of the matrix are laminated (Fig. 5.10D). Laminae are deformed into convolute folds. The proportions of pumice-A clasts, pumice-B clasts and green feldspar-phyric clasts vary considerably in intervals of polymictic pumice breccia. Locally, groups of pumice-A clasts have jigsaw-fit texture either with or without a fine-grained matrix between the clasts. In domains of jigsaw-fit pumice-A clasts, the tube vesicles in adjacent clasts are parallel. Elsewhere pumice-A clasts and green feldspar-phyric clasts are scattered among clasts of pumice-B, shards and feldspar crystal fragments. Pumice-B clasts and matrix (shards and feldspar crystal fragments) immediately surrounding (within 2-5 mm) pumice-A clasts and green plagioclase-phyric clasts are silicified and uncompacted (Fig. 5.11D).

5.5.5 Facies geometry and relationships
The distribution and contact relationships among the stratified pumice breccia, pumiceous rhyolite and polymictic pumice breccia are complex (Figs. 5.9 and 5.10). Intervals of coherent pumiceous rhyolite have sharp to gradational lower and upper contacts that are locally disconformable with bedding. Irregular lobes and stringers of pumiceous rhyolite extend up to 50 cm into the surrounding stratified pumice breccia or polymictic pumice breccia. Commonly there is a gradational contact from coherent pumiceous rhyolite to jigsaw-fit blocky clasts of pumice to polymictic pumice breccia. Near the contact between the pumiceous rhyolite and polymictic pumice breccia, clasts of pumice-A dominate the polymictic pumice breccia (Fig. 5.9). Areas of jigsaw-fit pumice-A clasts occur with or without silicified matrix. With increasing distance (between 50 cm and 5 m) from the contact with the pumiceous rhyolite, the polymictic pumice breccia is dominated by pumice-B clasts, with isolated pumice-A and green feldspar-phyric clasts. This in turn grades into stratified pumice breccia.

Contact geometries between the stratified pumice breccia and polymictic pumice breccia are different in the finer tops versus the coarser bases of the stratified pumice breccia. Contacts between the siltstone top of pumice breccia beds and polymictic pumice breccia are irregular and laminae in the siltstone are commonly distorted or absent within 10 cm of the contact. Immediately adjacent to the contact, the polymictic pumice breccia is composed of poorly sorted pumice-A clasts, fine-grained (< 2 mm) pumice-B clasts, feldspar crystal fragments and shards. The polymictic pumice breccia contains isolated domains of siltstone with convolute and disrupted laminae. Contacts between coarser grained pumice breccia and polymictic pumice breccia are very subtle and gradational, because pumice clasts in the stratified pumice breccia are texturally identical to pumice-B clasts. Thus contacts are implied by the presence of pumice-A clasts.

5.5.6 Interpretation
The pumiceous rhyolite, in situ jigsaw-fit pumice-A clasts at the margins of the rhyolite and pumice-A clasts in the polymictic pumice breccia are mineralogically and texturally identical. Gradational contacts among coherent pumiceous rhyolite, in situ jigsaw-fit pumice-A clasts and polymictic pumice breccia, and the similar phenocryst assemblages are consistent with the pumice-A clasts being derived from the pumiceous rhyolite. The presence of jigsaw-fit pumice-A clasts in the polymictic pumice breccia facies indicates that the clasts formed by in situ fragmentation. The curviplanar or scalloped surfaces on the long axis of some of the pumice-A clasts are consistent with brittle fragmentation, most likely involving quenching of pumiceous rhyolite (cf. Pichler, 1965; Yamagishi, 1987; Kano et al., 1996). Furthermore, pink feldspar-altered rims on pumice-A clasts may reflect fine chilled margins on the pumice clasts.
Pumice-A clasts and the green feldspar-phyric clasts in the polymictic pumice breccia are also mineralogically similar, the main difference being that pumice-A clasts contain well defined tube vesicles, whereas the green feldspar-phyric clasts are now commonly structureless. The rare preservation of feldspar-filled tube vesicles and the alignment of elongate green feldspar-phyric clasts parallel to bedding in the stratified pumice breccia suggest that the green feldspar-phyric clasts are altered and variably compacted pumice-A clasts.

Pumice-B clasts and pumice clasts in the stratified pumice breccia are similar, both being phenocryst-rich tube pumice with approximately 15%, 1 mm plagioclase phenocrysts. The stratified pumice breccia facies is composed of finely fragmented pumice clasts, shards and crystal fragments. These components are interpreted to be juvenile pyroclasts produced by an explosive silicic eruption.

The polymictic pumice breccia is thus composed of two pumice clast populations, one derived from the pumiceous rhyolite and the other derived from explosive eruptions that also supplied pumice clasts in the stratified pumice breccia. The gradation from close-packed jigsaw-fit pumice-A clasts to pumice-A clasts dispersed in stratified pumice breccia dominated by pumice-B clasts and shards, implies that mixing of pumice-A clasts with the stratified pumice breccia occurred in situ and did not involve significant transport of either component.

Pumice-B clasts and shards are uncompacted in the zones of silicification surrounding pumice-A clasts, whereas pumice-B clasts elsewhere show varying degrees of compaction, suggesting that silicification took place prior to compaction. One possibility is that pumice-A clasts were hot and locally baked or indurated pumice-B clasts and shards.

The disruption of laminae in the siltstone tops of the stratified pumice breccia both at the contacts with pumiceous rhyolite and in domains within the polymictic pumice breccia indicates that the stratified pumice breccia was unconsolidated and probably wet at the time of mixing. Local deformation of this nature may be the result of fluidisation and dynamic mixing of the wet unconsolidated sediment and the pumiceous rhyolite (Kokelaar, 1982).

In situ fragmentation of pumice-A clasts, interfingering relationships among the pumiceous rhyolite and pumice breccia facies, and local induration of the stratified pumice breccia are all consistent with the interpretation that the polymictic pumice breccia is pumiceous peperite. Pumiceous peperite was generated at both the top and bottom contacts of the pumiceous rhyolite. The irregular upper contacts, presence of peperite and conformable geometry of the rhyolite at Koonya suggest that it is a shallow syn-volcanic sill emplaced into wet unconsolidated pumice breccia (Fig. 5.9).

5.6 Pumiceous peperite and hyaloclastite associated with a lava dome in the Green Tuff Belt

5.6.1 Geological setting
Pumiceous peperite is associated with the base of a pumiceous rhyolitic lava dome emplaced onto siltstone in the Nishikurosawa Formation in the Hokuroku District of the Green Tuff Belt (Fig. 5.4). Pumiceous peperite and hyaloclastite were recognised in drill hole J6, southwest of the Fukazawa
mine in central Hokuroku Basin (Figs. 5.4 and 5.12). Here the Nishikurosawa Formation comprises intercalated basaltic lava, agglomerate, volcanic breccia and mudstone that are conformably overlain by rhyolitic lava, pumice-lithic clast-rich breccia, sandstone and minor mudstone (Fig. 5.5) (Tanimura et al., 1983).

5.6.2 Interbedded pumice-lithic clast-rich breccia and sandstone
Pumice-lithic clast-rich breccia beds are up to 40 m thick and normally graded with stratified siltstone tops and lithic clast-rich bases (500 to 620 m, Fig. 5.12). Pumice-lithic clast-rich sandstone beds are typically 10-20 m thick, normally graded and diffusely stratified (Fig. 5.12). In both facies, the components are tube pumice clasts (75%, 0.2-1.5 cm), glass shards (10%, 0.2-0.3 mm), non-vesicular rhyolite clasts (7%, 0.2-2 cm), feldspar crystal fragments (5%, 0.2-1.5 mm), green feldspar-phyric fiamme (5%, <2 cm) and mudstone clasts (1%). All original glass is completely altered. The plagioclase-phyric (5%, 1-1.5 mm) pumice clasts are variably altered to saponite, cristobalite, analcime, sericite or chlorite. The vesicles are commonly filled with mordenite. Pumice clasts are blocky or wispy and are both compacted and uncompacted. Glass shards have been altered to analcime. The non-vesicular rhyolite clasts include aphyric perlite rhyolite, and plagioclase-phyric (3%, 1 mm) spherulitic and flow-banded rhyolite. The non-vesicular clasts are sub-angular and blocky with arcuate surfaces. Plagioclase phenocrysts are partially replaced by montmorillonite and saponite, whereas the groundmass is cristobalite or a mosaic of fine quartz and feldspar. Perlitic fractures are filled with chlorite. The green feldspar-phyric fiamme contain 5%, 1.5 mm plagioclase phenocrysts in a groundmass of fine chlorite, sericite and saponite. The long axes of the fiamme are aligned parallel to bedding. In some fiamme, tube vesicles are preserved where they have been filled with analcime or mordenite. Mudstone clasts are elongate and ragged.

At the base of the pumice-lithic clast-rich breccia beds, pumice clasts average 1 to 1.5 cm, lithic clasts are less than 2 cm and rare mudstone clasts are between 0.5 to 5 cm in length. The stratified siltstone tops contain sparse outsize (1.5 -3 cm) pumice clasts and fiamme. Convolute lamination, flames and load structures are typical of the upper contacts. The diffusely stratified sandstone commonly has feldspar crystal-rich bases that grade up-hole into pumiceous siltstone and grey mudstone. Locally the mudstone is bioturbated.

5.6.3 Interbedded mudstone and sandstone
Interbedded brown to dark grey mudstone and volcanic sandstone occur in intervals between 60 cm and 6 m thick (795 to 810 m, Fig. 5.12). Sandstone beds are less than 20 cm thick, massive and tabular. The mudstone is laminated and bioturbated.

5.6.4 Rhyolite facies association
The rhyolite facies association consists of three facies: coherent rhyolite, pumiceous rhyolite, and monomictic pumiceous rhyolite breccia. The rhyolite facies association has a total maximum thickness of 90 m and has been intruded by syn-volcanic basaltic sills (Fig. 5.12). A basaltic sill separates the top of the rhyolite facies association from the overlying interbedded pumice-lithic clast-rich breccia and sandstone. At the base of the rhyolite, monomictic pumiceous rhyolite breccia grades into pumiceous rhyolite-mudstone breccia (806 m, Fig. 5.12).
Figure 5.12: Graphic log of diamond drill hole J6 from the central Hokurok basin, showing the distribution of interbedded pumice-lithic clast-rich breccia and sandstone, interbedded mudstone and sandstone, pumiceous rhyolite, monomictic pumiceous rhyolite breccia and pumiceous rhyolite-mudstone breccia facies. A. Photomicrograph (ppl) of the contact between pumiceous rhyolite and monomictic pumiceous rhyolite breccia. Tube vesicles in the pumice clasts are commonly aligned parallel to tube vesicles in the pumiceous rhyolite. B. Photomicrograph (ppl) of pumiceous rhyolite. Round vesicles are preserved adjacent to the plagioclase phenocryst. Vesicles are monticite-filled and originally gassy walls are replaced by sericite. C. Photomicrograph (ppl) of poorly vesicular coherent rhyolite. The groundmass contains abundant arcuate, chlorite-filled peditic fractures and sparse chlorite-monominellite-filled vesicles. D. Photomicrograph (ppl) of monomictic pumiceous rhyolite breccia with uncompacted and compacted (fiamme) tube pumice clasts.
The coherent rhyolite facies occurs in 1-5 m intervals and grades vertically into pumiceous rhyolite and jigsaw-fit and clast-rotated monomictic pumiceous rhyolite breccia (Fig. 5.12). The coherent rhyolite contains 3%, 1 mm plagioclase phenocrysts in a massive or flow-banded, fine groundmass of quartz-feldspar or cristobalite. Flow-bands are defined by either microspherulitic or formerly glassy perlitic bands. Overlapping arcuate perlitic fractures are filled with chlorite (Fig. 5.12C). Coherent rhyolite varies from non-vesicular to poorly vesicular rhyolite (~7 modal %). Vesicles are filled with montmorillonite or chlorite and quartz (Fig. 5.12C).

A pumiceous interval (~70 modal % vesicularity) occurs at the margins of the coherent rhyolite. Pumiceous and non-vesicular flow-bands also occur in the upper 30 m of the rhyolite (Fig. 5.12). Tube vesicles in the pumiceous rhyolite are filled with either mordenite or montmorillonite. Round vesicles are preserved immediately adjacent to plagioclase phenocrysts (Fig. 5.12B). The originally glassy walls are variably altered to sericite and mordenite.

The monomictic pumiceous rhyolite breccia facies occurs in intervals up to 20 m thick and grades into coherent pumiceous rhyolite and pumiceous rhyolite-mudstone breccia facies (Fig. 5.12). It is poorly sorted, clast-supported and massive with clast sizes varying from 0.5 mm to tens of cm. The plagioclase-phyric (3%, 2 mm) tube pumice clasts have been altered to sericite and mordenite. Round vesicles filled with mordenite are preserved adjacent to plagioclase phenocrysts in the pumice clasts. The clasts are angular with ragged ends and blocky to tubular shapes (Fig. 5.12A). Some clasts are compacted and altered to chlorite (Fig. 5.12D). The tube vesicles in adjacent clasts have random orientations (Fig. 5.12A) although locally groups of clasts show jigsaw-fit texture.

5.6.5 Pumiceous rhyolite-mudstone breccia facies
Three intervals of pumiceous rhyolite-mudstone breccia facies occur at the base of the rhyolitic facies association (790 to 810 m, Fig. 5.12). A 4 m-thick interval of pumiceous rhyolite-mudstone breccia grades vertically up into monomictic pumiceous rhyolite breccia facies and down into interbedded mudstone and sandstone. Intervals of pumiceous rhyolite-mudstone breccia a few cm thick also occur below and above a 2 m-thick interval of pumiceous rhyolite below the main contact.

The pumiceous rhyolite-mudstone breccia facies is poorly sorted and massive. It is dominated by close-packed pumice clasts in a fine-grained silicified matrix. The matrix is commonly limited to thin seams or stringers of mudstone between pumice clasts although at one contact pumiceous rhyolite clasts are isolated in massive mudstone. The pumice clasts vary in size from 1 mm to several tens of cm and have thin selvedges of pale green silicified mudstone. The pumice clasts are blocky, variably compacted and plagioclase-phyric (3%, 1 mm).

5.6.6 Interpretation
Coherent rhyolite, pumiceous rhyolite and monomictic pumiceous rhyolite breccia are closely spatially associated, and have gradational contacts and identical phenocryst populations and mineralogy. The pumice clasts in the monomictic pumiceous rhyolite breccia are texturally similar to the pumiceous rhyolite. This suggests that these three facies are genetically related and that the pumice clasts in the monomictic pumiceous rhyolite breccia are derived from disintegration of the pumiceous rhyolite. In particular, clast shapes and arrangement in the monomictic pumiceous rhyolite breccia are typical of

The gradational contacts between monomictic pumiceous rhyolite breccia, pumiceous rhyolite-mudstone breccia and mudstone are consistent with the interpretation that the pumiceous rhyolite intruded and mingled with mud to produce pumiceous peperite. Silicified mudstone between pumice clasts and in fractures in the rhyolite indicate that the mud was unconsolidated and remobilised during emplacement of the rhyolite. As the rhyolite lava flowed over or intruded the wet unconsolidated mud, mud was injected into fractures in the rhyolite and subsequently baked (cf. Busby-Spera and White, 1987). The thickness (90 m) of the rhyolite facies association and the abundance of clast-rotated textures in the monomictic pumiceous rhyolite breccia are consistent with a rhyolitic lava dome or cryptodome (cf. Scutter et al., 1998). The simple gradation from coherent non-vesicular rhyolite through pumiceous rhyolite to jigsaw-fit textured and clast-rotated monomictic pumiceous rhyolite breccia suggests that growth of the lava dome involved endogenous expansion from the interior during a single eruptive phase.

5.7 Pumiceous peperite and hyaloclastite associated with a cryptodome in the Green Tuff Belt

5.7.1 Geological setting
Pumiceous hyaloclastite and peperite in drill hole HO20 are associated with rhyolitic intrusions in Kagoya Formation, the hangingwall to the Fukazawa VHMS deposit, in the central Hokuroku Basin (Figs. 5.5 and 5.13). The Kagoya Formation is equivalent to part of the Onagawa Formation and consists of pumice breccia, sandstone and siltstone (pumice-rich facies association), and bioturbated mudstone interbedded with rhyolitic lavas and intrusions. The rhyolites are interpreted to be contemporaneous with the emplacement of the pumice breccias (Nakajima, 1988). The lower pumice breccia is extensive and has been used to correlate stratigraphy across the Hokuroku district (Urabe, 1987).

5.7.2 Pumice-rich facies association
Interbedded pumice breccia, sandstone and siltstone facies comprise normally graded, moderately well sorted beds of 20 m average thickness. The pumice breccia beds have lithic clast-rich bases and grade upwards to sandstone or siltstone.

The components of this facies are plagioclase-phyric tube pumice clasts (70%, 6 mm), shards (20%, 0.5 mm), feldspar crystal fragments (7%, 0.2-2 mm), fiamme (5%, 0.5 mm-3 cm) and non-vesicular volcanic clasts (3%, 0.3-4 cm) (Fig. 5.13C and D). Pumice clasts have 5%, 1 mm plagioclase phenocrysts, irregular shapes and ragged terminations perpendicular to the tube vesicles. Most are oriented roughly parallel to bedding, although some are oriented at steep angles. The originally glassy vesicle walls are altered to smectite that is variably replaced by sericite, and the vesicles are filled with mordenite. Plagioclase is partially to completely replaced by sericite or saponite. The green plagioclase-phyric fiamme are interpreted to be altered and compacted pumice clasts. Sub-rounded, non-vesicular volcanic clasts include plagioclase-phyric flow-banded, pelitic or densely microspherulitic rhyolite (2-5% total volume) and fine, massive, aphyric andesite (<1% total volume).
Figure 5.13: Graphic log of diamond drill hole HO20 from the central Hokuroku basin, showing the distribution of interbedded pumice-rich facies, coherent rhyolite, monomictic pumiceous rhyolite breccia facies and rhyolite-siltstone breccia facies. A. Monomictic pumiceous rhyolite breccia composed of green and white striped pumice clasts that are predominantly oriented parallel to the base of the photograph. B. Photomicrograph (ppl) of a feldspar-quartz-sericite-altered tube pumice clast in monomictic pumiceous rhyolite breccia. C. Lithic clast-rich base of a pumice breccia bed. D. Photomicrograph (ppl) of tube pumice clast and andesite clast in the lithic clast-rich base of a pumice breccia bed.
5.7.3 *Rhyolite facies association*

The rhyolite facies association consists of coherent rhyolite and monomictic pumiceous rhyolite breccia facies. The rhyolite facies association has a total thickness of 220 m and comprises thin intervals (< 10 m) of coherent rhyolite surrounded by jigsaw-fit and clast-rotated monomictic pumiceous rhyolite breccia (Fig. 5.13). Some intervals of monomictic pumiceous rhyolite breccia have gradational upper or lower contacts with rhyolite-siltstone breccia (Fig. 5.13).

The coherent rhyolite facies is massive, plagioclase-phyric (5%, 1 mm) and vesicular. Vesicles are filled with zeolites, and smectite, sericite, feldspar and quartz have variably replaced the originally glassy groundmass. Plagioclase phenocrysts are altered to sericite and coated by montmorillonite. The coherent rhyolite contains sparse clasts of pumiceous and shard-rich siltstone and andesite. Siltstone clasts occur mainly in the margins of the rhyolite (~137 m, Fig. 5.13) and are elongate (up to 20 cm).

The monomictic pumiceous rhyolite breccia facies occurs in massive, poorly sorted, and clast-supported intervals between 5 and 20 m thick (Fig. 5.13). Monomictic pumiceous rhyolite breccia comprises plagioclase-phyric (5%, 1 mm) tube pumice clasts in a matrix of fine sericite, quartz and feldspar (Fig. 5.13B). Pumice clasts average 1 cm in length (1 mm to 10 cm), and are angular, blocky and uncompacted. Tube vesicles are filled with zeolites and/or feldspar and the originally glassy vesicle walls are replaced by fine feldspar-quartz and sericite-chlorite assemblages resulting in green and white striped clasts (Fig. 5.13A). The tube vesicles and long axes of most pumice clasts are oriented perpendicular to bedding in the interbedded pumice-rich facies. Sparse andesite clasts are also present; these are sub-rounded and up to 1.5 cm in diameter.

5.7.4 *Rhyolite-siltstone breccia facies*

Rhyolite-siltstone breccia consists of a texturally complex mixture of pumiceous rhyolite clasts and siltstone. Intervals of rhyolite-siltstone breccia are 1 to 10 m thick and grade vertically into monomictic pumiceous rhyolite breccia or siltstone (Fig. 5.13 112-121 m; 148-166 m; 249-258 m). This facies is massive, poorly sorted and varies from clast- to matrix-supported.

Plagioclase-phyric (5%, <1 mm) pumiceous rhyolite clasts are uncompacted, blocky and are 2 mm to 10 cm in length. The siltstone is pale grey, massive and silicified and occurs as ragged clasts (less than 20 cm in length) and as a matrix enclosing isolated pumiceous rhyolite clasts. There is a gradation from close-packed pumiceous rhyolite clasts separated by fractures filled with silicified siltstone to pumiceous rhyolite clasts dispersed in siltstone.

5.7.5 *Interpretation*

The presence of jigsaw-fit texture in the monomictic pumiceous rhyolite breccia suggests that it is derived from in situ brittle fragmentation of coherent pumiceous rhyolite. The steep orientation of tube vesicles in pumice clasts in the monomictic pumiceous rhyolite breccia could reflect steeply dipping flow-bands in the rhyolite. The blocky, angular pumice clasts, abundance of domains with jigsaw-fit texture and the lack of matrix suggest that the monomictic pumiceous rhyolite is pumiceous hyaloclastite (cf. Pichler, 1965; Hanson, 1991).

The gradation from monomictic pumiceous rhyolite breccia to rhyolite-siltstone breccia, the
silicified and homogeneous character of the siltstone within the rhyolite-siltstone breccia facies, and complex clast-matrix relationships, are all consistent with the interpretation of the rhyolite-siltstone breccia facies as pumiceous peperite. The presence of pumiceous peperite, and the irregular and complex geometry of the upper contact of the rhyolite facies association (coherent rhyolite and pumiceous hyaloclastite) are interpreted to result from the intrusion of pumiceous rhyolite into unconsolidated host sediment facies. The host facies is the pumice-rich facies association, which is composed of interbedded bioturbated mudstone, pumice breccia and sandstone.

The rhyolite facies associations are not laterally extensive (<500 m) and they are composed of lobes of coherent rhyolite interfingering with thick (<20 m) monomictic pumiceous rhyolite breccia. This is typical of rhyolitic cryptodomes (cf. Allen, 1992a).

5.8 Comparison of pumiceous hyaloclastite and peperite with other submarine pumice-rich facies

Pumiceous hyaloclastite and peperite can resemble other pumice-rich facies that are common in submarine volcanic successions. Pumiceous debris in the submarine environment can be produced as a result of intrabasinal and extrabasinal explosive eruptions and autoclastic fragmentation (autobrecciation, quenching) of pumiceous lavas or intrusions.

5.8.1 Identification of pumiceous hyaloclastite
The identification of hyaloclastite generally requires evidence that the lava or magma was quenched and that fragmentation was in situ. Clasts produced by quench fragmentation are typically originally glassy and blocky with planar and curviplanar margins. If the original lava or magma is pumiceous, it may be exceedingly difficult to recognise the effects of quenching because pumice clasts are predominantly glassy and are easily compacted. In this chapter, examples of pumice breccia are interpreted as pumiceous hyaloclastite because:

(1) Units are monomictic.

(2) There are gradational contacts between non-vesicular and pumiceous rhyolite (or dacite), jigsaw-fit monomictic pumiceous breccia (in situ hyaloclastite) and clast-rotated monomictic pumiceous breccia (clast-rotated hyaloclastite).

(3) Abundant jigsaw-fit textures indicate that fragmentation was in situ and possibly non-explosive.

(4) They comprise originally glassy, equant, polyhedral, blocky clasts with curviplanar and cuspat surfaces, which suggests that fragmentation was produced by contraction accompanying quenching (cf. Pichler, 1965; Wohletz, 1983).

In submarine settings, pumice-rich facies can be generated by mechanisms other than the quenching of hot pumiceous rhyolite (Fig. 5.14). Most documented submarine pumice breccias are interpreted as mass-flow or water-settled fall deposits from subaerial or submarine explosive eruptions or their resedimented equivalents (Fiske and Matsuda, 1964; Fisher and Schmincke, 1984; Cashman

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and Fiske, 1991; Allen et al., 1996; Kano et al., 1996; Allen and McPhie, 2000). Deposits from pumice-rich mass flows typically form laterally extensive beds that have normally graded tops (Fig. 5.14B) (Fiske and Matsuda, 1964; Fiske, 1969; Yamagishi, 1987; Allen et al., 1997). Although these can resemble clast-rotated pumiceous hyaloclastite, hyaloclastite generally has limited extent and volume, is spatially associated with compositionally identical lavas or intrusions and locally shows jigsaw-fit textures.

Submarine pumice breccias with limited lateral extents, can also be generated by domes (Fig. 14C, dome-top tuff cones; Cas et al., 1990; Allen et al., 1997). Dome-top tuff cones are spatially associated with coherent rhyolite, and in situ and clast-rotated hyaloclastite and comprise poorly sorted, clast-supported deposits of pumice clasts, shards and crystal fragments (Cas et al., 1990; Allen et al., 1997). Although dome-top tuff cones may resemble clast-rotated pumiceous hyaloclastite, they are limited to the tops of domes (or lavas) and do not preserve jigsaw-fit textures (Fig. 5.14C). In addition, because the dome-top tuff cones typically result from small-volume eruptions they commonly comprise upward-fining stratified sequences. Because explosive eruptions commonly accompany the extrusion of felsic lavas and domes, pumiceous hyaloclastite and deposits of pyroclastic pumice breccia can occur in close association and be genetically related. Thus in ancient successions, there may be insufficient evidence to discriminate between quench fragmented, lava-derived pumice or pumice generated by explosions.

Pumiceous hyaloclastite could also be confused with pumiceous autobrecchia. Pumiceous autobrecchia commonly forms in small volumes at the margins of lavas (Kano et al., 1991). Autobreccias typically contain a chaotic arrangement of angular, blocky and slab-like or plastically deformed or folded clasts (Fig. 5.14D) (Hanson, 1991; Cas, 1992). Pumice clasts may have fractures perpendicular to the tube vesicles suggesting that fragmentation resulted from the stretching and pulling apart of a cool, relatively rigid, vesicular magma (Heiken, 1978). Although pumiceous autobrecchia closely resembles pumiceous hyaloclastite, jigsaw-fit textures, curviplanar clast surfaces and abundant fine clasts (<2 mm, up to 80%) are more common in hyaloclastite than autobreccia (Pichler, 1965; Hanson, 1991). However, quench fragmentation and autobreciation are likely to act in union in subaqueous settings (Pichler, 1965; Kokelaar, 1986; Scutter et al., 1998).

5.8.2 Recognition of pumiceous peperite
The positive identification of peperite requires evidence that the host sediment was unconsolidated at the time of mingling and that the igneous component was molten. The examples discussed in this chapter are interpreted as peperite because:

1. The sediment component in the peperite, whether that be pumice breccia, pumiceous siltstone, or mudstone, is massive and unstratified, whereas elsewhere the host sediment is graded, stratified or laminated. Local destruction of original depositional structures requires that the host sediment was unconsolidated or only poorly consolidated, allowing easy disruption of grain contacts.

2. Sediment immediately adjacent to pumiceous rhyolite clasts within the peperite, and sediment close to contacts with the coherent rhyolite are silicified compared to sediment away from the rhyolite. This local silicification is interpreted to reflect baking or induration of sediment in contact with hot rhyolite.
Figure 5.14: Cartoons of the different mechanisms that may generate pumice-rich facies in a submarine environment and schematic logs through the resulting deposits at the position indicated, showing the textural facies characteristics. A. Pumiceous hyaloclastite associated with a submarine pumiceous lava or dome and overlying siltstone. B. Pumiceous mass-flow deposit and overlying siltstone. C. Dome-top tuff cone (after Cas et al., 1990). D. Pumiceous autobreccia associated with a pumiceous lava or dome overlain by siltstone.
There are gradational contacts between coherent rhyolite, monomictic pumiceous rhyolite breccia, pumiceous rhyolite-sediment peperite (polymictic pumice breccia, pumiceous rhyolite-siltstone breccia and pumiceous rhyolite-mudstone breccia) and host sediment (pumice breccia, siltstone and mudstone respectively).

Dispersal of pumiceous rhyolite clasts in the host sediment is limited to distances of less than 5 m (usually less than 50 cm) from contacts with monomictic pumiceous rhyolite breccia and/or coherent rhyolite.

In submarine settings, pumice-sediment mixtures can be generated by mechanisms other than the mingling of hot pumiceous rhyolite with wet unconsolidated sediment. Pumiceous mass flows can incorporate sediment from the substrate. Unconsolidated clasts of mud or silt may remain intact or else disintegrate during transport, contributing a fine-grained matrix. Laminae in sediment intraclasts and in underlying sediment may be locally deformed or destroyed. Deposits from these mass flows typically form laterally continuous beds that may extend for hundreds of m or km. Although superficially similar, pumice-sediment peperite generally has limited extent (tens to hundreds of m) and volume, can be markedly disconformable, is spatially associated with the margins of intrusions, and the sediment component shows evidence of baking.

Pumice and sediment may also be mixed as a result of slumping and resedimentation of sediment and pumiceous dome margin debris during growth of a partly extrusive cryptodome. This pumice-sediment mixture can be distinguished from pumiceous peperite mainly by its occurrence in diffusely stratified or weakly graded lenticular beds. The distinction may however be far from clear as both facies can include groups of pumice clasts that show jigsaw-fit texture and sediment that is locally indurated adjacent to pumice clasts derived from the dome carapace.

Pumiceous peperite could also be confused with pumiceous hyaloclastite or autobreccia that has a fine sediment matrix due to infiltration of sediment into open spaces between clasts. Such infilling sediment is typically fine-grained (granules and finer) and planar stratified with bedding orientations consistent among all the sediment domains. In contrast to the locally indurated host sediment domains in pumiceous peperite, infilling sediment is not affected by contact metamorphism.

Pumiceous clasts that are initially buoyant eventually become water logged and sink, being deposited at the same time as much finer sediment settling from suspension. The result is a laterally extensive deposit composed of outsized pumice clasts in laminated siltstone and mudstone. Compaction causes a dramatic change in the shapes of pumice clasts and contortion of sedimentary laminae, producing a facies that can resemble pumiceous peperite. However, water-settled pumice-sediment mixtures typically occur in laterally continuous beds. Although contorted, stratification in the sediment domains is generally well preserved and may drape large pumice blocks, and the sediment shows no evidence of induration.
Figure 5.15: Cartoons of the different mechanisms that may generate pumice-sediment mixtures in a submarine environment and schematic logs through the resulting deposits at the position indicated, showing the textural facies characteristics. Refer to Figure 5.14 for legend. A. The intrusion of pumiceous rhyolite into wet unconsolidated sediment. B. Pumiceous mass flow incorporating intrabasinal sediment. The resulting mass-flow deposit was overlain by siltstone. C. Resedimentation of dome margin debris and sediment cover above an emerging cryptodome. D. Infiltration of sediment into pumiceous hyaloclastite or autobreccia. E. Outsized water-logged pumice clasts in fine-grained suspension sediment.
Such mixtures typically occur in the fine-grained tops of pumiceous mass-flow units or in overlying suspension sediment intervals, and may be far removed from any coherent pumiceous rhyolite in the succession.

5.9 The formation of pumiceous peperite and hyaloclastite

The examples of pumiceous peperite and hyaloclastite described here are characterised by a transition from coherent or pumiceous rhyolite or dacite to in situ pumiceous hyaloclastite or pumiceous peperite, the presence of pumice clasts with chilled margins and curviplanar surfaces, and abundant jigsaw-fit textures. This implies that quench fragmentation and autobrecciation were the dominant mechanism of clast formation (cf. Hanson and Wilson, 1993; Pichler, 1965; De Rosen-Spence et al., 1980).

In the first example of pumiceous hyaloclastite from the Mount Read Volcanics (112R), jigsaw-fit textures dominate. This suggests that fragmentation resulted from the propagation and interconnection of fractures in response to stress release due to the difference in contraction rates between the inner and outer parts of the dacite during quenching (cf. Pichler, 1965; Yamagishi, 1991). Subsequent examples of pumiceous hyaloclastite from both the Mount Read Volcanics and the Hokuroku Basin are characterised by a gradation from jigsaw-fit to clast-rotated textures. In the examples from 120R and HO65, clast-rotated hyaloclastite includes clasts derived from texturally distinct facies of the rhyolite facies association. Brittle fragmentation is interpreted to have been due to a combination of quenching and dynamic stressing of the more brittle parts of the lava (cf. Kokelaar, 1982). Mixing of texturally different clast types may have been the result of reorganisation of the hyaloclastite carapace during continued growth of the lava or limited resedimentation. Although some resedimentation may have occurred, these examples lack evidence for significant transport, such as stratification or grading, and still retain gradational contacts with jigsaw-fit hyaloclastite and local domains of jigsaw-fit texture.

In the two examples of pumiceous peperite from the Hokuroku Basin, jigsaw-fit texture predominates and the dispersal of pumice clasts was very limited. Dynamic stressing of more brittle parts of the pumiceous rhyolite, propagation of contraction cracks and the injection of mobile sediment along fractures can adequately account for the textural and facies characteristics observed. Pumice clasts in the Koonya pumiceous peperite have curviplanar surfaces and local jigsaw-fit texture, consistent with quench fragmentation, but the pumice clasts are more dispersed in the host stratified pumice breccia. In this case, the mingling of pumice clasts with the stratified pumice breccia may have been facilitated by steam explosions (cf. Wohletz, 1983; Kokelaar, 1986; Branney and Suthren, 1988) or the convective circulation of superheated pore-water and sediment (Kokelaar, 1982).

In this chapter, examples of hyaloclastite and peperite are highly vesicular and pumiceous with between 45 and 80 modal % vesicles. Many of the vesicles have been deformed during flow or expansion of the lava or intrusion, resulting in elongate or tube vesicles (cf. Kano et al., 1991). The pumiceous nature of the rhyolite in these examples implies that volatile exsolution was not inhibited by confining pressure nor arrested by cooling prior to fragmentation. Low confining pressures (less than 10 Mpa) are required to allow vesiculation (McBirney, 1963). Modern examples of pumiceous hyaloclastite associated with felsic lava domes in the eastern Manus and western Woodlark Basins are known to
occur at water depths up to 2000 m (Waters and Binns, 1998 unpub.). Pumiceous peperite associated with rhyolitic intrusions requires that vesiculation occurred beneath a thin sediment cover and at water depths probably less than 200 m (McBirney, 1963; Hunns and McPhie, 1999).

Delayed quenching of the magma is implied by the high degree of vesiculation and suggests that the rhyolite was, at least initially, insulated. This may have been achieved by the development of a vapour film at the contact between the molten rhyolite and water or unconsolidated host sediment.

### 5.10 Significance of pumiceous hyaloclastite and peperite

The recognition of pumiceous hyaloclastite and peperite has significant implications for the interpretation of the facies architecture and stratigraphic relationships in volcanic successions. In ancient submarine volcanic successions, pumice-rich facies are commonly interpreted as pyroclastic-flow deposits, water-supported mass-flow deposits, water-settled suspension deposits, and in situ and re-sedimented hyaloclastite (Fiske and Matsuda, 1964; Pichler, 1965; Furnes et al., 1980; Reynolds et al., 1980; Allen and Cas, 1990 unpub.; Kano, 1990; Allen et al., 1996; Kano et al., 1996). As such, pumice-rich facies are used as marker horizons that represent seafloor positions in the stratigraphic succession. However, it is clear that pumice clasts can instead be generated by non-explosive fragmentation in subsurface settings (pumiceous peperite). The context of pumice-rich facies should be carefully examined before they are used to make regional correlations or infer seafloor positions.

Felsic magmas typically form thick, short lavas or domes with thick deposits of hyaloclastite in the proximity of the vent (Pichler, 1965; Cas, 1978; De Rosen-Spence et al., 1980; Cas et al., 1990; Kurokawa, 1991; Kano et al., 1991; Yamagishi and Matsuda, 1991; Waters and Binns, 1998 unpub.). Thus, pumiceous hyaloclastite and peperite are important in providing a useful indicator of proximity to vent.

The recognition of pumiceous peperite also constrains the age relationships and timing of pumiceous intrusions and lavas. The pumiceous nature of this facies suggests that the emplacement occurred at shallow levels in the subsurface under a thin cover of unconsolidated sediment. The implication is that pumiceous peperite and the associated intrusion were contemporaneous or nearly contemporaneous with the host sedimentary facies (syn-sedimentary or syn-volcanic).

### 5.11 Conclusions

Pumiceous hyaloclastite and peperite are associated with rhyolitic and dacitic lavas and intrusions in the Hercules and Kershaw Pumice Formation. Other examples of pumiceous hyaloclastite and peperite occur in the Miocene Green Tuff Belt, Japan.

Intervals of pumiceous hyaloclastite are thick (2-40 m), laterally discontinuous, massive, clast-supported, and poorly sorted with jigsaw-fit and clast-rotated textures. They are typically monomictic, comprising blocky tube pumice clasts but may contain sparse perlite clasts. Pumiceous hyaloclastite has gradational contacts with coherent pumiceous rhyolite or dacite.
Intervals of pumiceous peperite are thin (<15 m), laterally discontinuous, massive, poorly sorted and the clast-to-matrix ratio varies significantly over short distances. They are composed of feldsparphyric tube pumice clasts and domains of sediment that include stratified pumice breccia, pumiceous siltstone and bioturbated mudstone. The sediment domains may be massive or display relic depositional structures. Sediment adjacent to pumice clasts is silicified, possibly reflecting induration on contact with hot pumice. Pumiceous peperite has gradational contacts with in situ and clast-rotated pumiceous hyaloclastite and coherent pumiceous rhyolite.

The recognition of pumiceous hyaloclastite and peperite is important for interpreting the facies architecture and stratigraphic relationships in the volcanic succession and provides limits on the age relationships and timing of the pumiceous intrusions. However, pumiceous hyaloclastite and peperite may easily be misinterpreted or overlooked as they resemble other pumice-rich facies that are common in submarine volcanic successions.

Diagnostic features of pumiceous hyaloclastite are: (1) monomictic clast population; (2) gradational contact with coherent pumiceous rhyolite; (3) abundant jigsaw-fit textures; and (4) blocky, angular pumice clasts with planar and curviplanar margins.

Diagnostic features of pumiceous peperite are: (1) gradational relationships among the host sediment, pumiceous peperite, in situ monomictic pumiceous rhyolite breccia and coherent pumiceous rhyolite; (2) local destruction of depositional structures in the sediment; (3) local silicification or induration of sediment adjacent to pumiceous rhyolite clasts; and (4) the massive, laterally discontinuous character of this facies.

Pumiceous hyaloclastite resulted from the quenching of vesicular magma by water, whereas pumiceous peperite was generated from the mingling of highly vesicular magma with wet unconsolidated sediment. During the formation of pumiceous peperite, sediment was injected into fractures propagating into the hot pumiceous rhyolite, resulting in local destruction of depositional structures in the host sediment and local induration.

The formation of pumiceous hyaloclastite and peperite requires the exsolution of magmatic volatiles prior to cooling and fragmentation. Conditions that favour this are low confining pressure and insulation of the magma from quenching during volatile exsolution.