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GEOLOGY OF THE AMULET RHYOLITE
FORMATION, TURCOTTE LAKE SECTION
NORANDA AREA, QUEBEC

by

● Harold Lorne Gibson, B.Sc.

A thesis submitted to the Faculty of
Graduate Studies in partial fulfilment
of the requirements for the degree of
Master of Science

Department of Geology
Carleton University
Ottawa, Ontario
June, 1979

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The undersigned hereby recommend to the Faculty of Graduate Studies acceptance of this thesis, submitted by Harold Lorne Gibson, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

The Amulet "rhyolite" formation, within the central Noranda volcanic complex, northwestern-Quebec, directly underlies three massive sulphide lenses; the Amulet C and F ore lenses and the Lac Dufault zinc lens. The larger Amulet lower A deposit and Millenbach deposit lie above the Amulet "rhyolite" formation, separated from it by the Millenbach andesite and at Millenbach by a quartz-feldspar porphyry dome and Millenbach andesite.

Detailed geologic mapping through a complete section of the Amulet "rhyolite" formation, northwest of the Corbet mine allowed its breakdown into two members. The lower member consists of a volcanic breccia marker unit, locally referred to as Beecham breccia, overlain by a rhyolite lava dome which is in turn overlain by chloritic andesite flows. The upper member is a succession of variably silicified andesite flows capped by a blocky, ribbon-textured mixed fragmental unit.

Alteration in the lower member is chloritization with feldspar breakdown. The alteration results in FeO and MgO enrichment and Na₂O depletion within the volcanic rocks.

Silicification is the dominant alteration of the upper member and is of two main types. The first is a pervasive, conformable, patchy "mottled" silicification characterized by the assemblage epidote-quartz with variable actinolite and carbonate. Mottled alteration occurs as envelopes mantling amygdules, chlorite fractures, and flow laminations; the alteration controlled by the original permeability of the flow rocks. Mottled alteration is interpreted as the result of hot water/rock interaction in the medial portion of a shallow, subseafloor geothermal system.

The second type of silicification is marked by cross-cutting clastic breccia dikes referred to as white-fragment breccias. The breccia occurs as linear fault or fracture controlled dikes of white silicified andesite fragments in a finer grained, chloritized, microbreccia matrix. Breccia dikes were emplaced by a fluidization process and are interpreted to have been generated and emplaced along hydrothermal discharge channelways. Clastic breccia dikes mark conduits which fed submarine hot springs at the top of the Amulet rhyolite formation.

In the field silicified andesite can be traced gradationally into unaltered andesite. Silicified andesite has preserved glomeroporphyritic albite microphenocrysts and albite microlites with a preserved pilotaxitic or felted texture identical to associated unaltered andesite. In the silicification process it appears that only interstitial groundmass chlorite, interpreted as devitrified glass, is replaced by quartz.

Silicified andesite (65 - 80% SiO_2) is characterized by an anomalously high TiO_2 content, 0.60 to 1.17 wt. % TiO_2 , similar to that of associated andesitic flows and twice that of rhyolite from lava domes at the base of the section. The Y and Zr content of silicified andesite is identical to that of associated andesite flows.

The net chemical change that occurred with silicification, assuming constant volume metasomatism, is an increase in SiO_2 and decrease in Al_2O_3 , FeO , MgO , TiO_2 , Cu and Zn. Progressive silicification converted an original tholeiitic andesite to a rock that chemically resembles a calc-alkaline rhyolite. Silicified rocks are interpreted as products of a geothermal system related to the circulation of hot, silica-saturated solution through a submarine volcanic pile.

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I INTRODUCTION

LOCATION

The Turcotte Lake section and Buttercup Hill map area, the focus of mapping for this thesis are located 10km northwest of the twin cities of Rouyn and Noranda, in northwestern Quebec. The area straddles the boundary between Duprat and Dufresnoy townships, west of Lac Dufault, in the Amulet "rhyolite nose" (Figure 1). The northwest portion of the map area is accessible by a bush road connecting the Bedford prospect, further to the west, with the main haulage road servicing the Killenbach and Corbet mines. The southeast portion of the area is accessible via the Corbet mine road.

PREVIOUS WORK

The Noranda area is rich in mining and exploration history. Since 1923 when Edmund Horne discovered the first massive sulphide deposit, to Falconbridge Copper's most recent discovery (1974), the Corbet mine, the area has been one of Canada's premier mining camps. Volcanogenic massive sulphide deposits from this area have been described in the literature as "Noranda type". Characteristics of these deposits are regarded by many to typify Canadian, Archean volcanogenic massive sulphide deposits and have influenced several generations of exploration and academic geologists.

Volcanic rocks of the Noranda area have been mapped by various workers, most notably by Wilson (1941) and De Rosen-Spence (1976).

Figure 1. General geology of the central Noranda area and location of study area (Spence and De Rosen-Spence, 1975).

The Amulet "rhyolite" formation, was previously interpreted as a rhyolite flow or flows. The location of several ore deposits at or near the contact of the Amulet rhyolite formation with overlying Amulet-Millennbach andesite introduced the concept of a favourable rhyolite-andesite contact. The search for massive sulphide deposits in Noranda and elsewhere was dominated by this "stratigraphic" concept throughout the late 1960's and early 1970's.

Comba (1977) through detailed mapping was the first to differentiate rhyolite flows at the base of the Amulet "rhyolite" formation from "andesitic looking" rocks characteristic of the upper Amulet rhyolite. B. Sakrison (personal communication, 1978) believed that anomalous TiO_2 values (.5 to 1.0 wt.% TiO_2) of siliceous rocks from the Amulet rhyolite formation indicated "silicification" of an original, more mafic rock. Spring (1976) in his mapping of alteration textures at Buttercup Hill, an outcrop of upper Amulet "rhyolite", provided the first concrete evidence for silicification.

GENERAL GEOLOGY

Volcanic rocks of the Noranda area are a small portion of the extensive Abitibi greenstone belt, the largest greenstone belt in the Canadian Shield. Goodwin and Ridler (1970) divided the Abitibi greenstone belt into 11 volcanic complexes; rocks of the Noranda area are contained within the Noranda-Benoit volcanic complex (Figure 2).

Within the Noranda-Benoit volcanic complex, the Blake River group of volcanic rocks comprise a 1100 - 1500m thick succession of basal

Figure 2. Location of volcanic complexes in the Abitibi greenstone belt (after Goodwin and Ridler, 1970). Felsic volcanic rocks shown by vertically lined pattern. Approximate boundaries of volcanic complexes are shown by heavy dashed lines.

tholeiitic and upper tholeiitic and calc-alkaline basalt, andesite and rhyolite flow rocks (Dimroth, 1975; Gelinas et al 1977). Rocks of the Noranda area are a subgroup (Figure 3), the Noranda subgroup, of the upper tholeiitic and calc-alkaline rocks of the Blake River group (Goodwin, 1974). The volcanic succession within the Noranda subgroup was divided into 5 alternating rhyolite and andesite-basalt formations by De Rosen-Spence (1976), who interpreted the volcanic rocks to have formed a large shield volcano some 40 - 50km wide. The third rhyolite formation, the Amulet or Mine "rhyolite" is the formation of the interest in this study.

Detailed geologic mapping was conducted through a complete and relatively undisturbed stratigraphic section of Amulet "rhyolite", along the McDougall fault, northwest of the Corbet mine (Figure 1). Striking slightly west of north, dipping gently east, the Amulet "rhyolite" is underlain by the Rusty Ridge andesite formation, and overlain by the Millenbach-Amulet andesite formation. The map area (Figure 1) is sandwiched between the Flavrian tonalite complex to the west and the Lac Dufault granodiorite body to the east.

PURPOSE

The three main objectives of this study are:

- 1) To produce a detailed geologic map of the Amulet "rhyolite" formation in the Turcotte Lake area.
- 2) To outline, as well as chemically and mineralogically define areas of silicification to gain an appreciation for the amount of true rhyolite versus silicified rock.

- 3) To develop a model to explain silicification and its relationship to volcanic stratigraphy.

METHODS

Field methods

Field studies occupied four months of the summer of 1978. Outcrops from airphotos at a scale of 1:2400 were enlarged, using a panograph, to a scale of 1:1200 and 1:600 for a base map. Distortion inherent in the airphotos and subsequent enlargement required approximately 50% of the mapping time to redraw and measure (by pace) outcrops.

Five days, in late November, 1978, were used to map an exposure of Amulet rhyolite in the Millenbach mine. The results of the underground mapping are contained in the appendix.

Laboratory methods

Laboratory studies included:

- 1) The examination of 180 thin sections with special attention to volcanic textures and mineralogy to serve as a basis for classification of altered rocks. The mineralogy of 7 representative samples was checked by X-ray powder diffractometry.
- 2) 62 samples were selected for chemical analysis. The samples were analyzed for major and trace elements at the University of Ottawa using a fused pellet X-ray fluorescence (XRF) technique. In addition 32 of the above specimens were re-analyzed for 9 trace elements at Laurentian University.

PRESENTATION

The map area is divided into two areas, the Turcotte Lake section and Buttercup Hill. The Turcotte Lake section is a complete and representative stratigraphic section through the Amulet "rhyolite" formation (C.D.A. Comba, personal communication, 1978). Buttercup Hill is a unique exposure of Amulet "rhyolite" representative of volcanic rocks and alteration found within the upper member.

The general geology, description of map units, structural geology and alteration of the Turcotte Lake section are described first, followed by a discussion of the geology and alteration present at Buttercup Hill. The chapter concerning geochemistry describes and discusses the chemical characteristics of various rock types recognized, and quantitatively assesses chemical changes that occurred during silicification. The last major chapter discusses alteration in the upper Amulet rhyolite in the framework of processes active in modern geothermal systems.

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I would like to thank Falconbridge Copper Ltd. and Noranda Mines Ltd. for permission to conduct geologic mapping on their respective properties. Falconbridge Copper Ltd. made available all maps, drill-hole data, and chemical analyses pertaining to the map area.

This study benefits from many hours of discussion with J.M. Franklin, M.B. Lambert and J.W. Lydon of the Geological Survey of Canada, and C.D.A. Comba, and D.H. Watkins of Falconbridge Copper Ltd.

C.D.A. Comba suggested the map area and introduced the writer to Noranda geology on several enlightening field trips. M.B. Lambert introduced the writer to the petrographic study of volcanic textures.

A.D. Hunter, Carleton University, and S. Parry, University of Western Ontario, working on similar problems west of central Noranda, shared ideas.

Michael Johnston and Mark Clark were able field assistants.

My wife Denise, typed several drafts of this manuscript and her encouragement and patience throughout this study is gratefully acknowledged.

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II. DESCRIPTION OF MAP UNITS

Volcanic rocks of the study area are part of a homoclinal, submarine volcanic succession that strikes north-northeast and dips (30° - 40°) to the southeast. The succession was divided into three formations (Comba, 1977; De Rosen-Spence, 1976; Wilson, 1941); the Rusty Ridge andesite, Amulet "rhyolite", and Amulet andesite formations (Figure 4).

The existing formation names are misleading. Both the Rusty Ridge andesite and Amulet andesite are mixed successions of basaltic and andesitic lavas (De Rosen-Spence, 1976) and the Amulet "rhyolite" contains little true rhyolite (<30 percent). The formation names have been retained, because of firm entrenchment in the literature.

Both mafic and felsic intrusions cross-cut the volcanic rocks; the majority are high-level, synvolcanic intrusions, the others, later diorite dikes.

THE RUSTY RIDGE ANDESITE FORMATION

The Rusty Ridge andesite formation is a succession of brown-weathering, pillowed and massive andesite-basalt flows (Table 6). Rusty Ridge andesite underlies the Amulet "rhyolite" formation and is found at the base of the section mapped (Figure 4). The andesitic lavas are divided into eight flow units whose apparent thicknesses range from 25m to 80m.

A flow unit, as used in this study, refers to a mappable unit composed of one or more flows. Flows within a flow unit have identical textural characteristics distinguishing them from other flow units and

are recognizable, but not mappable. The contacts of individual flows and flow units are marked by amygdule or breccia zones.

Flow unit RR8 is a brown weathering, fine-grained massive andesite flow and flow breccia. The massive portion is characterized by quartz-filled laminations and fractures, which parallel the flow contacts. A blocky flow-top breccia, consisting of large rafts (up to 15 x 8m) of laminated andesite in a blocky breccia matrix, overlies massive andesite. The andesite rafts, like the underlying massive andesite, are laminated and contain zones of egg-shaped, quartz amydules (up to 5cm long) elongated parallel to the laminations.

Ribbons, or amoeboid tongues of laminated andesite project from the massive andesite into the breccia matrix, producing an imbricate structure (Figure 5) similar to that described by Coté and Dimroth (1976). Imbricate structure is locally developed at the contact of massive andesite and blocky breccia flow-top. Andesite tongues are parallel and consistently oblique to the flow contact. Coté and Dimroth (1976) proposed that the structure is formed by plastic shear during flowage of basaltic lava, and can be used to determine flow direction. Imbrication, in this case, indicates a west to east flow direction.

The blocky nature of the flow-top and gradation into underlying massive andesite is reminiscent of a blocky or aa-type lava flow (MacDonald, 1971). The blocky flow top is the equivalent of a clinker flow top, and massive andesite equivalent to the massive interior of aa flows.

Flow unit RR7 is a brown-weathering, dark green pillowed andesite. Pillows range from a 2 x 4m tube to 0.7 x 0.8m bun-shaped pillows in

Figure 5 . Imbricate structure in flow-top breccia, flow unit RR8.

Figure 6 . Pillow lava of flow unit RR6.

a hyaloclastite matrix. The tube-like "pillow" may be a lava tube or massive flow.

Quartz-filled, concentric laminations characterized the pillow lavas (Figure 7). Laminations, filled by quartz, are a few mm thick and best developed along pillow margins. The distance between parallel laminations increases towards the pillow core. This "onion skin" texture is interpreted to be a primary cooling feature.

Intensely fractured and collapsed pillows are not common. The hyaloclastite matrix is chloritized and cemented by quartz producing a characteristic "vein-network" texture on weathered surface.

Flow unit RR6 is a brown-weathering, aphanitic to fine-grained, dark green pillowed andesite. Pillows are of two types; bun or sack-like forms with an average size of 12 x 30cm, and mattress-shaped pillows with an average size of 2.5 x 0.75m. Quartz amygdules are found throughout the pillows but are concentrated along pillow-margins. Amygdules range in size from 0.8 to 2cm. At the base of the flow unit pillows contain an average of 5-10 percent quartz amygdules, increasing upwards in abundance to a maximum of 35 percent.

Pillows of this flow unit are characterized by polygonal or a diamond-patterned jointing (Figure 6). Quartz-lined joints are confined to pillow interiors.

Chilled margins of individual pillows are difficult to distinguish. The pillows are rimmed by a 5 - 22cm thick hyaloclastite margin, composed of chloritized, angular andesite fragments and shards in a quartzose matrix, imparting a vein-network texture to pillow margins and matrix hyaloclastite.

Figure 7. Pillow lava of flow unit RR7, with well developed concentric cooling laminations.

Pillow breccia occurs as thin lenses within pillowed andesite. Contacts with underlying and overlying andesite are sharp; underlying andesite is extremely amygdaloidal (up to 35 percent quartz amygdules) adjacent to pillow-breccia units.

Pillow breccia consists of isolated intact pillows and massive and amygdaloidal andesite fragments in a fine-grained brown fragmental matrix containing irregular patches of cream-coloured chert. Flows above pillow breccia lenses, and within cooling unit RR7 contain similar chert patches with hyaloclastite as interpillow detritus.

Flow unit RR5 is a massive, brown-weathering aphanitic to coarse-grained andesite. It is uniform, massive and has well developed columnar joints (Figure 9). The latter are five- or six-sided columns with concave or convex ends.

The columns dip consistently at 60° to the northwest, indicating a flat underlying topography. The flow unit is weakly amygdaloidal but does contain amygdular zones (20 percent quartz amygdules) adjacent and parallel to flow contacts.

Flow units RR1 and RR3 are massive andesite, similar to RR5 except for the paucity of columnar joints.

Flow unit RR2 and RR4 are rusty-weathering, dark green, aphanitic pillowed flows. The pillows are bun or amoeboid in shape (Figure 8) and range to 1 x 5m to 0.2 x 0.7m in size. They contain a maximum of 25 percent quartz "pipe" amygdules radial to pillow margins, have a thin 0.5 to 4cm reddish brown selvage and are densely packed.

Figure 8 . Amoeboid pillow lava from flow unit RR2 and RR4.

Figure 9 . Columnar jointed lava in flow unit RR5.

THE AMULET "RHYOLITE" FORMATION

Detailed geologic mapping was conducted through a complete and relatively undisturbed section of Amulet "rhyolite". A stratigraphic section of the map area is shown in Figure 10, which relates the important geologic features from the detailed map (Figure 4). In the map area, Rusty Ridge andesite and Amulet andesite conformably underlie and overlie the Amulet "rhyolite" formation respectively.

The Amulet "rhyolite" formation was divided into two members, the upper and lower Amulet rhyolite, as had Comba (1977). The lower member consists of a volcanic breccia unit locally referred to as Beecham breccia, overlain by a flow-banded, spherulitic rhyolite lava-dome which is mantled by chloritic flows. The upper member consists of variably silicified andesite flows capped by a conformable, blocky, white-fragment breccia marker horizon.

Massive flows of the upper and lower Amulet "rhyolite" are interpreted as a submarine volcanic succession. Pillow lavas of the underlying Rusty Ridge andesite, intervening Bedford andesite and overlying Amulet-Millenbach andesite with associated "exhalative" sediments support this interpretation.

The flows of the upper member are transected by northeast striking, steeply dipping (70° - 80°) shear zones of two types; dike-like zones of angular white-fragment breccia, and chloritic shears containing pyrite, quartz and chalcopyrite. These cross-cutting alteration zones will be discussed in later chapters.

FIGURE 10

A reconstructed stratigraphic section of
Amulet "rhyolite" in the Turcotte Lake area

LEGEND

Intrusive Rocks
Rhyolite and basalt dikes

— intrusive contact —

Volcanic Rocks
Andesite ash tuff

Pillowed andesite-basalt

Massive andesite-basalt

Blocky white-fragment breccia with ribbon structure

Angular white-fragment breccia

Chloritized and silicified vitrophyre

Chloritic flows

Flowbanded rhyolite

Beecham breccia

Alteration symbols

Chloritic shear zone

Mottled alteration (quartz-epidote)

Silicified white andesite

Breccia

Chlorite breccia network

AMULET RHYOLITE FORMATION TURCOTTE LAKE SECTION

THE LOWER AMULET "RHYOLITE" MEMBER

Beecham breccia

Beecham breccia (Map unit 2i) is a distinct, mappable unit marking the base of the Amulet rhyolite formation. The breccia is a laterally extensive horizon (C.D.A. Comba, personal communication, 1978) which in the map area has an apparent thickness of 0 - 5m. The contact with underlying Rusty Ridge andesite is sharp and irregular. A rhyolite lava-dome conformably overlies the breccia, but the contact is not well exposed.

Beecham breccia is thick-to thin-bedded, consisting of variably silicified volcanic fragments (Figure 36) in a fine-grained quartz-rich matrix, interlayered with a finely laminated white-weathering felsic sediment (Figure 35). Cross-bedding in fine "ash" layers and both reverse and normal grading in coarser breccia layers were recognized. A distinctive feature of the breccia is disrupted bedding, a result of ubiquitous minor faults within the unit.

The erratic variation in thickness, faults and irregular contact with underlying andesite indicate an irregular depositional topography. The numerous faults within the unit- are interpreted as slump features, produced in an active volcanic environment.

The presence of mafic and felsic fragments and fine ash-sediment indicate a complex provenance. The fine sediment resembles "exhalative" sediments of the Noranda area and felsic fragments, if they are rhyolitic, may be derived from felsic volcanics. Silicified fragments are reminiscent of fragments in hyaloclastite and breccias of the underlying Rusty Ridge andesite.

The breccia has previously been interpreted as a felsic breccia, produced by pyroclastic activity in a shallow submarine environment (Comba, 1977). Its origin is unclear because of overprinting by silicification; however Beecham breccia is a distinct marker horizon defining the base of the Amulet rhyolite formation.

A specimen of Beecham breccia containing small clasts and finely bedded sediment contains 68.2 percent SiO_2 and 0.3 percent TiO_2 (Comba, 1977), similar to the overlying rhyolite lava-dome.

Rhyolite lava-dome

The rhyolite lava-dome (Map units 2g, 2h) is a texturally composite body. In the field, rhyolite was classified as massive spherulitic or flow-banded spherulitic, with both phases having amygdules and distinctly lacking quartz or feldspar phenocrysts. Both types weather buff to light green-grey, the green colour attributable to pervasive chlorite-sericite alteration. Adjacent to fault or shear zones rhyolite weathers rusty brown.

Massive rhyolite and flow-banded rhyolite are interpreted to be one continuous body, separated in the map area (Figure 4) by a veneer of brown chloritic flows. The rhyolite lava-dome displays both intrusive and conformable contacts with underlying rocks but appears to be conformably overlain by chloritic flows. The rhyolite body attains a maximum apparent thickness of 150 metres.

Flow-banded rhyolite and to a lesser extent massive rhyolite are characterized by zones of quartz amygdules. Individual zones range in

thickness from 0.2 to 0.8 metres and contain up to 25 percent elliptical and aligned amygdules in a fine-grained microspherulitic matrix. The zones are mappable horizons that parallel flow banding and are folded. Amygdules (2cm to 1mm) within each zone consistently increase in number towards one edge which is in sharp contact with flow-banded or massive rhyolite; the other edge is gradational into rhyolite. Occasionally amygdules coalesce to form a fine reticulate network of quartz veins (Figure 12).

Flow banded rhyolite

Flow-banded rhyolite is characterized by a flow-folded layering; traceable for only a few metres. This internal layering is a reflection of a variation in colour (grey, brown, white and green) and grain size. Flow-banding was only recognized on a weathered surface; recrystallization of groundmass quartz obscures its recognition in thin section. Fine layering has individual lamellae 4mm to 3mm thick whereas coarse layering has 0.5cm to 10cm thick layers.

An intra flow breccia dike intrudes flow-banded and amygdaloidal rhyolite. The breccia dike consists of massive, angular, unsorted rhyolite blocks (1m to 0.5mm) in a fine-grained sericitic matrix. Where the breccia dike cross-cuts an amygdular horizon, blocks of the amygdular zone are rafted in the dike (Figure 11). Similar breccia dikes were described by Wachendorf (1973) in rhyolitic lava flows of the Lebombo area southeast Africa.

Figure 11 . Breccia dike in massive, amygdaloidal rhyolite.

Figure 12 . Flow-folded layering and amygdule zone in rhyolite.

Although, the contact is not exposed, the conformable nature of flow-banded rhyolite to underlying Beecham breccia suggests that the rhyolite is a flow.

An intermediate to felsic body (Map unit 6c) intrudes flow-banded rhyolite, underlying Beecham breccia and Rusty Ridge Andesite (Flow units RR8 and 7). The intrusion is light green to grey weathering, chlorite amygdaloidal, brecciated and columnar jointed. Its distinctive "pitted" surface is a result of weathered, angular chloritic fragments. This intrusion is a feeder to overlying flows or an intrusive phase of the rhyolite.

Massive rhyolite

Massive rhyolite, (Map unit 2g) like flow-banded rhyolite is light green-grey and microspherulitic. It is characterized by a massive, uniform nature and occasional columnar joints.

Massive rhyolite is intrusive; contacts with underlying brown-weathering brecciated flows dip 50° - 70° to the northwest. Rhyolite is weakly flow-laminated and pyritic (rust coloured) adjacent to the contact. Massive rhyolite is interpreted as an intrusive dome; flow-banded rhyolite to the north is its extrusive equivalent.

Petrography of massive and flow-banded rhyolite

In thin section rhyolite is characterized by quartz spherulites which display all stages of recrystallization and replacement by quartz

(Figure 55c). Perlitic cracks are common (Figure 55b). The ground-mass is a mosaic of granular quartz, recrystallized spherulites, quartz amygdules, chlorite, sericite, and rare potassic feldspar. Quartz pseudomorphs after feldspar phenocrysts and quartz phenocrysts are rare and only recognized in massive rhyolite (Figure 55b). Texturally the rhyolite lava-dome is comparable to the stratigraphically lower Northwest rhyolite.

Chloritic flows

Chloritic flows (Map unit 2e) overlie flow-banded rhyolite and underlie and overlie massive rhyolite, (Figure 4). Chloritic flows are exposed on a dip slope; consequently individual flow thicknesses were not determined. The unit has a maximum apparent thickness of 90 metres.

Massive chloritic flows

Massive chloritic flows weather red-brown to brown, are fine-grained to aphanitic, and grey-green. The flows are chlorite-amygdaloidal, but do contain quartz amygdules adjacent to "vitrophyric" zones. Amygdules are rounded to elliptical, and range from 1mm to >2.5cm in diameter. Tiny (<0.1mm) quartz grains are visible on a fresh surface. The rusty colour of the flows results from weathering of 1 - 2 percent disseminated sulphides (dominantly pyrite, trace chalcopyrite).

Locally the massive chloritic flows are laminated. Laminations are thin chlorite-quartz filled fractures mantled by white, siliceous

envelopes. Laminations are discordant or concordant to the host andesite which is distinctly lighter in colour. Chlorite amygdules within laminated zones are mantled by white, siliceous halos.

Breccia zones within chloritic flows consist of angular to sub-rounded blocks similar to the massive host, in a fine-grained, dark-brown matrix. Fractures containing matrix material extend into the surrounding massive flow.

Massive chloritic flows consist of elliptical to round quartz-chlorite amygdules in a fine-grained (<1.0mm) matrix of quartz and interstitial chlorite, muscovite, and carbonate. Muscovite occasionally occurs as randomly oriented blades producing a felted texture reminiscent of microlites in andesitic lavas. Matrix quartz has a "dusty" appearance and is riddled with fine inclusions. Spherulites and microlites are rare. Feldspar phenocrysts are replaced by sericite or quartz. All apparent quartz phenocrysts in hand specimen are actually drusy quartz amygdale fillings (Figure 55d).

Chloritic flows are in contact with underlying flow-banded rhyolite, Beecham breccia and massive rhyolite. The contact with flow-banded rhyolite is marked by an intervening breccia (Map unit 2f). The breccia consists of unsorted, angular to subrounded fragments (3mm to 30cm) in a dark brown, weathered matrix (Figure 47). Fragments resemble overlying chloritic flows. The contact between the intervening breccia and flow-banded rhyolite is sharp, probably because of faulting. Contact with overlying chloritic flows is sharp where the breccia is thin, but gradational where the breccia is thick. The breccia dips 60° - 70° south and is interpreted as an intrusive or fault breccia.

Altered "vitrophyre"

As shown on the detailed map (Figure 4) irregular patches of altered "vitrophyre" are sporadically distributed within massive chloritic flows. "Vitrophyric" units are grey-brown, weather rough and are interpreted as altered "glassy" flow-tops. Massive chloritic flows and "vitrophyre" are exposed on a dip surface; consequently, altered "vitrophyric" patches are erosional remnants of a once continuous flow-top. Many of the textures observed in the "vitrophyre" such as ball, ribbon and swirl textures, flow-banding and brecciation can be explained by this unique erosional surface (Figure 13).

"Vitrophyric" zones are transitional to chloritic flows. The transition is amygdular, containing up to 35 percent quartz amygdules or more rarely quartz vein-networks and amygdules. Amygdules are elongate and parallel the borders of "vitrophyric" patches; their proportion increases towards "vitrophyric" zones but decreases, and become chloritic in adjacent chloritic flows. The amygdular transition zones ranges in thickness from 1 to 10cm (Figure 13).

In thin section the "vitrophyre" consists of fine-grained quartz, chlorite and minor actinolite, muscovite and carbonate. Quartz is fine-grained but occasionally forms micropoikilitic clots containing chlorite and muscovite. Quartz has a distinctive "dusty" appearance, a result of many fine inclusions. Feldspar phenocrysts are pseudomorphed by quartz or sericite-carbonate.

The "vitrophyre" is characteristically flow-banded, with alternating silicified and chloritized layers (Figure 55e). Spherulites are

Figure 13 . Idealized representation of the relationship between massive chloritic flow and altered vitrophyre.

rare and are recrystallized to granular quartz. Flow-banded "vitrophyre" is commonly scoriaceous, containing up to 35 percent quartz amygdules. The amygdules are aligned parallel to the layering and are often rimmed by fine-grained quartz (Figure 55e).

Brecciated flow-banding resembles a fragmental rock in which chloritized and silicified fragments rest in a fine-grained quartz matrix, texturally and mineralogically reminiscent of hyaloclastite from the underlying Rusty Ridge formation.

Interpretation

The massive chloritic flows and altered "vitrophyre" are extremely altered, chloritized lavas. Alteration has destroyed most primary textures that can be used to classify them, but the occurrence of feldspar phenocrysts and rare microlites indicate, possibly, an andesitic or dacitic composition. SiO_2 values (Table 5) are similar to rhyolites and rhyodacites but TiO_2 values are twice those of underlying rhyolite flows.

THE UPPER AMULET "RHYOLITE" MEMBER

The upper member of the Amulet "rhyolite" formation consists of variably silicified andesite flows, overlain by ribbon-textured white-fragment breccia. The contact between upper and lower Amulet "rhyolite" is not exposed. Comba (1977) in his mapping of the Amulet rhyolite formation to the northwest, found unaltered pillowed andesite, Bedford

andesite, and an associated exhalative sediment, the Comba "tuff", occurring at this break, suggesting a time gap between deposition of upper and lower Amulet rhyolite.

Within the map area, the upper member constitutes approximately 75 - 80 percent of the Amulet rhyolite and is the focus of this thesis. The top of the Amulet rhyolite formation is marked by an "exhalative" sediment, the C contact "tuff" (Spence and De Rosen-Spence, 1975). Small, volcanogenic massive sulphide lenses formed at this horizon (the Amulet C and F lenses and Lac Dufault's Zinc deposit). The large Amulet lower A and Millenbach deposits occur above this horizon, as shown in Figure 14.

Massive andesite

Massive, brown-weathering, medium-grained to aphanitic, dark green andesite forms the bulk of the upper Amulet rhyolite (Figure 37). Subdivision into flows is based on a systematic variation in grain size and vesicularity; and by the occurrence of altered vitrophyre throughout the succession. Four flows, separated by altered vitrophyre were mapped. Flow thicknesses range from 80 - 150m. Local, conformable breccia zones within the main flows indicate that they are composite flows. The flows are massive, but occasionally laminated or columnar jointed (Figure 40).

Brown andesite flows are weakly feldspar porphyritic, containing 1 - 2 percent (1 - 2mm) white feldspar phenocrysts. Flows are coarse-grained at the base and become finer-grained and light in colour towards the top.

Massive flows rarely contain greater than 1 - 5 percent chlorite-actinolite amygdules (Figure 38). Adjacent to flow contacts the andesite is increasingly amygdaloidal with an average amygdale content of 15 - 20 percent. Amygdules are typically angular but are also round to elliptical and range 1 - 20mm in size. At the flow-top, andesite weathers lighter brown-green, is finer-grained and cross-cut by fine fractures (Figure 44).

In thin section andesites are typically glomeroporphyritic, containing up to 10 percent albite microphenocrysts (Figure 55f). The groundmass is a felted or pilotaxitic network of albite microlites and coarse-grained quartz with interstitial chlorite, actinolite, quartz and accessory epidote and sphene (Figure 56a). Interstitial chlorite is presumed to represent devitrified glass. Large quartz grains, in the groundmass have grown at the expense of chlorite (actinolite) and micropoikilitically enclose albite microlites (Figure 56b). Microlites enclosed by quartz are ragged and are partially replaced.

The amount of quartz and chlorite-actinolite in the groundmass varies with stratigraphic position. Flows at the base of the upper Amulet rhyolite contain more micropoikilitic quartz and less chlorite than those from the top. Albite microlites from the basal flows are stubby and short, compared to lath-like microlites in andesites from the top of the section. The variation in microlite habit and ratio of quartz to chlorite-actionolite may be a reflection of a primary change in chemistry with stratigraphy or a product of secondary alteration-silicification. Angular amygdules throughout the section are peculiar to these flows and according to MacDonald (1971) usually form in a viscous lava.

The upper Amulet "rhyolite" is chemically and texturally similar to De Rosen-Spence's (1976) low - SiO_2 rhyolite. In this study rocks analogous to low- SiO_2 rhyolite are interpreted as altered andesites, on the basis of field relationships, petrography and chemistry.

Altered vitrophyre

Andesite flows of the upper Amulet rhyolite are capped by chloritized and silicified autobrecciated "vitrophyre", which rarely exceeds 5m in thickness.

Contacts with underlying white andesite are irregular and sharp (Figure 42). Adjacent to "vitrophyre", underlying andesite is extremely amygdaloidal and contains up to 20 percent elongate quartz and quartz-chlorite amygdules. Ribbon breccia is locally developed at the contact; tongues or ribbon-like pods of massive lava similar to the underlying andesite are included in the "vitrophyre" (Figure 45). The andesite ribbons are enveloped by a thin 2 - 10cm zone of brown, chloritized finely brecciated "vitrophyre" (Figure 45). The andesite ribbons or pods have chlorite-quartz amygdules near margins which are elongate parallel to the borders. Contact with the brecciated matrix is usually sharp; however, frequently thin ribbon-like whisps separate from the pod and are enveloped in the brown fragmental matrix. De Rosen-Spence (1976) described similar textures from rhyolite flow-top breccias.

In the field, altered "vitrophyre" has a texture which may best be described as pseudoscoriaceous (Figure 41). It is grey to brown, rough weathering, irregularly ribbed and quartz "veined" on weathered

surface. On fresh surface, the "vitrophyre" is distinctly purple-green and has a recognizable perlitic texture.

Altered "vitrophyre" is extremely fine-grained, composed of chlorite and quartz with accessory, albite, epidote, sericite, and carbonate. Feldspar microphenocrysts and rare microlites are pseudomorphed by quartz or sericite. Quartz amygdules (up to 30 percent) are ubiquitous, often mantled by a corona of fine quartz.

Flow-banding or layering in the "vitrophyre" is defined by alternating chlorite and quartz-rich layers (Figure 56d). Both chlorite and quartz lamellae contain fibrous spherulites (variably replaced by quartz) and quartz amygdules, although they are most prominent in the former. Flow banding is commonly folded and brecciated, with chlorite and quartz-rich fragments in a fine-grained quartzose matrix (Figure 56e). In a few examples fine fragments are completely devitrified and silicified (Figure 56f).

Where spherulites are well developed the resulting texture is a devitrification network (Figure 43). Fibrous quartz spherulites, nucleating on albite microphenocrysts or quartz amygdules collectively form irregular patches or a vein-network in a chloritized "glassy" matrix, (Figures 56b,c,d). Perlitic cracks within chloritized "glassy" fragments are healed by fine-grained quartz (Figure 58a).

Ribbon-textured, white-fragment breccia

The top of the Amulet rhyolite, in the Turcotte Lake section and elsewhere (C.D.A. Comba, personal communication, 1978) is characterized by ribbon-textured blocky, white-fragment breccia (Figure 46). The

breccia conformably overlies and fills depressions within the underlying altered andesite of the upper Amulet rhyolite. The blocky breccia is a thin unit, but laterally extensive; estimated apparent thicknesses range from 10 - 50m.

The contact with underlying altered, white andesite is sharp but irregular. The brown andesitic matrix of the breccia is laminated adjacent to the contact. Angular blocks within the breccia resemble white andesite texturally (and chemically) and appear to be rafted blocks derived from the underlying altered flows. The contact with overlying Amulet andesite is conformable but not exposed in the Turcotte Lake section.

The breccia consists of angular, white, quartz-amygdaloidal, feldspar-porphyritic fragments and irregular white ribbon forms in a brown, massive, andesite matrix.

Andesite matrix

A distinctive feature of the matrix is its massive, structureless texture. The matrix weathers rusty brown, is quartz-chlorite amygdaloidal (1 - 10 percent) and laminated around angular white fragments. Colour on fresh surface is typically dark green. White feldspar phenocrysts are easily recognized.

Although assumed to be massive andesite in the field, petrographic work indicated that the flow was originally "glassy". The groundmass is aphyric or weakly glomeroporphyritic, with albite microphenocrysts and rare microlites (replaced by quartz and sericite) in a fine-grained

groundmass of quartz, chlorite-actinolite and epidote. Perlitic texture is ubiquitous (Figure 56b) and the matrix shows all stages of replacement by quartz (Figures 57b,c).

Locally the matrix is a breccia, consisting of quartz-amygdaloidal chloritic fragments in a matrix of silicified scoriaceous fragments and fine-grained quartz (Figure 57d). The chloritic fragments are weakly flow-laminated, and feldspar-porphyritic. Contacts between matrix and angular white fragments are sharp.

Fragments

The andesite matrix hosts two "fragment" types; both are quartz-amygdaloidal and feldspar-porphyritic, but one occurs as angular white blocks, the second as irregular ribbons.

On close inspection ribbon forms grade into the matrix through a quartz-amygdale zone. Amygdules in the zone are elongate parallel to the ribbon structure and mantled by quartz envelopes which merge to form irregular quartz patches that grade into the ribbon forms. The gradation occurs over a width of <10cm. Ribbon structures are interpreted as "in situ" alteration.

White, angular fragments are chaotically dispersed throughout the brown andesite matrix. Fragments are poorly sorted with respect to size and range from 0.5m to 2m.

Texturally, white fragments resemble andesite, having glomeroporphyritic albite microphenocrysts in a felted or pilotaxitic groundmass of albite microlites with interstitial chlorite-actinolite, epidote and carbonate (Figure 57e). Micropoikilitic quartz forms the

bulk of the groundmass and encloses albite microlites. Quartz-enclosed microlites are ragged and partially replaced by quartz. Fragments differ from andesite only in the proportion of quartz to chlorite.

Many of the fragments are brecciated. Breccia consists of broken albite phenocrysts, and silicified andesite fragments in a fine-grained quartz matrix.

Interpretation

The ribbon-textured, white-fragment breccia is interpreted to be a mixed fragmental andesite flow. The angular shape of the blocks, sharp contacts with the matrix and similarity to underlying andesite indicate that the blocks are surface debris incorporated and transported by the andesite flow. Ribbon forms are interpreted as an in situ alteration texture.

The andesite matrix is chemically similar to underlying andesite flows of the upper Amulet rhyolite.

AMULET-MILLENBACH ANDESITE

Conformably overlying the Amulet rhyolite formation is a succession of massive to pillowed andesite and basalt flows referred to as Millenbach andesite (Table 6). Millenbach andesite is a wedge of andesitic lavas (Figure 14) separated from the Amulet andesite by an exhalative sediment, the main contact "tuff" (Simmons, 1973, Spence and De Rosen-Spence, 1976).

Massive flows are distinctly feldspar porphyritic, fine to coarse-grained and rarely contain greater than 5 percent quartz amygdules.

Pillowed flows are feldspar-porphyrritic, amygdaloidal and are finer-grained than massive flows. Amygdules are chiefly quartz with some feldspar and occur as round vesicle fillings throughout the pillow or as elongate radial amygdules adjacent to pillow margins.

Contacts between flows are sharp and locally marked by a breccia zone; flow thicknesses range from 10 to 40m.

INTRUSIVE ROCKS

Synvolcanic intrusive rocks

Northwest-striking, synvolcanic rhyolite and basalt dikes cross-cut volcanic stratigraphy and parallel the larger McDougall fault-dike. The dikes are presumed feeders for overlying, eroded flows. Many of the dikes are composite, with a rhyolitic core and basaltic margin.

Rhyolite dikes vary in texture from massive to flow-banded, to weakly feldspar-quartz porphyritic. Basalt dikes are dark brown, weakly amygdaloidal (<1 percent) and aphanitic. Spherulitic and perlitic textures in rhyolite dikes indicate an original glassy groundmass typical of high level intrusions.

Similar rhyolite dikes to the north west, cut an early "dioritic" phase of the Flavrian intrusive complex (C.D.A. Comba, personal communication, 1978). The dikes unlike the andesite host, are not altered.

Late intrusive rocks

Fine-to coarse-grained, massive brown weathering diorite dikes

cross-cut all rock types in the map area. Diorite dikes strike north-east or less commonly northwest, and probably fed flows higher in the stratigraphic succession.

III. STRUCTURE AND METAMORPHISM

STRUCTURE

Within the map area volcanic rocks strike north-northeast and dip gently at 30° - 40° to the southeast. Although the rocks have been affected by both synvolcanic deformation and the Kenoran orogeny they are remarkably well preserved and represent one of the best exposed sections of Amulet "rhyolite" within the Noranda camp.

The volcanic rocks are dissected by innumerable faults and shears, but lack a penetrative deformational fabric as shown by the preservation of delicate, primary volcanic textures. Joints, faults and shear zones were the only structural features mapped.

All rock types in the map area are jointed. The common joints are; a set striking 035° - 045° , dipping 80° - 85° north, and a set striking 140° - 155° , dipping 60° - 70° east.

The strike, dip, and apparent movement of major faults in the Turcotte Lake section are listed in table 1. The faults are divided into a northeast striking 070° - 090° set, and a northwest striking set (Comba, 1977).

Comba (1977) believed the northeast striking 070° set to be younger than the northwest striking set. Most shears and faults (Figure 4) parallel the 070° trend, and are commonly mantled by chlorite or sericite-quartz alteration envelopes up to 2m wide (Figures 39 & 48). The faults and shears are presumed synvolcanic because:

- 1) Where faults offset early rhyolite or basalt dikes, the dikes are not altered as in adjacent andesite, suggesting reactivation of an earlier structural feature.

TABLE 1. FAULTS OF THE TURCOTTE LAKE SECTION

Fault name	Strike and dip of fault trace	*Strike separation and movement
Red fox fault ¹	090	60m L.H.
Vandals fault	090 - 080	120m L.H.
Sow bear fault	090 north	120m L.H.
"C" shaft fault	070 80 - 85NW	240m ² L.H.
Turcotte fault	070 60 - 50SE	30m ³ L.H.
McDougall fault ⁴	310 - 320	1500m R.H.
Despina fault ⁴	315 80E	1500m R.H.

* as measured from dike offset, offset in volcanic rocks may be larger as faults were probably active over a period of time.

1 from Comba, 1977.

2 from Comba, 1977.

3 actual displacement of volcanic rocks 90m (D.H. Watkins, personal communication, 1978).

4 treated as one system, offset measured from G.S.C. map 454A by

M.E. Wilson, 1941

2) Synvolcanic breccia dikes (white-fragment breccias) strike 070 and are controlled by faults and shears.

The McDougall and Despina faults constitute the northwest striking fault set. They dip towards each other and are occupied by flow-banded rhyolite dikes. Ancillary rhyolite dikes parallel the northwest trending fault set (Figure 4). Evidence of movement along these parallel dikes was not observed.

A characteristic feature of mapped synvolcanic faults is the lack of deformation and brecciation in adjacent wall rock. Volcanic rocks adjacent to the McDougall fault are massive; which is remarkable, considering the McDougall-Despina fault system offsets the Amulet rhyolite by approximately 1500m (apparent movement estimated from G.S.C. map 454A by Wilson, 1941).

If the rocks were restored to their original sub-horizontal attitude, as proposed by De Rosen-Spence (1976), faults and shears would be nearly vertical, suggestive of an original block-faulted structural setting, typical of modern volcanic centres (MacDonald, 1971).

The consistent 30° - 40° southeasterly dip may indicate the presence of a large, open, east-plunging fold. Dip attitudes however, are shallower towards the Flavrian tonalite complex to the west, where they are subhorizontal (C.D.A. Combé, personal communication, 1978). This suggests that early tilting may have been in response to synvolcanic doming during emplacement of the Flavrian intrusion.

METAMORPHISM

The minerals albite-actinolite-chlorite-epidote-quartz common in

volcanic rocks of the Amulet rhyolite formation are typical of green-schist-facies, regionally metamorphosed mafic volcanic rocks (Winkler, 1974). The assemblage epidote-quartz (minor actinolite and carbonate) within flow rocks of the upper Amulet rhyolite has unusual characteristics which are important to its interpretation:

- 1) The assemblage epidote-quartz (minor actinolite and carbonate) is restricted to permeable areas of flows, developed as irregular, light coloured, "mottled" patches and envelopes around amygdules and fractures. The massive andesite host to the patches consists of albite phenocrysts and microlites in a groundmass of interstitial chlorite, minor actinolite and rare epidote.

- 2) Adjacent, synvolcanic rhyolite and basalt dikes are not affected by the "mottled" epidote-quartz assemblage.

- 3) Within the stratigraphic succession the epidote-quartz assemblage is better developed in the lowermost flows of upper Amulet rhyolite.

Epidote-quartz "mottled" assemblage reflects an early alteration, as adjacent synvolcanic dikes were not affected. The restriction of epidote-quartz (actinolite) assemblage to mottled patches controlled by fractures, amygdules and flow laminations and the conversion of an originally anhydrous mineralogy to a hydrous one implies the presence of a fluid phase. As discussed in a later chapter, the fluid phase that accompanied metamorphism was capable of transporting chemical components to and from the altered rock resulting in a significant compositional difference between mottled patches and rocks and massive andesite. These features are not consistent with an isochemical regional

metamorphic interpretation for the "mottled" assemblage and can be better explained by alteration during hydrothermal metamorphism; similar to that occurring in modern hydrothermal systems in Iceland or New Zealand.

No doubt a later greenschist facies regional metamorphism superimposed on alteration products of an earlier hydrothermal metamorphism could result in the observed mineralogy. However, the formation of chlorite, actinolite, quartz and epidote now, in hydrothermal systems such as Reykjanes in Iceland (Tommasson et al, 1972) and the Salton Sea field, California (Keith et al, 1968) lend support to the interpretation of an early hydrothermal metamorphic origin for the epidote-quartz (minor actinolite and carbonate) assemblage.

A similar alteration mineralogy described from volcanic rocks at Matagami, Quebec (MacGeehan, 1977) and in ophiolitic rocks of E. Liguria, Italy (Spooner and Fyfe, 1973) was attributed to an earlier hydrothermal metamorphism which predated later regional metamorphism.

IV. ALTERATION AND ITS RELATIONSHIP TO VOLCANIC STRATIGRAPHY

A reconstructed stratigraphic section of the map area is shown in Figure 10, which relates volcanic stratigraphy to alteration types. Volcanic rocks of the map area are variably altered from weakly silicified lavas of the Rusty Ridge andesite, to chloritized rhyolite and flows of the lower Amulet "rhyolite" member and silicified lavas of the upper member.

ALTERATION IN THE RUSTY RIDGE ANDESITE FORMATION

Alteration within the Rusty Ridge andesite is confined to the upper three flow units, RR6, 7 and 8. In massive flows alteration manifests itself as quartz-filled cooling laminations and concentric laminations or polygonal joints in pillowed flows. Quartz laminations are 1 - 3mm wide and weather high. In handspecimen, andesite does not appear to be altered adjacent to laminations.

Silicification in associated hyaloclastite and flow-breccia is pronounced; fine-grained quartz is the matrix constituent and upon weathering produces a texture referred to as vein-network silicification. Fragments within the breccias are silicified. Margins of individual fragments are selectively replaced by quartz, or the fragments are completely replaced (Figure 55a). Unaltered fragments consist of quartz microlites and interstitial chlorite. Microlitic texture is preserved in silicified fragments but the matrix is predominantly micropoikilitic quartz. Irregular pyrite-sericite veins cross-cut both fragments and matrix (Figure 55a).

Silicification in the Rusty Ridge andesite is controlled by primary permeability of the flows, and is confined to fractures and cooling laminations in lava flows and breccia-hyaloclastite lenses within the volcanic succession. Underlying units are not silicified and consist of massive lava and densely packed pillow lava.

ALTERATION IN THE LOWER AMULET RHYOLITE MEMBER

Rhyolite lava-dome

Both massive and flow-banded rhyolite are pervasively chloritized and weakly sericitized as described in chapter II.

Northeast striking, steeply dipping (60° 80° NW) chlorite-quartz shears cross-cut massive and flow-banded rhyolite. Shears are enveloped by a 20cm to 2cm rusty chloritic envelope and contain up to 6 percent combined sulphides (pyrite and chalcopyrite).

Chloritic flows

As described in chapter II, intermediate chloritic flows overlying the rhyolite lava-dome are intensely chloritized. A large dalmatianite zone is located just north of the mapped exposure of chloritic lavas (Figure 4). Dalmatianite alteration is essentially a contact metamorphic texture imposed upon an original magnesium-rich chlorite alteration (Riverin, 1977). The result is a spotted-hornfelsic texture in which original cordierite porphyroblasts (now retrograded to chlorite and biotite) are distributed in a fine-grained magnesian matrix of chlorite

and biotite. Chloritic flows in the north are spotted, suggesting a relationship to the larger magnesium-rich dalmatianite alteration zone.

Where chloritic flows directly overlie flow-banded rhyolite (Figure 4) they are transected by northeast-striking, steeply dipping (60° - 80° N) shear zones. The shears are mantled by discontinuous, asymmetric or symmetric siliceous envelopes (Figure 48) composed of fine-grained sutured quartz and interstitial sericite and chlorite.

The white, siliceous envelopes are internally brecciated and healed by vein-network quartz. Contacts with host are gradational, alteration increasing towards the shear which is commonly pyritic (1 - 2 percent pyrite). Chloritic shears of similar character and strike and dip, in underlying rhyolite, contain appreciable pyrite and chalcopyrite.

Alteration summary for the lower Amulet "rhyolite"

- 1) The lower Amulet "rhyolite" is characterized by pervasive chlorite alteration, possibly related to a dalmatianite alteration zone to the northwest.

- 2) Northeast-striking and northwest-dipping mineralized shears cross-cut the lower Amulet "rhyolite". Shears are mantled by chloritic or quartz-sericite alteration envelopes, the former most intensely mineralized. Shears are localized zones of intense alteration and interpreted to have been zones of high fluid flow.

- 3) Beecham breccia at the base of the Amulet "rhyolite" formation is silicified, yielding textures reminiscent of hyaloclastite and flow breccias in underlying Rusty Ridge andesite.

DEVITRIFICATION

Although not an alteration process, devitrification occurred before silicification and chloritization within altered rhyolite and vitrophyre of the upper and lower Amulet "rhyolite".

Devitrification textures in both massive and flow-banded rhyolite such as fibrous and bowtie spherulites, micropoikilitic quartz and quartz amygdules indicate temperatures of 600° - 400°C for devitrification (Lofgren, 1971a, 1971b, 1970). Complete devitrification of rhyolite at this temperature implies slow cooling.

Altered vitrophyre, unlike rhyolite, is composed of chloritized and silicified glass. Devitrification textures (spherulites) occur but are not prominent. Perlitic cracks are ubiquitous, except in highly altered samples.

Incomplete devitrification of altered vitrophyre can be explained by their occurrence as rapidly quenched "crusts" on altered andesitic lavas. Rapid cooling (quenching) arrests the devitrification process (Lofgren, 1971a). The submarine setting and brecciated texture of the vitrophyre permitted sufficient water and permeability for complete hydration of remaining glass, which was then easily converted to chlorite and quartz during alteration. Devitrification, recrystallization and alteration textures for rhyolite and vitrophyre are illustrated in Figures 55a, b; 58a, b, c, d.

Silicification and chloritic alteration is difficult, if not impossible, to distinguish from quartz and chlorite formed during devitrification. In most examples, later alteration has mimicked and

enhanced original devitrification textures. From thin section examination evidence for later alteration includes:

- 1) Albite microlites and phenocrysts are replaced by quartz or sericite-carbonate.
- 2) Spherulitic and axiolitic textures are recrystallized and replaced by granular quartz (Figure 58e).
- 3) Irregular fractures are mantled by envelopes of fine quartz (Figure 57a).
- 4) Irregular fractures of sericite, carbonate or epidote cross-cut altered vitrophyre and rhyolite (Figure 58f).
- 5) Spherulites are often replaced by chlorite, epidote, sericite and carbonate.

ALTERATION IN THE UPPER AMULET "RHYOLITE"

Alteration is of two main types; a conformable, widespread, patchy alteration and localized cross-cutting alteration. In both cases the alteration is primarily silicification; the alteration assemblage is chiefly quartz with appreciable amounts of epidote, actinolite and carbonate.

Conformable alteration

Conformable silicification manifests itself in the development of "mottled" textured alteration. Mottled alteration is controlled primarily by the original permeability of andesitic lavas. In

andesite flows the proportion of mottled alteration increases sympathetically with percentage of amygdules and degree of fracturing.

Andesite near the base of flows is massive but towards the flow top the number and size of amygdules increase. Adjacent to flow contacts andesite is extremely amygdaloidal (up to 20 percent quartz amygdules) and cross-cut by irregular chlorite-epidote filled fractures, both of which are surrounded by white alteration envelopes up to 2cm wide (Figure 49). White envelopes merge to form irregular white patches up to 0.5m, producing a distinctive "mottled" texture (Figure 50). Adjacent vitrophyre is chloritized and silicified. Contacts between mottled patches and massive andesite host are sharp or gradational. Where the contacts are sharp, the rock has a distinctive fragmental appearance. This pattern of alteration within a single flow is repeated throughout the upper Amulet "rhyolite" (Figure 10).

At the Millenbach mine, a spectacular exposure of Amulet "rhyolite" along the 4-01 exploration drift was mapped (Figure 62). Many of the "mottled" quartz-epidote patches observed coalesced to form irregular pipe or cylindrical bodies similar to those described by Harrigan and MacLean (1976). This unique exposure implies that similar mottled patches observed during field mapping may be "connected", rather than occurring as separate, individual areas of alteration.

Mottled alteration is characterized by the mineral assemblage epidote-quartz with minor actinolite and carbonate, similar to a green-schist facies metamorphic assemblage. Alteration occurs as irregular patches in the andesite and as envelopes mantling amygdules and fractures.

Alteration patches and envelopes are mineralogically zoned, composed of variable amounts of epidote, quartz, actinolite and carbonate. Individual alteration envelopes rarely exceed 1cm and are irregular in shape (Figures 59d,e). Similar, zoned, alteration patches were described by Harrigan and MacLean (1976) in gabbro dikes from Matagami, north-western Quebec.

Patches and envelopes grade into massive andesite through a quartz transition zone. In the transition zone (2mm wide) interstitial chlorite of the massive andesite matrix is replaced by quartz which micropoikilitically encloses "ragged" albite microlites (Figure 59f). Albite phenocrysts, microlites and interstitial chlorite are replaced and destroyed within alteration patches resulting in a granular mosaic texture.

Mottled alteration is interpreted to be nearly contemporaneous with volcanism and earlier than regional metamorphism because:

- 1) High-level, synvolcanic rhyolite and basalt dikes are not affected by the alteration.
- 2) Mottled alteration is apparently controlled by the original permeability of the andesite flows. This restriction of alteration to irregular patches and envelopes mantling amygdules and veins implies the presence of a fluid phase.

Cross-cutting alteration

Breccia dikes, referred to by Comba (1977) as white-fragment breccias, are fault or shear controlled zones of cross-cutting

brecciation and alteration located at or near the top of the Amulet "rhyolite" formation (Figures 4 and 10). Breccia dikes north of the Turcotte fault and west of Turcotte Lake (Figure 4) strike approximately 070° , parallel to the Turcotte fault. West of the McDougall fault, at the base of the section, a breccia dike strikes northwest, parallel to the fault, whereas at Buttercup Hill breccia dikes strike north-northeast (Figure 4).

One of the best exposures of white-fragment breccia is north of the Turcotte fault (Figure 15). The breccia intrudes shattered and brecciated andesite that is cut by numerous parallel striking shears and faults (Figure 15). The breccia dike bifurcates and pinches and swells along strike. Where the breccia intrudes shattered and brecciated andesite the contacts are gradational, where it intrudes massive white andesite the contacts are generally sharp.

Fragments within breccia dikes are andesite, although variably altered. The large white fragments are silicified andesite. White fragments are typically quartz amygdaloidal, scoriaceous, feldspar-porphyrritic and flow-banded (Figures 51 and 52). Matrix to the large white fragments is a microbreccia composed of chloritized, feldspar-porphyrritic, quartz-amygdaloidal andesite fragments and broken feldspar phenocrysts, in a fine-grained patchy matrix of chlorite and minor quartz (Figure 59b). Albite microlites with a felted or pilotaxitic texture are preserved in most fragments (Figure 59c). Chloritic margins of white fragments resemble chloritized matrix fragments (Figure 59a).

Fragments in breccia dikes are poorly sorted with respect to size

LEGEND

INTRUSIVE ROCKS

- Feldspar porphyritic felsic dike
- Aphanitic mafic dike
- Andesite dike or Millenbach andesite

intrusive contact

- Ribbon to blocky white-fragment breccia
- Angular white-fragment breccia dike
- Chloritized and silicified, autobrecciated vitrophyre
- Amygdaloidal, weakly mottled, feldspar porphyritic white andesite
- Amygdaloidal, mottled, feldspar porphyritic andesite
- Amygdaloidal, feldspar porphyritic andesite

MAP SYMBOLS

- Shear, shear with chloritic envelope
- Fault
- Geologic contact, located, approximate
- Foliation
- C.J. Columnar joints
- Breccia
- PY Pyrite
- CCP Chalcopyrite

Grid lines approximately 16m apart

Figure 15. Detailed geologic map of the upper Amulet rhyolite north of the Turcotte fault.

and shape, and show a complete size gradation from less than 0.1mm to large blocks greater than 0.5m. The breccias are chaotic and lack internal structures such as flow-banding or size gradation.

White fragments within the breccia dike are angular and derived from adjacent white andesite (Figure 51). Fragments show all stages of detachment from silicified andesitic wall rocks and from each other within the breccia, resulting in an in situ breccia texture.

Massive andesite of the upper Amulet "rhyolite" is locally shattered, i.e., broken by numerous irregular chlorite-actinolite veins which form discontinuous patches and pods (Figures 53 and 54). Veins range in width to 0.5m, are mantled by white siliceous envelopes (<2cm wide) and are commonly brecciated. Brecciated veins contain white, silicified andesite fragments (Figure 53). Shattered andesite is most common at the top of the Amulet "rhyolite" but occurs throughout the section.

Alteration associated with white-fragment breccias

White-fragment breccia dikes are found in fault or shear controlled zones of alteration (typically silicification and chloritization). Breccia dikes intrude white silicified andesite that is similar texturally to white fragments within the breccia. Fragments of silicified wall rock indicate that silica-alteration occurred before emplacement of the breccia dike. This early alteration controlled by faults and shears was superimposed on mottled or massive andesite.

Silicified andesite, like massive andesite, contains albite

phenocrysts and microlites, but interstitial chlorite is replaced by micropoikilitic quartz (Figure 56c).

In breccia dikes, the microbreccia matrix and margins of larger white fragments are chloritic, indicating chloritization occurred after or during emplacement of the breccia dikes.

Interpretation

White-fragment breccia dikes are texturally similar to breccia dikes of the Bennett Lake cauldron subsidence complex (M.B. Lambert, personal communication, 1978). Lambert (1972) interpreted breccia dikes of the Bennett Lake complex to be "fluidized injections of granitic breccia that were mobilized and emplaced by compressed air blasts".

Fluidization is a transportation mechanism whereby brecciated rock of all sizes is carried in a rapidly moving, expanding, turbulent gas. A chaotic mixture of brecciated rock fragments suspended in an upward moving streaming gas is apparently capable of eroding its way to surface (Holmes, 1965). The end result is a breccia dike, superficially similar in field occurrence to pyroclastic or other igneous dikes, but different in texture, mode of emplacement and origin.

For a discussion of fluidization and geologic examples the reader is referred to papers by Reynolds (1954), Holmes (1965), Ollier (1973), and Lambert (1972). Textural features of the Amulet breccia dikes are consistent with other fluidized breccias (Reynolds, 1954 and Lambert 1972), and are interpreted to have formed by a fluidization process. The lack of pyroclastic material, such as glass shards; spatial relationship

to faults and fault breccias and local extrusive character (as at Buttercup Hill) support a fluidization rather than an explosive pyroclastic or tectonic origin.

Ribbon-textured, white-fragment breccia

As discussed previously, siliceous, quartz amygdaloidal and feldspar porphyritic ribbon forms are interpreted as an in situ alteration texture (Figure 46). Gradational contacts with, and textural similarity to surrounding massive andesite is the basis for this interpretation.

Individual ribbon forms range to 2m in length, and 25cm in width. Ribbon forms are scoriaceous (up to 35 percent round quartz amygdules). Amygdules are aligned parallel to the ribbon form and are surrounded by irregular fine-grained quartz halos which merge to form siliceous networks and patches, similar to mottled alteration patches (Figure 57f). North of the Turcotte Lake fault (Figure 4 and 15) siliceous, amygdaloidal, ribbon forms outline laminated ovoid forms reminiscent of pillows.

V. GEOLOGY AND ALTERATION OF ANDESITE LAVAS FROM BUTTERCUP HILL

Buttercup Hill is located in the northwest corner of the map area (Figure 4). From detailed mapping the outcrop is thought to be upper Amulet rhyolite displaced along the McDougall fault. Buttercup Hill is a unique exposure, representative of all rock types and alteration in the upper Amulet rhyolite, described in earlier chapters.

The outcrop was previously mapped by Comba (1977), De Rosen-Spence (1976) and Spring (1976). In his study of alteration textures, Spring (1976) proposed that the alteration was a product of submarine hot-spring activity. De Rosen-Spence (1976) referred to Buttercup Hill as Bedford rhyolite, a low - SiO_2 rhyolite in her classification. Buttercup Hill was remapped and reinterpreted in this study.

GEOLOGY OF BUTTERCUP HILL

A geologic map and accompanying cross-sections of Buttercup Hill, are shown in Figures 16a and b. The outcrop is divided into six mappable units. Green weathering, fine-grained andesite flows form the base of the Buttercup Hill section, identical to flows described from the upper Amulet rhyolite, northwest of Turcotte Lake. They display flow lamination, are feldspar porphyritic, columnar jointed (Figure 60a) and have amygdules that parallel flow direction.

Andesite flows consist of glomeroporphyritic albite microphenocrysts in a felted or pilotaxitic groundmass of albite microlites, interstitial chlorite, actinolite, quartz and accessory epidote and sphene (Figure 61d). Angular vesicles are filled by chlorite, quartz, actinolite and carbonate.

BUTTERCUP HILL

LEGEND

- Pyritic, andesitic ash tuff, minor chert.
- Conformable, blocky breccia with ribbon texture.
- Discordant, angular white-fragment breccia.
- Chloritized and silicified autobrecciated vitrophyre.
- Brown andesite.
- Massive amygdaloidal, feldspar porphyritic andesite.

SYMBOLS

- Strike and dip of bed or geologic contact
- Shear
- Breccia
- Silicified white andesite
- Mottled alteration
- "Vent" zone, chlorite - quartz alteration
- Contour interval in feet (Wilson, 1943).

Figure 16a Geology of Buttercup Hill

Figure 16b Geological cross-sections through
Buttercup Hill

The andesite flows are capped by patches of altered "vitrophyre", shown as cross-hatched areas in Figure 16a. The "vitrophyre" is grey weathering and purple-green, with a rough "psuedoscoriaceous" weathered surface. Spherulites are variably replaced by quartz and nucleate around quartz amygdules and albite phenocrysts. Perlitic cracks are ubiquitous; the bulk of the "vitrophyre" is brecciated, chloritized and silicified glass.

A rusty brown andesite flow conformably overlies the green andesites; the contact is locally marked by a siliceous sediment-ash "tuff". The brown andesite is massive and brecciated, the rusty colour reminiscent of that of the Rusty Ridge andesite. Pillow-like forms are developed within the massive portion.

Three parallel zones of discordant, angular, white-fragment breccia cut the green andesitic flows (Figure 16b). White-fragment breccia grades vertically into a conformable blanket of ribbon-textured white-fragment breccia. Contact relationships with the brown rusty andesite are unclear. Fragments within the dikes show all stages of detachment from surrounding white andesite host (Figure 16b), resulting in an "in situ" breccia texture. The matrix is a fine-grained, poorly sorted, chloritized, andesite microbreccia.

Breccia dikes are surrounded by an envelope of intensely silicified white andesite (Figures 16a & 16b). Gradational contacts with green andesite and preserved glomeroporphyritic albite microphenocrysts, and microlites attest to the original andesitic nature of the rocks.

Ribbon-textured, blocky, white-fragment breccia conformably overlies brown and green andesite flows (Figure 16b). The breccia is

characterized by a mixture of unaltered, and dominantly silicified white andesite fragments in a massive andesite or fine-breccia matrix. White fragments are angular with bleached borders, weakly feldspar-porphyrific and quartz amygdaloidal (Figure 60e). In thin section the fragments are characterized by albite phenocrysts in a felted ground-mass of albite microlites and quartz, identical texturally to underlying green andesite and white silicified andesite (Figure 61e). "Unaltered" fragments are rusty brown and resemble the brown andesite flow.

Knolls of silicified andesite, texturally similar to green andesite flows, project through the breccia. Angular, white, quartz amygdaloidal silicified fragments show varying degrees of detachment from knolls and incorporation into conformable breccia.

A pyritic, exhalative sediment rests conformably at the top of, upon and within the conformable breccia unit. The sediment is well bedded and laminated, typical of Noranda camp exhalative "tuffs" (Figure 60f).

ALTERATION

Green andesite flows at the base of the section are mottled; white siliceous envelopes surround amygdules and chlorite fractures within andesite. The mottled andesite flows are cross-cut by breccia dikes or white-fragment breccia. Adjacent to dikes mottled andesite is silicified and weathers white. Fragments within dikes are derived from adjacent white andesite.

A second zone of intense chlorite-quartz alteration transects the

outcrop parallel to a local shear direction and the larger scale McDougall fault (Figure 16a). Spring (1976) referred to this alteration as a "vent zone". The "vent zone" grades laterally into altered andesite; contacts with discordant white-fragment breccia dikes and conformable breccia are uncertain.

The "vent zone" is an area of shattered and brecciated andesite, in sharp contact with mottled andesite to the north (Figure 61a). Mottled texture is developed within the "vent zone". Large, irregular siliceous patches (<1m) are cut by irregular fractures, producing an "in situ" breccia texture (Figure 61b). The white patches texturally and mineralogically resemble andesite; fractures contain fine-grained, chloritized, fragments.

White, siliceous, mottled patches are surrounded by brecciated andesite in a matrix of quartz and chlorite with a characteristic vein-network texture on weathered surface (Figures 61c). The andesitic fragments are variably silicified, alteration occurring along fractures and amygdules.

The intensity of chlorite-quartz alteration and brecciation decreases towards the edges of the "vent zone". The southern contact with white andesite is gradational.

Where brecciated, the rusty brown andesite flows contain a mixture of dominantly unaltered andesite, silicified andesite and chloritized glass fragments in a fine-grained matrix of quartz and chlorite. Contacts between brecciated rusty andesite and overlying conformable white-fragment breccia are gradational.

Matrix of the conformable, white-fragment breccia consist of

massive andesite, fine chloritized andesite fragments, chlorite and vein-network quartz. The matrix is weakly mottled and locally characterized by ribbon-textured alteration.

INTERPRETATION

Buttercup Hill is interpreted to be an outcrop of silicified andesite. White-fragment breccia dikes are identical to those at the top of the Amulet rhyolite and are interpreted as fluidized, breccia dikes. Silicified andesite fragments in breccia dikes indicate that silicification occurred prior to emplacement of the fluidized dikes. Unlike mottled alteration, intense silicification occurs as zones controlled by synvolcanic faults now occupied by breccia dikes:

Conformable white-fragment breccia is conformable to stratigraphy and consists of "in situ" brecciated fragments and transported blocks that are similar in texture to fragments in underlying breccia dikes and altered andesite. The angular nature of large fragments and textural similarity to underlying andesite indicate that the fragments were locally derived, brecciated and transported to surface by a fluidized system. Where breccia dikes broke through to the sea floor, streaming, turbulent, rapidly expanding gas would blast fragments from the orifice. Dependant on the depth of water and explosive force, deposition of ejecta may have been restricted to or scattered widely from the vent.

Rusty, brown weathered, andesite blocks in the breccia indicate that massive brown andesite was brecciated and incorporated into the fluidized dikes. Similar brecciation and shattering may account for textures observed in the "vent zone".

Brecciated and shattered andesite and breccia dikes provide excellent chanelways for renewed hydrothermal activity as evidenced by several overlapping episodes of chloritization and silicification within fragmented rock (Figure 6lf). Ash-tuff layers within conformable, white-fragment breccia indicate the process described occurred at the sea floor.

If the interpretation that Buttercup Hill is an outcrop of upper Amulet rhyolite is correct, then the associated exhalative sediment may represent the C contact "tuff" at the top of the Amulet "rhyolite" formation. Accordingly the brown andesitic flows may be interpreted as Millenbach or Amulet andesite.

VI. ALTERATION GEOCHEMISTRY

CHEMISTRY OF ALTERED ROCKS IN THE LOWER AMULET RHYOLITE MEMBER

In the lower Amulet "rhyolite" both the rhyolite lava-dome and overlying chloritic flows are pervasively chloritized and locally silicified. Samples were collected of least altered rhyolite and chloritic flows in order to minimize the affects of alteration; the results are shown in Table 5.

Pervasive alteration is reflected in the chemistry of both rhyolite and chloritic flows. By comparison with underlying Northwest rhyolite, rhyolite from the map area is depleted in alkalis and enriched in Fe and MgO. Significantly, the rhyolite lava-dome is anomalous in Cu and Zn content (111 and 1027 ppm respectively, Table 5).

As in underlying rhyolite, chloritic flows are depleted in alkalis, especially Na_2O and enriched in Fe_2O_3 and MgO. Alkali depletion and $\text{MgO} - \text{Fe}_2\text{O}_3$ enrichment in both rhyolite and chloritic flows are attributed to feldspar breakdown and chloritization. The lower Amulet rhyolite, in the Turcotte Lake section, is a classical Na_2O - depleted area (Franklin et al 1975), possibly related to the dalmatianite zone northeast of the map area.

Preserved textures and field characteristics indicate an original rhyolitic composition for the lava-dome. Unfortunately in overlying chloritic flows primary textures have been obliterated. The SiO_2 content of chloritic flows is similar to rhyolite, but the TiO_2 content is twice that of underlying rhyolite. Based on field characteristics,

the chloritic unit was interpreted as a flow of originally andesitic or dacitic composition.

Trace element distribution of various rock types from the map area are shown in Figures 27a & 27b. The Y, and Zr contents of chloritic flows more closely resemble andesite of the map area than rhyolite. Interestingly, both chloritic flows and rhyolite have low Sr contents compared to massive and silicified andesite. Low Sr values are perhaps attributed to feldspar breakdown and chloritic alteration common to both rock types.

CHEMISTRY OF ALTERED ROCKS IN THE UPPER AMULET "RHYOLITE" MEMBER

The purpose of this chemical study is to assess variations of chemical components with progressive alteration, and to document the gross chemical characteristics of the upper-Amulet "rhyolite". To this aim, 62 samples of massive "unaltered" andesite, mottled andesite and white silicified andesite, including white fragments from breccia dikes were analyzed for 11 major elements and 8 trace elements (Tables 2,3,4,5). Thirty-two of the above samples were reanalyzed for 9 trace elements (Table 7).

Massive andesite, as mapped in the field, was presumed to be unaltered; however inspection of the data in Table 2 and comparison with analyses (Table 6) of lavas from underlying Rusty Ridge and overlying Amulet andesite suggest several differences. The SiO_2 content of andesite from the Amulet "rhyolite" is generally high, 58 - 66wt. percent compared to a SiO_2 content of 52 - 62wt. percent for the Rusty

Ridge and Amulet andesites. Al_2O_3 and TiO_2 are generally lower in the Amulet "rhyolite" (<15wt. percent Al_2O_3 and <1.3wt. percent TiO_2) whereas the MgO contents are comparable. These differences may reflect alteration of the Amulet "rhyolite" or a primary difference. Flows of the Amulet rhyolite formation may be andesites (58 - 66 percent SiO_2) different from the underlying and overlying succession of basalts and basaltic-andesites.

The most significant chemical characteristics of massive andesite from the Amulet rhyolite formation are the CaO and Na_2O contents (table 2). Andesitic lavas are depleted in CaO (generally less than 2.5 percent) and enriched in Na_2O (4 - 5wt. percent).

Data from Buttercup Hill and upper Amulet rhyolite of the Turcotte Lake section are shown separately in Figure 17a and b; these are alkali ratio diagrams developed by Hughes (1973) to distinguish the spectrum of igneous rocks from spilites and keratophyres. The dashed lines in Figures 17a and b enclose the field in which igneous rocks generally lie. All but one of the Buttercup Hill samples lie in the spilitic field (Figure 17a) and the majority of samples from the Turcotte Lake section lie outside the igneous spectrum field boundaries (Figure 17b) indicating spilitic affinities.

The anomalously low CaO content of massive andesite, the ubiquitous preservation of albite microlites and resulting high Na_2O content indicate an early alkali metasomatism or "spilitization".

Figure 17. Spilitic character of andesite from Buttermilk Hill (a) and upper Amulet rhyolite of the Turcotte lake section (b).

Silicification of andesitic lavas

On comparison of the weight percent ~~oxides~~ of massive and variably silicified andesite (Tables 2,3,4) it is apparent that SiO_2 increases and Fe_2O_3 , MgO , MnO and TiO_2 decrease with silicification. In order to determine if the chemical change stated above is real or apparent, gains and losses of chemical components during metasomatism were calculated using a computational method outlined by Gresens (1967) and Babcock (1973). Gresens (1967) derived an equation that relates compositional variation to volume changes, allowing calculation of metasomatic effects. The equation used in this study is a modification of Gresens (1967) equation by Babcock (1973):

$$\Delta X_n = a \left[(K_v \cdot X^B \cdot \frac{\rho^B}{\rho^A}) - X^A \right]$$

where:

ΔX_n = is the chemical transfer of component n
between unaltered rock (A) and altered rock (B).

X = grams or moles of material.

K_v = is the volume factor, or the ratio of final
volume (B) to initial volume (A).

ρ = density.

a = is the weight, arbitrarily chosen as 100
grams, so that ΔX_n becomes gms/100gms.,
easily converted to mole percent for calculation.

As outlined by Babcock (1973) the following data must be known to use the above equation.

- 1) the chemical composition of unaltered and altered rock.
- 2) the density of unaltered and altered rock.
- 3) either the volume change or the magnitude of the chemical transfer of any chemical component during alteration.

To satisfy the above requirements the specific gravity of analyzed samples was measured and the calculation done using mole percent and a volume factor (Kv) of 1, i.e., constant volume metasomatism. The assumption of constant volume during metasomatism is based on the preservation of delicate volcanic textures in even the most intensely altered samples. Riverin (1976) assumed constant volume metasomatism in assessing variation of chemical components across chloritic alteration pipes underlying massive sulphide lenses at the nearby Millenbach mine.

Volume changes that result from assuming constant SiO_2 , Al_2O_3 , or TiO_2 were calculated. Assuming constant Al_2O_3 a 3 - 10 percent volume increase would accompany weak mottled alteration, whereas a 12 - 35 percent volume increase is implied for more intense alteration. A 10 - 70 percent volume increase is required if TiO_2 is considered immobile. Surprisingly only a 2 - 12 percent volume decrease results if SiO_2 is considered immobile.

A volume increase or decrease of 10-15 percent is considered the maximum permissible, in this study, in order that volcanic textures would have been preserved; therefore SiO_2 or Al_2O_3 could have been considered immobile in calculations of metasomatic exchange during weak mottled alteration. This assumption would only affect the magnitude of the chemical changes but not their direction, i.e., additional or subtraction of components other than the component assumed immobile.

Mottled Alteration

Chemical changes that occur with mottled alteration and silicification are shown as bar diagrams in Figures 18a & b. Assuming constant volume metasomatism, SiO_2 and CaO are the components added during mottled alteration, whereas Al_2O_3 , Fe_2O_3 , MgO , and TiO_2 are consistently removed. Mottled alteration is controlled by amygdules, fractures and flow laminations in andesitic lavas; the CaO increase is a reflection of ubiquitous epidote and minor carbonate.

Harrigan and Maclean (1976) described quartz-epidote alteration patches in gabbro dikes at Matagami, Quebec. The mineralogy and textures of quartz-epidote patches at Matagami are similar to "mottled" patches of the upper Amulet rhyolite. Harrigan and Maclean (1976) systematically sampled sections across individual patches into adjacent gabbro to assess chemical variations with alteration. Assuming constant Al_2O_3 , they determined that SiO_2 and CaO increased and FeO , MgO , TiO_2 , Na_2O , and P_2O_5 decreased in the alteration patches, with respect to adjacent gabbro. Except for constant Al_2O_3 , variations in chemical components they documented are similar to those proposed for epidote-quartz alteration patches in andesitic lavas of the upper Amulet rhyolite.

Silicification

Alteration resulting in white, silicified andesite as well as white fragments is characterized by SiO_2 - addition and depletion of Al_2O_3 , Fe_2O_3 , MgO , TiO_2 and CaO . White silicified andesite is a product of the most intense alteration and is best developed at top of the

Figure 18 a + b: Variation of chemical components, in mole percent, assuming constant volume metasomatism in andesitic flows of the upper Amulet rhyolite. SiO_2 and CaO are enriched and Al_2O_3 , Fe_2O_3 , MgO and TiO_2 depleted in mottled andesite relative to massive andesite. With increasing alteration CaO is also removed and the resulting white andesite and fragments are enriched in SiO_2 only.

Figure 18a. Variation in SiO₂, Al₂O₃, Fe₂O₃ and MgO during alteration of andesitic flows, upper Amulet rhyolite.

Figure 18b. Variation in CaO, Na₂O, K₂O and TiO₂ during alteration of andesitic flows, upper Amulet rhyolite.

Amulet "rhyolite" formation adjacent to altered vitrophyric flow tops and white-fragment breccia dikes. White andesite is massive, lacks a "mottled" texture and contains very little if any epidote.

Chemical gains and losses in samples from Buttercup Hill, an outcrop of presumed upper Amulet rhyolite, were calculated and are shown in Figure 19. Assuming constant volume metasomatism SiO_2 is added and Al_2O_3 , Fe_2O_3 , MgO and TiO_2 are depleted. CaO data show no consistent trend. Thus, the chemical effects are virtually identical to those calculated for the upper Amulet rhyolite of the Turcotte Lake section.

Although not illustrated, P_2O_5 and MnO decrease with progressive alteration, the magnitude of the decrease being within the error of the analyses.

The progressive increase in SiO_2 and depletion in Al_2O_3 , Fe_2O_3 , MgO , CaO and TiO_2 with alteration is consistent with the mineralogy of the andesite flows as discussed previously. Interstitial chlorite (presumably devitrified glass) is replaced by quartz which micropoikilitically encloses and occasionally replaces albite microlites. Replacement of chlorite and albite microlites by quartz released Fe_2O_3 , MgO , Al_2O_3 , TiO_2 , Na_2O plus CaO to solution. Flows at the base of the upper Amulet rhyolite member have higher SiO_2 and lower Fe_2O_3 and MgO contents than andesite from the top of the section, reflecting a higher proportion of matrix quartz to chlorite, and therefore greater alteration, in the lowermost flows.

As shown in figure 18, Na_2O plus K_2O lack systematic variation with alteration. Figure 20, is a mole percent triangular diagram of $\text{Na}_2\text{O}+\text{K}_2\text{O}$, SiO_2 and $\text{Fe}_2\text{O}_3+\text{MgO}$. Data from the upper Amulet rhyolite and

Buttercup Hill

Figure 19. Variation of chemical components, in mole percent, assuming constant volume metasomatism, in andesitic flows of Buttercup Hill.

Buttercup Hill plotted on this diagram form a distinct trend which essentially parallels the $\text{SiO}_2 - \text{Fe}_2\text{O}_3 + \text{MgO}$ sideline. During silicification, the silica/alkali ratio has remained relatively constant, with respect to components of the diagram. Replacement of $\text{MgO} + \text{Fe}_2\text{O}_3$, for SiO_2 , during alteration, appears not to have affected the alkali content of the rock.

Constant volume calculations indicate that SiO_2 is the dominant component added to altered rock. To illustrate the relationship of other chemical components to SiO_2 during alteration data from the upper Amulet rhyolite and Buttercup Hill were plotted on a Harker-type variation diagram with mole percent SiO_2 against other oxides (Figures 21, 22 & 23). Al_2O_3 , Fe_2O_3 , MgO , and TiO_2 show a systematic decrease with increasing SiO_2 content (Figures 21, 22). Na_2O , K_2O and CaO values, however, show no correlation with increasing SiO_2 (Figure 23), indicating that the alkali content of altered rocks is not reflected by the silica content.

Copper and zinc contents of altered and massive andesite from Buttercup Hill and massive and mottled andesite pairs from the Turcotte Lake section are plotted in Figure 24. Copper values are erratic and low, whereas zinc values decrease in mottled andesitic lavas.

Copper and zinc contents of massive, mottled and silicified andesite representative of the Turcotte Lake section are shown in Figure 25. Copper values are variable; however, zinc content is systematically lower in mottled and silicified andesite and anomalously high in white fragments with respect to massive andesite. During silicification the behaviour of Zn and possibly Cu is similar to that of Fe_2O_3 , MgO and TiO_2 ; addition of SiO_2 to the rock releases Zn and possibly Cu to solution.

Figure 20: A $\text{SiO}_2 - \text{Na}_2\text{O} + \text{K}_2\text{O} - \text{Fe}_2\text{O}_3 + \text{MgO}$ mole percent ternary diagram. Twenty-eight representative samples from Buttercup Hill and upper Amulet rhyolite of the Turcotte Lake area are plotted, the data form a distinct trend parallel to the $\text{SiO}_2 - \text{FeO} + \text{MgO}$ tie line. The $\text{SiO}_2 - \text{Na}_2\text{O} + \text{K}_2\text{O}$ ratio has not changed during progressive silicification.

Symbols*

Massive andesite ○
Mottled andesite ●
White silicified andesite ●
White fragments ▲
Rhyolite ■

*Symbols used in Figures 20, 21, 22, 23, 24, 25, 26, 27, 28, 29 and 30.

Figure 20: A SiO_2 - Na_2O - K_2O - Fe_2O_3 - MgO mole percent ternary diagram.

Figure 26: A comparison of the TiO_2 and SiO_2 content of massive and variably silicified andesite from the upper Amulet rhyolite to rhyolite from a lava-dome at the base of the Turcotte lake section.

Figure 21: Mole percent variation diagram illustrating the variation of Al_2O_3 (a) and Fe_2O_3 (b) with SiO_2 during progressive silicification.

Figure 22: Mole percent variation diagram illustrating the variation of MgO (a) + TiO₂ (b) with SiO₂ during progressive silicification.

Figure 23: Mole percent variation diagram illustrating the variation of CaO (a), Na_2O (b) and K_2O (c) with SiO_2 during progressive silicification.

MacGeehan (1977) in a study of altered volcanic rocks at Matagami, Quebec determined that Zn and Cu were similarly released to solution during silicification of basaltic rocks.

Differentiating silicified andesite from rhyolite

In the field silicified andesite is difficult to distinguish from rhyolite, especially where the two rock types are intimately associated. Chemical analyses are not definitive since silicified andesite is chemically similar to rhyolite, except for TiO_2 content as found in this study. The TiO_2 content of rhyolite from the map area ranges from 0.20 to 0.30 weight percent, whereas silicified andesite has a TiO_2 content of 0.45 to 1.17 weight percent (Figure 26), considerably higher than that of associated rhyolite. TiO_2 content as a means to distinguish altered rock is not new; Comba (1977) and B. Sakrison (1978, personal communication) believed that anomalously high TiO_2 values in siliceous rocks may be indicative of an originally more mafic composition.

Thirty-two samples were analyzed for 7 trace elements (Rb, Y, Sr, Cr, Ni, Zr, Ba) to determine if any could be used to distinguish true rhyolite from silicified andesite (Figure 27). Of the 7 elements, only Y, and Zr show some promise. Y values for massive and silicified andesite span the range 33 - 53 ppm, whereas rhyolite from the map area contains >60 ppm Y. Nickel is slightly higher in andesitic rocks, 8 - 14 ppm, and lower in rhyolite <8 ppm. Zr ranges from 90 - 270 ppm in andesite whereas rhyolite contains 280 - 310 ppm. One Zr value for silicified andesite is 360 ppm, similar to that of rhyolite; however

Figure 24: Variation in copper and zinc content of massive and altered pairs from the Turcotte lake section and variably altered andesite from Buttercup Hill.

Figure 25: Comparison of copper and zinc content of massive and variably silicified andesite.

Figure 26: A comparison of the TiO_2 and SiO_2 content of massive and variably silicified andesite from the upper Amulet rhyolite to rhyolite from a lava-dome at the base of the Turcotte lake section.

Figure 27 a: A comparison of the Rb, Y, Sr, Cr content of variably silicified andesite from the upper Amulet rhyolite to chloritic flows and rhyolite from the lower member.

Figure 27 b: A comparison of the Ni, Zr, Ba content of variably silicified andesite from the upper member to chloritic flows and rhyolite lava-dome from the lower member.

this value is suspect since the value from the University of Ottawa analysis was 168 ppm.

Rb, Sr and Ba values show an increase in scatter with progressive alteration; values for Cr are erratic even in massive andesite.

A tholeiitic to calc-alkaline trend with silicification

Miyashiro (1974), proposed that $\text{SiO}_2 - \text{Fe/MgO}$ and $\text{FeO/MgO} - \text{FeO}$ diagrams would distinguish rocks of calc-alkaline and tholeiitic affinity. Data from the Turcotte Lake section and Buttercup Hill are shown separately in such diagrams (Figures 28 and 29). Data points for massive andesite, mottled andesite, white andesite and white fragments project onto both tholeiitic and calc-alkaline fields of the diagrams. Massive andesite tends to plot in the tholeiitic field and altered andesite in both tholeiitic and calc-alkaline fields.

Data from Buttercup Hill and upper Amulet "rhyolite" plotted on an AFM diagram (Figure 30) developed by Irvine and Baragar (1971) show tholeiitic to calc-alkaline trends with progressive silicification.

A tholeiitic to calc-alkaline trend with silicification was recognized in volcanic rocks at Matagami, Quebec, by MacGeehan (1977) and in volcanic rocks of the Aldermac area, west of Noranda, by A.D. Hunter (personal communication, 1979). It is important to note that silica metasomatism produces an apparent tholeiitic to calc-alkaline trend indistinguishable from a magmatic trend on existing chemical variation diagrams.

Figure 28: SiO₂ - FeO/MgO diagram. Tholeiitic to calc-alkaline character of andesite and silicified andesite from Buttercup Hill (a) and Turcotte Lake section (b). Total iron as FeO.

Figure 29: FeO - FeO/MgO diagram. Tholeiitic to calc-alkaline trend with silicification. Data from Buttercup Hill (a) and the Turcotte Lake section (B). Total iron as FeO.

Figure 30: A TAS diagram showing tholeiitic to calc-alkaline trend with silicification. Data from Buttercup Hill (a) and Turcotte Lake section (b).

Summary

- 1) The lower Amulet rhyolite in the Turcotte Lake section is pervasively chloritized. Chloritization and feldspar breakdown result in an increased Fe_2O_3 and MgO content and depletion in alkalis. The lower Amulet rhyolite is Na_2O - depleted probably because of its close spatial relationship to a dalmatianite alteration zone to the northeast.
- 2) Unaltered pillowed flows, the Bedford andesite, separate the upper and lower Amulet rhyolite northwest of the area (C.D.A. Comba, personal communication 1979). The presence of unaltered flows at this contact implies a time break between extrusion and alteration of both upper and lower Amulet rhyolite. The time "gap" has significance for base metal exploration as the underlying chloritic flows of the lower Amulet "rhyolite" are anomalously enriched in Cu and Zn and Na_2O - depleted.
- 3) Mottled alteration manifests itself in the development of irregular epidote-quartz patches that are mineralogically zoned. The patches are enriched in SiO_2 and CaO and depleted in Al_2O_3 , MgO , TiO_2 relative to adjacent andesite.
- 4) White silicified andesite, as well as white fragments, are depleted in Al_2O_3 , Fe_2O_3 , MgO , CaO , and TiO_2 and enriched in SiO_2 relative to massive and mottled andesite, assuming constant-volume metasomatism.
- 5) The restriction of alteration to amygdules, fractures and fault-shear zones implies that an aqueous phase was capable of transporting chemical components to and away from alteration sites.

The pervasive and widespread nature of the alteration implies that a large volume of fluid was involved.

6) Na_2O , K_2O and CaO contents of the rocks do not appear to be related to the degree of silicification, although there is a slight CaO increase in areas of mottled alteration. Anomalously low CaO and high Na_2O content of massive andesite indicate an early "Na" metasomatism or spilitization, during sea-floor weathering (Spooner and Fyfe, 1973) or burial metamorphism (Smith, 1968).

7) Massive andesite from the top of the Amulet rhyolite is less altered than massive andesite from flows lower in the stratigraphic succession.

8) Silicification produces an apparent tholeiitic to calc-alkaline trend indistinguishable from a magmatic trend on existing chemical variation diagrams.

9) As chemical analyses are not definitive, field and petrographic (textural) criteria are essential to distinguish silicified rocks from rhyolite.

VII. A GEOTHERMAL MODEL FOR ALTERATION IN THE UPPER AMULET RHYOLITE

✓ On the basis of preceding field, petrologic and chemical descriptions and a literature survey of alteration in modern hydrothermal systems, alteration in the upper Amulet rhyolite is interpreted as the result of hot water-rock interaction in a sub-seafloor geothermal system. Assuming Archean geothermal systems and their surface manifestations, hot-springs, are similar to modern geothermal areas analogies can be made which are usefull in developing an initial alteration model. It is worth stating that the model proposed is only one possible hypothesis for explaining alteration in the upper Amulet rhyolite. Further field work will be done to test this model.

The occurrence and characteristics of geothermal systems associated with volcanic activity are well documented. The better known examples include the Reykjanes geothermal field in Iceland (Tomasson and Kristmannsdottir, 1972), the Ohaki-Broadlands hydrothermal area, New Zealand (Browne and Ellis, 1970) and hydrothermal systems at mid-ocean ridges (Worley and Sleep, 1976 and Rona and Lowell, 1978). Geothermal systems are now recognized as an integral part of volcanic activity.

The characteristic features of hydrothermal systems were reviewed by White (1970, 1974), and Ellis (1970, 1975). In general there are four features common to all hydrothermal systems:

- 1) a heat source.
- 2) a reservoir or aquifer to store solutions.
- 3) an overlying cap rock.
- 4) channelways for recharge and discharge of solution to and from the aquifer.

The map area is interpreted as a cross-section through a larger geothermal system within the upper Amulet "rhyolite". Mottled alteration is a product of hot water-rock interaction controlled by primary permeability of the flow rocks (Fridleifsson, 1975, and Grindley and Browne, 1975), in a sub-seafloor aquifer or reservoir. White silicified andesite and white-fragment breccia dikes are products of hydrothermal alteration and self-sealing processes (Facca and Tona, 1967) along discharge zones at or near the top of the Amulet "rhyolite" formation.

The heat source necessary to drive the system may be regional, related to high, regional heat flow from an underlying shallow ~~magma~~ chamber or local. Evidence for a local heat source is high level intrusive activity which manifests itself in the plexus of rhyolite, basalt and composite dikes of the upper Amulet "rhyolite". These intrusions may be related to a shallow, intrusive apophysis of an underlying magma chamber, which if large enough would provide a heat source.

GEOMETRY OF THE GEOTHERMAL SYSTEM

Information concerning the size and shape of the geothermal system, as shown by hydrothermally altered rock, is limited on one cross-section. The lower Amulet "rhyolite" member is not affected by the same alteration as is the upper Amulet "rhyolite". This limits the geothermal system to the upper Amulet "rhyolite", which in the Turcotte Lake section is 600m in apparent thickness, implying a shallow sub-seafloor aquifer or reservoir.

The conformable character of the alteration and its restriction

to permeable zones within flows implies that:

- 1) within the area of the system represented by the Turcotte Lake section solution flow was parallel to stratigraphy.
- 2) that solution responsible for the alteration was derived from areas lateral to, but not below the upper Amulet "rhyolite".

The numerous faults and shears within the map area provided permeable zones for cross-stratal migration of solution and ultimately provided channels for the solution to reach the seafloor.

TEMPERATURE OF THE SOLUTION

The temperature of solution that migrated through volcanic rocks of the upper Amulet "rhyolite" can be estimated by comparing the alteration assemblage produced by the solution to assemblages in active geothermal systems where the temperature of the solution is known. In the Reykjanes geothermal field in Iceland the assemblage chlorite-epidote is developed in rocks of basaltic composition altered by heated seawater in the temperature range $200^{\circ} - 300^{\circ}\text{C}$ (Tomasson and Kristmannsdottir, 1972). Pervasive epidote alteration, however, occurs only in rocks in contact with a solution of temperature $>260^{\circ}\text{C}$ (Tomasson and Kristmannsdottir, 1974). Amphibole is rare and is thought to be representative of the alteration zone at the highest temperature, approximately 300°C (Tomasson and Kristmannsdottir, 1972, Kristmannsdottir, 1975).

Keith et al (1968) documented the assemblages ferro-actinolite-epidote and chlorite-epidote in altered rocks of the Salton Sea geothermal system in California. The assemblages were interpreted by Keith et al

(1968) to have been produced during hydrothermal metamorphism by solutions with a temperature of approximately 320°C .

Mottl and Holland (1978) conducted experiments to determine alteration assemblages produced in basaltic rocks (glass) in contact with heated seawater. Actinolite-tremolite developed as an alteration assemblage at temperatures near 400°C and abundantly at a temperature of 500°C . Tremolite-actinolite was not produced in experimental runs at temperatures near or less than 300°C .

Temperatures from field measurements and experimental studies imply that the assemblage actinolite-epidote-quartz in altered andesite lavas of the upper Amulet "rhyolite" was produced by interaction with solutions of a temperature of at least 320°C and probably in the range $350 - 370^{\circ}\text{C}$. The above assemblage is interpreted to have formed during early hydrothermal metasomatism similar to that occurring in modern geothermal systems and is not a product of regional isochemical metamorphism.

The upper Amulet "rhyolite" has an apparent thickness of 600m. Assuming that to be a maximum thickness, the hydrothermal metamorphic assemblage indicates that temperatures in the range of $320^{\circ} - 370^{\circ}$ occurred at a depth of 600m below the seawater-rock surface. Spooner and Fyfe (1973) described a similar alteration of ophiolitic rocks at E. Liguria, Italy; they envisaged temperatures as high as 400°C at depths as shallow as 300m, or a geothermal gradient of approximately 1300°C/km .

To heat a large volume of solution within a aquifer to a temperature of 350°C as postulated for the upper Amulet "rhyolite" would require a tremendous heat flow. If the heat source is solely regional, i.e.,

generated by an underlying magma chamber, one would expect that stratigraphically lower units would show a higher temperature hydrothermal assemblage, analogous to "amphibolite facies metamorphism", but this is not the case. A local heat source within the upper Amulet "rhyolite" would not alter stratigraphically lower units; however there is some doubt whether a high level dome or intrusion could generate enough heat to account for the alteration (Cathles, 1978). It seems that a combination of the two heat sources may be required, with alteration occurring where the flows were still hot.

HYDROTHERMAL ALTERATION

The introduction of hot aqueous solution ($>320^{\circ}\text{C}$) to hot volcanic rocks results in chemical interaction and exchange of chemical components during alteration. Constant volume calculations indicate that during alteration SiO_2 (and minor CaO) is added to the rock, whereas the solution acquires Fe_2O_3 , MgO , Al_2O_3 and TiO_2 from the rock. As a result the chemistry and mineralogy of the rock changes, and the composition of the migrating solution evolves from its original composition. In a rock dominated system (low water/rock ratio) the composition of the solution changes towards that of the rock, whereas in a water dominated system (high water/rock ratio) the rock changes composition in favor of the solution (Seyfried and Bischoff, 1977).

The water/rock ratio for alteration in the upper Amulet "rhyolite" can be inferred from experimental studies of hydrothermal alteration of basaltic glass. With a low water/rock ratio (<50), MgO in solution is

usually reduced to <3 percent of its original value; at higher water/rock ratios (>50) MgO is retained in solution (Bischoff and Dickson, 1975; Seyfried and Bischoff, 1977). The Reykjanes geothermal field is characterized by a low water/rock ratio (<2) and hydrothermal solutions are typified by a low MgO content (Bischoff and Dickson, 1975). MgO depletion in altered lavas of the upper Amulet "rhyolite" implies a high water/rock ratio and therefore a high flux of solution through the system.

Constant volume calculations and petrographic evidence indicate that SiO_2 is the dominant chemical component added; therefore the solutions were oversaturated with respect to SiO_2 . The exact chemical exchange mechanism whereby silica in solution replaces various oxides dissolved from the rock is uncertain.

The solubility of SiO_2 in an aqueous solution is relatively independent of the concentration of other chemical species in solution, and the pH of the solution (Fournier, 1975, Holland, 1967). Therefore, solution and deposition of silica from a solution can be discussed neglecting effects of chemical interactions of solution and wall rock and resultant variation in the concentration (molality) of other chemical components. As in most hydrothermal systems, and in experimental studies, Figures 31 & 32, (Kennedy, 1950 and Fournier and Rowe, 1966) the solubility of silica depends upon the nature of the silica phase in contact with solution, and the temperature and pressure of the solution. Silica oversaturation in a solution at a temperature of approximately 300 - 350°C as required by the alteration process may occur in respect to two processes:

1) The first process involves a decrease in silica solubility with increasing temperature. As shown in Figure 31, at pressures less than 600 - 650 bars, silica saturated solutions heated above 340° - 350°C would become oversaturated and deposit silica. The 350°C temperature for dissolution of silica required by this process is similar to temperatures estimated for the solution based on the alteration mineral assemblage. This process involves influx of a SiO_2 saturated solution into a "hotter" area of the aquifer resulting in SiO_2 deposition. MacGeehan (1977) proposed a similar silicification process for volcanic rocks at Matagami, Quebec.

2) The second process is based on the greater solubility of SiO_2 in a solution in contact with amorphous SiO_2 (as in volcanic glass) than in contact with quartz (Holland, 1972, Fournier and Rowe 1966). It is not unusual for amorphous SiO_2 to persist at high temperatures and govern the solubility of SiO_2 in solution in a volcanic environment where continued faulting exposes "fresh" unaltered rock to solution (Fournier, 1975). Such a solution moving into a "hotter" area within the aquifer where quartz is the stable phase would be strongly oversaturated (Figure 32) and deposit SiO_2 to achieve equilibrium.

In both cases the amount of silica deposited is small, considering the volume of rock altered and degree of alteration; this implies that a high flux of SiO_2 saturated solutions passed through the system. Considering the volume of solution required, and the submarine volcanic setting, seawater is favoured as a source for the solution.

As mentioned, solution interacting with volcanic rocks to produce alteration in the upper Amulet "rhyolite" must have been oversaturated

Figure 31. The solubility of quartz in water at temperatures up to 560° and pressures up to 1750 bars (1750×10^2 kPa) from Kennedy (1950).

Figure 32. The solubilities of quartz, chalcedony, cristobalite and amorphous silica at the vapor pressure of the solution, from Fournier and Rowe, 1966.

with respect to SiO_2 and therefore had evolved from an original seawater composition before alteration. The source of SiO_2 in solution is believed to be the result of chloritization of volcanic glass by seawater during downward migration in recharge zones of the geothermal system. That chloritization of volcanic glass can release SiO_2 to solution has been shown in experimental studies where a Mg-rich clay mineral or chlorite at higher temperatures is the alteration product (Seyfried and Bischoff, 1977; Bischoff and Dickson, 1975; Mottl and Holland, 1978, and Ellis and Mahon, 1964) in equilibrium with a SiO_2 rich solution, and by microprobe analyses of chloritized and devitrified phases of volcanic glasses (D.H. Watkinson, personal communication, 1979).

In summary, Figure 33 is a cartoon illustrating the chemical evolution of seawater moving through the proposed geothermal system within the upper Amulet rhyolite member. The chemical gains and losses are those calculated in the preceding chapter.

WHITE-FRAGMENT BRECCIAS

White-fragment breccias are interpreted as fluidized breccia dikes, emplaced as a turbulent mixture of fragmental debris and gas. Although many possibilities exist, only two phenomena are envisaged as being capable of generating fault-controlled breccia dikes as found in the upper Amulet "rhyolite" member.

The first phenomenon is related to cauldron subsidence as proposed by Lambert (1972), as an explanation for breccia dikes of the Bennett Lake cauldron subsidence complex. During foundering of fault bounded

Figure 33: Cartoon illustrating the chemical gains and losses of seawater moving through a geothermal system within the Amulet "rhyolite" formation.

(A) Recharge area-introduction of seawater to geothermal system.

(B) Medial portion of system-dominated by lateral fluid migration.

(C) Discharge area - submarine hot springs - discharge of evolved seawater of seawater/rock interface.

blocks (of tremendously large volume) into a subterranean cavity (a result of magma evacuation) trapped gas and air would be compressed and then explosively released along open faults or shears. Expanding gas and air would transport shattered and brecciated rock to surface forming breccia dikes.

De Rosen-Spence (1976) interpreted the central Noranda volcanic complex as a shield-like edifice some 40 - 50km wide with a 20km - wide subsidence area. White-fragment breccia dikes of the map area lie within the proposed area of collapse and many represent zones of weakness related to subsidence intruded by breccia dikes.

The second phenomenon is related to hydrothermal explosive activity along active discharge zones in a volcanic geothermal system. This model is preferred for the Amulet rocks.

Mottled alteration is presumed to result from hot water-rock interaction, by a large volume of fluid, in a probable volcanic aquifer. Chloritic faults, shears and associated breccia are interpreted as channelways for such a solution to reach the seafloor. The solution is likely heated seawater chemically evolved by interaction with reservoir rocks. Alteration mineralogy and chemistry indicate that the solution was silica-saturated in the temperature range of 350°C. Upon ascent the solution would cool near surface and mix with downward percolating seawater. Depending on the mixing ratio of solution to seawater (Seyfried, and Bischoff, 1977), silica would rapidly precipitate (probably as amorphous silica) along channelways. Deposition of silica by ascending solutions would eventually seal the channel (Facca and Tanali, 1967) unless maintained open, by faulting, during

continuous volcanic activity. Adjacent volcanic rocks in contact with large volumes of ascending, hot silica-saturated solution would eventually be silicified and form an insulating cap rock for the underlying aquifer.

During a pause in volcanic activity and faulting silica deposition would seal the channel. With self-sealing, fluid pressure of the hydrothermal solution would increase. When fluid pressure exceeded load pressure boiling would result and steam produced would collect at the top of the solution column. Where hydrostatic pressure exceeded load pressure by an amount equal to the tensile strength of the silicified cap rock, the cap would fracture (Grindley and Browne, 1975) and expansion of trapped gas would result in a steam-blast or hydrothermal explosion (Muffler, et al 1971). Similarly, if volcanic activity re-opened the channel (fault) sudden release in pressure would result in fracturing and a hydrothermal explosion. Hydraulic fracturing and steam blast explosions would also account for pods of shattered and brecciated andesite within the upper Amulet "rhyolite".

As a modern analogy, processes described here, have been proposed as an explanation for maar formation (Ollier, 1974) and hydrothermal explosion craters (Muffler, et al 1971). The potential explosive force developed in hydrothermal explosions is tremendous; Muffler, et al (1971) described hydrothermal explosion craters up to 1500m across in Yellowstone National Park.

The explosively released expanding gas would transport pulverized fragments and blocks to surface along the fault or shear to form a breccia dike at the top of the Amulet "rhyolite". At surface, fluidized

breccias may scatter fragments or leave the fissure as a coherent fluidized flow. Scattered fragments and slabs of brecciated cap rock might become incorporated into later flows or debris flows forming conformable breccias as reported at Buttercup Hill and the top of the Amulet rhyolite in the Turcotte Lake section. A possible reconstruction of the upper Amulet rhyolite showing the relationship between breccia dikes, volcanic stratigraphy and breccia piles, as at Buttercup Hill, is illustrated in Figure 34.

The breccia dikes because of their fragmental nature are open channelways for later ascending solution to reach the seafloor. In breccia dikes at the top of the Amulet "rhyolite" formation chloritization occurred after emplacement of the dikes. It is suggested that silicification with accompanying self-sealing and hydrothermal explosion products, breccia dikes, represent an early manifestation of hydrothermal activity. Secondary permeability, a result of silicification, provides channelways for later ascending solution to reach the seafloor.

RELATIONSHIP OF SILICIFICATION AND CU-ZN MINERALIZATION

Recent theories on the formation of volcanogenic massive sulphide deposits explain their origin in light of processes active in hydrothermal systems, now recognized as an integral part of volcanic activity. Metals contained in the deposit are presumed to be derived from underlying rocks. The ore solution is presumed to be evolved seawater that is saturated with respect to metals and other components by reaction with reservoir rocks. The similarity of the process postulated for

Figure 34: Cartoon illustrating one possible reconstruction of the upper Amulet "rhyolite" member before extrusion of the Millenbach - Amulet andesite.

massive sulphide formation to that described for alteration in the upper "Amulet" rhyolite is apparent.

The following characteristics of silicification, as demonstrated in alteration within the upper Amulet "rhyolite", are useful in evaluating its relationship to massive sulphide deposits:

- 1) Field evidence indicates a close spatial and temporal relationship of silicification to mineralization. Silicified andesite of the Amulet "rhyolite" formation is the footwall to the Amulet C ore lenses and underlies the larger Amulet lower "A" deposit and Millenbach orebodies; however it is separated from these by the Millenbach andesite (Figure 14).

- 2) White-fragment breccia dikes apparently occupying "discharge zones" have an 070 trend. Ore lenses at the nearby Millenbach are aligned along a similar 070 trend and a northwest trend.

- 3) Field and petrographic evidence indicate that in "discharge zones" occupied by breccia dikes an early episode of silicification and brecciation was overprinted by chloritization. Occasionally these breccias are anomalous in Zn and Cu.

- 4) During silicification the behavior of Zn and possibly Cu is similar to that of Fe_2O_3 , MgO and TiO_2 ; addition of SiO_2 to the rock releases Zn and Cu to solution.

- 5) The chemical components required for formation of a massive sulphide deposit (Cu, Zn, Fe) and underlying alteration (Mg, Fe) and those released to solution during silicification. The behavior of sulphur during silicification is uncertain, as the analytical values are within the error of the analyses.

The above features suggest a relationship between silicification and formation of massive sulphide deposits. Solutions that evolved during alteration reactions in the upper Amulet "rhyolite" may have ultimately been responsible for or were involved in the formation of the deposits along "discharge zones" at the sea floor. Alternatively, the solution, if not directly involved in the ore forming process may have established permeable zones (by hydrothermal explosions) along which a later metal-rich solution could reach the sea floor. Components enriched in seawater by these early exhalations might be incorporated into associated ash-tuff horizons.

VIII. CONCLUSIONS AND VOLCANIC HISTORY

The Turcotte Lake section is a complete stratigraphic section through the Amulet "rhyolite" formation within the central Noranda volcanic complex. The Amulet "rhyolite" was divided into two members.

The lower member consists of a volcanic breccia marker unit referred to as Beecham breccia, overlain by a flow-banded to massive, spherulitic lava-dome that is mantled by chloritic flows.

The upper member consists of variably silicified andesite flows that have been previously mapped as rhyolite (De Rosen-Spence, 1976; Wilson, 1941). True rhyolite constitutes less than 30 percent of the section mapped.

Lineament directions within the map area are defined by rhyolitic, basaltic and composite dikes with a northwest trend parallel to the McDougall-Despina fault system; and altered faults, shears and breccia dikes with a northeast (070) trend. Northwest-trending lineaments appear to have been active in localizing high-level intrusive activity that may have fed fissure-type eruptions, whereas 070 lineaments are characterized by hydrothermal activity. Significantly, ore lenses at the nearby Millenbach mine and associated quartz-feldspar porphyry dome are aligned parallel to an 070 and northwest trending lineament (Knuckey, 1975). Volcanic rocks and massive sulphide lenses at the Corbet mine (J.J. Watkins, personal communication, 1978) some 1000m lower in stratigraphy are associated with similar trending lineaments, the McDougall and 070 trending faults. This association implies that both lineament directions have been active in controlling intrusive and extrusive volcanic activity, hydrothermal solutions and mineralization during development of the volcanic pile.

Within the upper Amulet "rhyolite" member silicification is of two main types: conformable, widespread mottled alteration and localized cross-cutting alteration. Silicification is interpreted as the result of hydrothermal alteration. Mottled alteration is a product of hotwater-rock interaction in a shallow, sub-seafloor aquifer or reservoir. White, silicified andesite is a product of hydrothermal alteration and self-sealing processes along discharge zones at the top of the Amulet "rhyolite" formation. White-fragment breccia dikes are interpreted to have been fluidized clastic dikes generated by hydrothermal explosions within discharge zones.

The net chemical exchange that occurred with silicification assuming constant volume metasomatism was an increase in SiO_2 (minor CaO increase) and decrease in Al_2O_3 , MgO , TiO_2 , Fe_2O_3 and Zn . Silicified andesite chemically resembles rhyolite and has a calc-alkaline affinity according to commonly used chemical criteria. Relatively unaltered andesite on the other hand is tholeiitic. As chemical analyses are not definitive, field and petrographic criteria are clearly essential to distinguish silicified mafic rock from rhyolite.

VOLCANIC HISTORY

A discussion of the volcanic history for the Amulet "rhyolite" formation is limited by the area of the section mapped. Evidence from the Turcotte Lake section indicates the following sequence of events:

- 1) After extrusion of the Rusty Ridge andesite volcanic activity temporarily ceased. In this interval Beecham breccia was

deposited. The presence of variably silicified and unaltered andesite and "rhyolite" clasts within the coarse breccia component suggest a complex provenance; with fragments derived, perhaps, by erosion of existing altered volcanic rocks and explosive volcanic activity. Recent work by J.J. Watkins (personal communication, 1979) demonstrates that Beecham breccia is thickest adjacent to the McDougall fault and is related to that structure.

2) The rhyolite lava-dome was emplaced during a period of andesitic extrusive activity. The lava-dome intruded andesitic lava near the McDougall fault and became extrusive to the north where it conformably covered Beecham breccia. Continuing andesitic volcanism covered the lava-dome. The source of the rhyolite lava-dome may have been a fissure now occupied by the McDougall fault, as the rhyolite is intrusive adjacent to this structure. Hydrothermal alteration, mainly chloritization, of andesitic flows and the rhyolite lava-dome may have occurred in response to a local convective system generated by emplacement of the lava-dome or be part of larger system related to areas of dalmatianite alteration to the north and east.

3) Flows of the upper member were extruded after alteration of the lower member. The thick, massive nature of the andesitic flows is interpreted to indicate proximity to an extrusive vent or fissure, possibly the northwest-trending McDougall fault. Alternatively, thick massive andesitic flows could have formed by ponding, in fault blocks adjacent to the McDougall structure. Lava of the upper member was subsequently silicified, the alteration a product of hydrothermal alteration in a shallow sub-seafloor geothermal system.

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APPENDIX I

Photographs and photomicrographs

Figure 35. Beecham breccia in contact with pillow breccia of underlying Rusty Ridge andesite. Laminated ash tuff layers interbedded with a thick-bedded coarse breccia.

Figure 36. Coarse breccia component of Beecham breccia. A mixture of white felsic fragments, mafic fragments and silicified mafic fragments.

Figure 37. Massive "unaltered" andesite of the upper Amulet "rhyolite".

Figure 38. Chlorite-actinolite amygdules in massive andesite of the upper Amulet "rhyolite".

Figure 39 Chloritic envelope (light brown) developed adjacent to a shear in weakly mottled andesite (under hammer) of the upper Amulet "rhyolite".

Figure 40. Columnar joints in chloritic andesite flows of the upper Amulet "rhyolite".

Figure 41. Psuedoscoriaceous texture of altered vitrophyre.

Figure 42. Contact between mottled andesite and altered vitrophyre. Contact marked by a fine-grained, brown, chloritized microbreccia.

Figure 43. Silicified, devitrification network in vitrophyre flow top.

Figure 44. Vein-network silicification and devitrification in andesite adjacent to vitrophyre.

Figure 45. Amoeboid ribbon forms in a fine-grained chloritized fragmental matrix.

Figure 46. Ribbon "fragment" from the top of the Amulet "rhyolite".

Figure 47. Breccia at contact between chloritic flows and underlying rhyolite. Angular fragments resemble chloritic flow rock.

Figure 48. Sericite-quartz envelope developed around shear in chloritic flows.

Figure 49. Mottled alteration in andesite of the upper Amulet "rhyolite". White siliceous (quartz-epidote) patches developed around amygdules.

Figure 50. White patches in andesite, typical of mottled alteration in the upper Amulet "rhyolite".

Figure 51. Angular, white, silicified andesite fragments , from white-fragment breccia dike.

Figure 52. Quartz amygdaloidal, silicified andesite fragment from breccia dike.

Figure 53 Breccia pods in andesite of the upper Amulet rhyolite. White silicified fragments in a chloritic fragmental matrix.

Figure 54 Cross-cutting brecciation and silicification in andesite of the upper Amulet rhyolite.

Figure 55.

- (a) Hyaloclastite breccia from the Rusty Ridge andesite formation. Dark fragments are chloritic and feldspar porphyritic, the light fragment is silicified andesite in a matrix of fine-grained quartz. Irregular sericite veins cross-cut both fragments and matrix.
- (b) Perlitic textured rhyolite. Perlitic cracks outlined by chlorite; feldspar phenocryst replaced by quartz.
- (c) Recrystallized spherulite in massive rhyolite. Matrix is a granular mosaic of quartz, chlorite and sericite.
- (d) Quartz-chlorite amygdaloidal chloritic flow rock. Drusy quartz in chlorite amygdules, matrix is chiefly quartz and chlorite with lath-like pseudomorphs after feldspar.
- (e) Silicified and chloritized, quartz amygdaloidal vitrophyre. Fine-grained, "dusty" quartz (grey) envelopes quartz amygdules to form a layering within a darker chloritic groundmass (dark).
- (f) Massive andesite from flows of the upper Amulet "rhyolite" member. Glomeroporphyritic albite phenocrysts and microlites with interstitial chlorite and granular quartz.

Field of view for all photos 20mm

Figure 56.

- (a) Randomly oriented albite microlites in a groundmass of interstitial chlorite and coarser-grained quartz. Texture is typical of massive andesite from the upper Amulet "rhyolite". Field of view 5.5mm.
- (b) Micropoiki litic quartz enclosing albite microlites, typical of mottled andesite from the upper Amulet "rhyolite". Field of view 2mm.
- (c) White silicified andesite from the top of the Amulet rhyolite formation. Albite phenocrysts and quartz amygdules in a groundmass of albite microlites, micropoiki litic quartz and minor chlorite. Field of view 20mm.
- (d) Flow banded, quartz amygdaloidal vitrophyre from the top of Amulet rhyolite formation. Layering a result of alternating quartz and chlorite-rich layers. Fine internal lamination may be recrystallized vesicles. Field of view 20mm.
- (e) Flow-brecciated, flow-banded vitrophyre. Feldspar phenocrysts are replaced by quartz. Field of view 20mm.
- (f) Brecciated, flow-top vitrophyre. Scoriaceous fragments and feldspar phenocrysts are replaced by fine-grained quartz. Field of view 20mm.

Figure 57.

- (a) Vein-network silicification in vitrophyre. Fine-grained "dusty" quartz envelopes quartz-filled fractures. Field of view 5.5mm.
- (b) Perlitic texture in andesitic matrix of conformable white-fragment breccia. Field of view 20mm.
- (c) Cross-cutting pyrite-quartz fracture mantled by an envelope of fine-grained dusty quartz. Feldspar phenocrysts replaced by quartz. Field of view 1.8mm.
- (d) Breccia matrix to conformable white-fragment breccia unit. Quartz-amygdaloidal chloritic fragments are engulfed in a matrix of finer, silicified, scoriaceous fragments. Amygdules in chloritic fragments are mantled by a halo of fine-grained quartz (grey). Field of view 20mm.
- (e) Angular white fragment. Fragment is silicified andesite and consists of albite phenocrysts and microlites in a matrix of micropoiki litic quartz and minor chlorite. Field of view 1.8mm.
- (f) Ribbon "fragment". Consists of quartz amygdules and quartz pseudomorphs after feldspar phenocrysts in a fine grained matrix of quartz and chlorite. Field of view 1.8mm.

Figure 58.

- (a) Perlitic texture in chloritic vitrophyre. Perlitic cracks outlined by "grey" quartz and occasionally pyrite-chalcopyrite. Field of view 20mm.
- (b) Devitrification network (after De Rosen-Spence, 1976) in chloritized vitrophyre. Spherulites nucleating around quartz amygdules and albite phenocrysts collectively form the devitrification network. Field of view 20mm.
- (c) Impinging spherulites from devitrification network describe in Figure 43. Spherulite on left has nucleated around a quartz amygdale. Field of view 1.8mm.
- (d) Spherulitic overgrowth on albite phenocrysts, from devitrification network in Figure 58c. Field of view 1.8mm.
- (e) Silicification along perlitic cracks in chloritic vitrophyre. Field of view 20mm.
- (f) Vein-network epidote replacing perlitic textured chloritic vitrophyre. Feldspar phenocrysts replaced by quartz and carbonate. Field of view 5.5mm.

Figure 59.

- (a) White-fragment breccia from a breccia dike at the top of the Amulet "rhyolite" formation. The white fragment is silicified andesite, in a matrix of chloritic andesite fragments. The border of the white fragment is chloritic in contact with the matrix. Field of view 20mm.
- (b) Chloritic andesite fragments which form the matrix of the breccia dike described in Figure 60b. Broken albite phenocrysts and chlorite form the matrix of the fragments. Field of view 20mm.
- (c) Quartz amygdaloidal, silicified andesite fragment from a breccia dike. Microclitic texture (albite microclites) is preserved in the quartz-rich groundmass. Field of view 20mm.
- (d) Mottled textured andesite. Epidote patches and fractures (dark) surrounded by a halo of fine quartz and minor carbonate. Field of view 20mm.
- (e) Mottled alteration developed around carbonate amygdule. Amygdule mantled by a zoned envelope of epidote (dark grey) then quartz (lighter). Field of view 5.5mm.
- (f) Mottled textured alteration, a magnification of Figure 59c. Albite microclites and chlorite (right) are replaced by a granular epidote-quartz alteration (center) adjacent to carbonate amygdule (left). Field of view 2mm:

Figure 60.

- (a) Columnar jointed, mottled andesite. White envelopes developed around amygdules.
- (b) Discordant white-fragment breccia dike.
- (c) Fragments within breccia dike. White, flow-banded andesite fragments in a chlorite matrix.
- (d) Gently dipping (30°) contact of blocky, white-fragment breccia on underlying andesite.
- (e) Blocky white-fragment breccia. Andesite fragments have silicified borders, and halos around amygdules.
- (f) Pyritic ash tuff intercalated with blocky white-fragment breccia.

Figure 61.

- (a) Contact between mottled andesite (lower half of photo) and "vent zone"
Mottled alteration persists in "vent zone" but is contained in a brecciated andesite matrix.
- (b) In situ brecciated mottled patch from "vent zone", enveloped within brecciated andesite with a characteristic quartz vein-network alteration.
- (c) Brecciated andesite of vent zone. Angular, chloritic, andesite fragments contained in a matrix of fine quartz.
- (d) Feldspar porphyritic andesite. Albite phenocrysts and microlites in a fine-grained matrix of chlorite and granular quartz. Field of view 20mm.
- (e) White fragment from conformable breccia. Albite phenocrysts and microlites in a fine-grained quartz matrix. Field of view 20mm.
- (f) Chloritization of mottled patch from "vent zone". Chlorite veins (dark) are mantled by a chloritic envelope (dark grey). Field of view 20mm.

APPENDIX II

Underground mapping at the
Millenbach Mine

Appendix II

Underground mapping at the
Millenbach Mine

Introduction

Underground mapping was conducted at the Millenbach mine during a five day period in late November 1978. Millenbach, a classical volcanogenic massive sulphide deposit, is located some 2000m west-southwest of the Turcotte Lake section. Mapping was confined to the Amulet rhyolite - Millenbach andesite contact exposed along the 401 exploration drift some 700m below surface.

Results

Approximately 70m. of drift was mapped with samples selected for thin section examination. The results of the mapping and petrographic study are:

- 1) Although affected by upper greenschist facies contact metamorphism (albite-actinolite - epidote assemblage) the Amulet rhyolite is texturally similar to that mapped on surface. Black, feldspar porphyritic, amygdaloidal andesite is "mottled", ie; dotted with irregular, light green epidote-quartz patches. Both "mottled and massive andesite are cross-cut by breccia pods consisting of white silicified andesite fragments in a chloritic vein network matrix. The breccia pods are local areas of shattered and altered andesite.
- 2) Within altered Amulet "rhyolite" garnet occurs as idioblastic porphyroblasts in alteration haloes and selvages mantling amygdules

and veins respectively. The restriction of garnet to alteration envelopes implies that altered andesite is enriched in Al with respect to the massive andesite host.

3) Epidote-quartz mottled patches locally merge and coalesce to form a reticulate network or cylindrical pipe-like bodies. The distribution of rock and alteration types is shown in Figure 62.

Figure 62: Detailed geology of the Amulet rhyolite - Millenbach andesite contact, 401 exploration drift, Millenbach mine.

LEGEND

- °° Mottled andesite
- Dalmatianite
- △△ Insitu breccia, silicified shattered andesite
- 4 Millenbach andesite
- 3 Cherty, thin bedded to laminated, pyritic, ash tuff
- 2 Flow top breccia - hyaloclastite - silicified, chloritized and pyritic
- 1 Feldspar porphyritic, amygdaloidal andesite

MILLENBACH MINE
4th LEVEL PLAN
1" = 20'

APPENDIX III

Chemical composition of rock specimens
from the Amulet "rhyolite" formation

Appendix III

General notes and symbols

- Massive andesite
- Mottled andesite
- White, silicified andesite
- ▲ White fragments
- x Altered vitrophyre.
- Rhyolite

Fe_2O_3^* total iron as Fe_2O_3
 FeO^* total iron as Feo

Discussion

Chemical analyses of selected specimens from the map area were performed at two analytical laboratories;

- 1) Analyses in tables 2, 3, 4, 5, 6 (62 in total) were performed using a fused pellet X-ray fluorescence (XRF) technique at the University of Ottawa, Ottawa, Ontario. Samples were analyzed for 11 major and 8 trace elements.
- 2) Analyses in table 7 (32 in total) were performed using a pressed pellet XRF technique at Laurentian University, Sudbury, Ontario. The samples were analysed for 7 trace elements, the results checked periodically by AA analysis.

Results of the internal reference and control standards used by the laboratories were not included but the batch of 62 samples, analyzed at the University of Ottawa, contained a duplicate and a standard, LUL. The

standard, LU1, was donated by J. M. Franklin of the Geological Survey of Canada. Table 8 shows the results of the duplicate and standard analyses.

Density

Density measurements involved determining the apparent weight loss of the sample in air, then water, using a technique outlined by Riverin, (1977).

The density of each rock specimen was calculated using the formula outlined by Berry and Mason (pg. 187, 1959);

$$G = \frac{W_1}{W_1 - W_2} \times L$$

where G = density

W_1 = weight in air

W_2 = weight in liquid (water)

L = density of liquid (water)

Table 2. Massive andesite, upper Amulet "rhyolite" formation

Sample no.	GT157	GT159	GT192	GT194	GT257B	GT319	GT426	GT434	GT454	GT117A	GT419	GT422	GT13	GT13A	GT13B
Symbol	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Density	2.74	2.77	2.75	2.75	2.78	2.75	2.73	2.80	2.66	2.76	2.72	2.73	2.78	2.77	2.74
Wt. %	65.80	66.16	64.50	65.14	58.32	62.36	67.82	58.93	64.71	60.33	63.71	67.80	65.06	66.13	63.33
Al2O3	13.68	13.32	13.97	13.85	15.88	14.25	13.92	14.88	13.98	16.34	15.70	14.20	13.62	13.74	16.40
Fe2O3	7.53	7.56	8.02	8.17	10.47	9.07	7.00	11.41	7.45	9.32	7.21	6.18	10.39	9.46	6.23
MgO	3.20	3.04	2.64	3.10	3.67	3.69	2.15	3.70	2.40	2.77	3.78	2.45	2.66	2.34	1.19
CaO	1.67	3.18	1.98	1.89	1.61	1.81	1.31	2.56	2.55	1.41	0.57	1.04	2.04	2.02	4.94
Na2O	3.71	3.87	5.00	4.57	3.83	4.26	5.27	4.73	5.12	6.12	5.53	3.97	3.36	4.02	5.52
K2O	1.11	0.49	0.36	0.41	0.76	0.93	0.54	0.36	0.20	0.10	0.51	1.19	0.11	0.08	0.21
TiO2	0.91	0.90	0.92	0.93	1.36	1.28	0.85	1.32	0.96	1.53	0.82	0.67	0.91	0.89	0.98
P2O5	0.25	0.24	0.27	0.24	0.34	0.34	0.25	0.45	0.27	0.35	0.21	0.18	0.27	0.27	0.28
MnO	0.11	0.09	0.21	0.12	0.30	0.20	0.14	0.20	0.17	0.19	0.13	0.22	0.20	0.18	0.11
S	0.00	0.00	0.009	0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.05	0.00	0.00	0.00
PPM	Ba	391	178	144	0	237	227	176	181	74	185	909	77	63	76
	Cr	0	0	0	0	0	0	0	0	0	1	0	0	2	0
	Zr	168	161	161	144	134	168	116	150	149	233	205	168	161	203
	Sr	77	171	46	66	57	56	46	78	44	46	37	89	90	195
	Rb	12	8	2	19	9	6	2	9	0	0	22	0	0	0
	Zn	69	53	78	161	102	96	110	59	118	108	282	74	73	14
	Cu	0	35	0	9	0	0	0	0	0	0	58	0	0	0
	Ni	11	0	0	5	0	0	0	0	0	0	1	0	0	0
Total		98.05	98.92	98.01	98.48	96.58	99.31	98.59	97.89	98.52	98.24	98.13	98.68	99.17	99.26

Table 3, Mottled and white silicified andesite, upper Amulet "rhyolite" formation

Sample no.	GT11	GT122	GT124B	GT174	GT178	GT208	GT209	GT233	GT304	GT306	GT308	GT337	GT339	GT357	GT362	GT369	GT432
Symbol	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Density	2.75	2.74	2.77	2.74	2.74	2.71	2.71	2.69	2.71	2.74	2.80	2.70	2.72	2.73	2.68	2.74	2.76
Wt. %	67.80	68.39	70.54	70.19	67.82	69.08	72.70	74.36	69.79	68.02	62.16	70.77	70.16	68.52	71.89	71.19	68.63
SiO ₂	13.20	13.17	12.52	13.41	13.45	13.98	12.87	11.91	13.42	13.15	14.10	13.38	12.81	12.87	13.44	12.41	13.51
Al ₂ O ₃	7.20	7.46	5.91	4.90	6.13	5.54	4.16	4.35	4.27	6.62	8.75	3.72	5.47	5.59	3.59	5.90	5.47
Fe ₂ O ₃	2.12	1.77	1.39	1.15	2.30	2.39	1.83	2.10	0.82	2.16	2.65	1.45	2.02	1.69	1.67	1.10	1.32
MgO	2.28	1.81	3.30	3.21	2.80	0.89	0.67	0.59	3.00	2.10	4.21	1.58	1.90	2.11	1.22	3.11	2.33
CaO	4.79	4.34	4.16	4.90	4.33	5.32	4.27	4.66	5.31	4.00	3.61	4.79	3.81	1.68	6.24	2.89	4.87
Na ₂ O	0.63	0.31	0.08	0.32	1.04	0.49	1.01	0.21	0.95	1.24	1.37	1.70	1.47	4.55	0.37	1.92	1.39
K ₂ O	0.68	0.64	0.54	0.57	0.88	0.73	0.67	0.58	0.77	0.74	1.17	0.81	0.59	0.59	0.72	0.61	0.73
TiO ₂	0.13	0.17	0.13	0.14	0.26	0.22	0.18	0.16	0.20	0.21	0.31	0.19	0.16	0.14	0.20	0.16	0.20
P ₂ O ₅	0.13	0.16	0.17	0.08	0.11	0.16	0.15	0.15	0.09	0.16	0.21	0.11	0.15	0.24	0.17	0.14	0.12
MnO	0.03	0.00	0.01	0.00	0.00	0.08	0.02	0.00	0.00	0.00	0.00	0.0	0.00	0.06	0.02	0.01	0.00
PPM																	
Ba	299	116	67	135	390	149	295	85	196	363	268	609	441	2583	109	249	275
Cr	0	10	0	11	0	0	0	0	1	0	5	0	0	0	0	0	0
Zr	172	194	196	198	157	179	163	163	168	164	134	182	65	58	66	196	170
Sr	74	57	125	140	75	29	28	33	111	88	113	56	87	73	45	68	65
Rb	6	3	0	2	13	0	16	0	6	16	19	21	14	50	3	31	21
Zn	36	76	54	20	49	54	88	144	2	86	103	40	66	87	61	58	20
Cu	101	0	28	0	14	0	2	119	0	0	0	20	4	8	14	0	0
Ni	22	35	0	27	2	0	7	8	0	9	0	0	2	0	0	5	2
Total	99.09	98.28	98.60	98.94	99.20	98.93	98.59	99.14	98.68	98.47	98.61	98.60	98.64	98.36	99.56	99.51	98.64

Table 3, continued

Sample no.	GT450	GT361	GT422	GT455	BC11	BC12	BC14	BC16
Symbol	●	●	●	●	●	●	●	●
Density	2.72	2.73	2.73	2.78	2.76	2.78	2.85	2.74
Wt. % SiO ₂	68.68	71.08	67.80	65.82	68.32	66.53	63.33	68.10
Al ₂ O ₃	14.00	12.10	14.20	13.55	13.61	14.11	16.40	14.44
Fe ₂ O ₃	5.94	6.33	6.18	7.35	6.49	7.70	6.23	5.33
MgO	2.15	2.30	2.45	2.00	1.79	1.91	1.19	2.29
CaO	1.48	1.45	1.04	3.70	3.28	3.30	4.94	2.21
Na ₂ O	5.77	3.36	3.97	4.88	4.34	3.13	5.52	5.12
K ₂ O	0.09	1.62	1.19	0.87	0.15	0.55	0.21	0.18
TiO ₂	0.93	0.54	0.67	0.85	0.82	0.86	0.98	0.85
P ₂ O ₅	0.25	0.13	0.18	0.22	0.23	0.23	0.28	0.23
MnO	0.16	0.18	0.22	0.15	0.15	0.13	0.11	0.10
S	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.0
PPM								
Ba	99	343	909	363	89	196	76	77
Cr	0	0	0	0	0	0	0	0
Zr	160	181	205	169	184	188	203	174
Sr	39	56	37	112	178	166	195	80
Rb	0	23	22	9	0	6	0	1
Zn	58	68	282	36	44	22	14	31
Cu	0	0	58	0	0	0	0	0
Ni	0	0	1	0	0	0	0	0
Total	99.49	99.21	98.13	99.46	99.24	98.51	99.26	98.91

Table 4. Silicified white fragments, and altered vitrophyre, upper Amulet "rhyolite"

Sample no.	GT 2	GT 4	GT13	GT366	GT367	GT374	GT375	GT418	BC7A	BC7B	GT 6	GT10	GT119B	GT162	GT307	GT408
Symbol	A	A	A	A	A	A	A	A	A	A	X	X	X	X	X	X
Density	2.70	2.64	2.67	2.66	2.70	2.64	2.55	2.67	2.70	2.69	2.74	2.76	2.76	2.70	2.77	2.63
Wt. %	78.17	79.31	74.08	78.64	81.00	79.49	77.49	77.26	79.00	79.04	67.94	69.95	72.18	78.67	64.69	81.48
SiO2	10.75	11.21	12.42	10.82	10.13	10.94	11.93	11.66	10.28	10.51	13.51	11.99	12.32	9.78	15.04	10.90
Al2O3	2.67	1.25	3.60	1.75	1.91	0.52	1.65	1.73	2.04	1.81	6.43	8.52	4.79	3.64	6.68	0.27
Fe2O3	1.54	0.58	1.14	0.85	0.92	0.0	0.83	0.88	0.17	0.24	2.54	3.30	0.98	1.17	1.68	0.07
MgO	0.45	0.59	0.96	0.51	0.23	1.43	0.78	1.24	3.92	3.03	1.61	0.42	2.73	1.01	3.57	0.41
CaO	1.87	5.56	5.12	5.09	1.77	5.87	5.81	4.88	3.49	3.90	3.18	0.11	3.54	3.97	3.62	5.85
Mn2O	1.97	0.39	1.23	0.46	2.42	0.39	0.64	1.15	0.23	0.35	1.61	2.08	0.67	0.41	2.06	0.30
TiO2	0.53	0.56	0.52	0.60	0.46	0.49	0.58	0.59	0.63	0.62	0.57	0.54	0.54	0.25	0.71	0.47
P2O5	0.15	0.15	0.13	0.18	0.11	0.13	0.16	0.17	0.18	0.18	0.13	0.14	0.13	0.03	0.18	0.12
MnO	0.07	0.07	0.11	0.05	0.04	0.14	0.05	0.06	0.04	0.04	0.32	0.21	0.14	0.06	0.16	0.01
S	0.01	0.00	0.20	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.06	0.0	0.00	0.00	0.00	0.00
PPM																
Ba	296	164	209	115	311	95	118	539	79	97	1199	293	258	83	483	80
Cr	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Zr	155	165	182	151	143	164	161	155	124	126	204	160	201	200	209	165
Sr	9	20	48	39	19	60	27	64	135	109	71	0	125	41	157	48
Rb	39	3	11	5	34	4	4	11	7	7	22	45	11	4	38	0
Zn	363	178	10	146	567	0	6	0	0	0	110	181	24	15	59	0
Cu	39	11	36	1	0	0	0	0	0	0	39	1	0	7	35	0
Mi	3	8	5	6	18	5	9	0	4	0	4	11	0	2	7	9
Total	98.29	99.74	99.56	99.01	99.12	99.33	99.96	99.71	100.04	99.75	98.08	97.33	98.08	99.03	98.50	100.02

Table 5, Analyses of rhyolite lava-dome and chloritic flows, lower
Amulet "rhyolite" formation

Sample no.	GT131	GT600	GT601	GT45	GT75	GT77
Symbol	■	■	■	●	x	●
Density	2.78	2.76	2.74	2.77	2.77	2.79
Wt. % SiO ₂	72.92	73.76	77.28	72.15	70.51	68.76
Al ₂ O ₃	11.56	10.98	9.86	12.07	12.45	12.36
Fe ₂ O ₃	9.05	9.21	7.68	8.61	9.74	10.85
MgO	1.68	2.48	2.09	2.81	2.64	2.99
CaO	0.06	0.05	0.05	0.18	0.18	0.19
Na ₂ O	0.03	0.08	0.03	0.13	0.13	0.10
K ₂ O	2.03	1.44	1.42	1.87	1.85	1.61
TiO ₂	0.26	0.25	0.22	0.51	0.55	0.55
P ₂ O ₅	0.01	0.04	0.02	0.12	0.13	0.13
MnO	0.18	0.15	0.13	0.12	0.11	0.13
S.	0.12	0.00	0.00	0.0	0.00	0.00
PPM Ba	387	325	366	514	523	536
Cr	0	0	0	0	0	0
Zr	248	244	200	174	184	181
Sr	0	0	2	1	1	0
Rb	26	13	20	24	26	18
Zn	1027	57	32	56	32	36
Cu	111	26	34	0	0	10
Ni	0	0	0	0	0	0
Total	98.13	98.51	98.86	98.67	98.37	97.75

Table 6, Analyses of the Northwest rhyolite, Rusty Ridge andesite and Amulet Andesite formations
(from De-Rosen Spence, 1976)

	Rusty Ridge andesite				Amulet andesite				Northwest rhyolite			
Wt. % oxides	1		2		1		2		mean (avg. 19 analyses)		Std. Dev.	
	mean (12 analyses)		mean (12 analyses)		mean (12 analyses)		mean (12 analyses)		mean (avg. 19 analyses)		Std. Dev.	
SiO ₂	60.50	52.60	57.32	2.27	62.28	52.36	57.59	2.86	75.01			
TiO ₂	13.98	17.06	15.14	1.05	14.57	17.25	15.88	0.73	14.01			
*FeO	10.40	14.70	11.25	1.32	6.93	10.62	8.22	1.09	3.83			
MgO	2.52	6.74	4.55	1.36	3.83	5.35	4.37	0.79	1.11			
CaO	4.94	4.9	4.37	1.02	4.27	8.16	6.94	1.56	0.04			
Na ₂ O	5.45	1.63	4.64	1.08	4.72	3.38	3.74	0.76	4.84			
K ₂ O	0.25	0.92	0.47	0.04	1.33	0.59	0.81	0.44	0.30			
TiO ₂	1.31	1.51	1.37	0.12	1.14	1.42	1.25	0.24	0.39			
MnO	0.14	0.44	0.19	0.84	0.13	0.21	0.18	0.03	0.10			
Total	99.44	99.79			99.21	99.34			99.99			

*FeO as total iron

Table 7: Trace element analyses

Sample no.	values in ppm									
	DUP-duplicate, ()-AA analyses									
	Rb 2.8	Y 2.3	Sr 3.0	Zr 7.0	Cu 6.0	Zn 5.0	Ba 40.0	Cr 5.7	Ni 2.6	
BC7A	4.1	41.4	132.7	168.3	0	6.6	89.5	3.3	10.7	
BC11	4.0	44.9	151.2	230.5	0	74.1	126.7	3.8	8.1	
BC13	2.5	43.7	81.8	191.8	3.9	107.6	90.7	0	8.4	
BC14	2.7	45.1	183.3	267.5	0	45.7	84.2	1.5	13.8	
BC16	3.3	48.6	76.8	234.3	0	61.5	97.2	0	8.7	
GT2	39.7	37.1	11.0	195.5	45.5	376.6	258.3	3.2	8.6	
GT4	7.2	38.3	25.9	213.9	24.5	230.8	97.6	.3	8.0	
GT10	36.0	50.2	4.0	206.4	8.6	218.3	243.5	1.9	7.7	
GT11					(90.0)	(75.)			(5.0)	
GT13	9.4	45.7	80.8	225.6	81.5	75.7	235.8	5.9	10.6	
GT45	17.2	48.4	55.1	231.0	10.5	50.3	195.5	0	8.4	
GT45	26.9	49.2	4.7	220.4	.8	81.6	427.1	0	6.7	
(DUP)										
GT45	25.9	46.9	4.1	217.9	.6	80.1	416.0	.2	8.3	
GT75	26.4	51.1	4.8	232.3	2.0	57.5	426.0	0	7.9	
GT117A	2.8	35.1	41.9	184.1	0	149.6	102.3	0	8.2	
GT122	7.3	41.5	57.9	235.5	1.6	106.0	113.1	.2	12.3	
GT124B	2.1	47.5	109.8	238.6	1.2	81.8	74.9	0	8.1	
GT131	31.6	62.9	4.7	299.9	115.6	965.6	325.8	0	7.7	
GT174	4.3	49.8	135.5	258.8	0	51.1	134.5	1.0	8.1	
GT178	17.5	47.5	74.0	203.7	8.6	81.0	310.6	01.4	8.9	
(DUP)										
GT178	17.3	45.3	73.9	199.2	5.7	77.5	295.6	0	8.8	
GT208	8.1	48.8	39.0	236.1	0	82.5	132.5	0	7.7	
GT233	3.3	53.2	32.3	216.8	127.3	164.8	80.8	1.8	7.5	
GT257B	18.7	46.8	65.8	188.7	1.6	189.4	186.9	1.2	8.3	
GT304	11.7	46.5	111.0	360.3	0	38.2	184.1	0	8.9	
GT319	11.9	37.7	52.2	156.4	0	137.1	213.4	0	8.4	

Table 7: Trace element analyses (continued)

Sample no.	Rb 2.8	Y 2.3	Sr 3.0	Zr 7.0	Cu 6.0	Zn 5.0	Ba 40.0	Cr 5.7	Ni 2.6
GT337	23.8	41.9	57.1	223.2	0	64.2	510.5	.8	8.0
GT374	4.5	42.1	60.3	207.3	6.3	6.0	116.7	2.3	7.4
GT432	22.3	49.2	61.6	227.2	0	71.4	236.2	0	8.3
GT434	5.2	45.8	47.3	147.6	6.0	148.7	154.0	6.3	11.7
GT450	1.4	47.0	42.3	206.2	0	72.3	94.2	.4	8.2
GT454	2.7	41.4	76.2	201.5	0	93.0	150.9	.07	8.4
GT455	9.5	47.2	104.2	206.2	0	76.3	291.7	2.3	8.8
GT600	19.2	62.2	3.8	280.4	45.8	95.8	292.9	0	7.6

Table 8, Duplicate and Reference analyses

Sample no.		GT-13	Dupl.	LU1 (1)	STD. (2)
Wt. %	SiO ₂	74.08	73.32	49.98	49.13
	Al ₂ O ₃	12.42	12.35	15.41	15.62
	Fe ₂ O ₃	3.60	3.53	8.86	9.16
	MgO	1.14	1.10	4.02	4.26
	CaO	0.96	0.96	10.38	10.36
	Na ₂ O	5.12	4.93	1.99	1.97
	K ₂ O	1.23	1.22	0.48	0.43
	TiO ₂	0.52	0.52	0.72	0.76
	P ₂ O ₅	0.13	0.14	0.06	0.08
	MnO	0.11	0.11	0.19	0.19
	S	0.20	0.18	0.03	0.09
PPM	Ba	209	213	246	234
	Cr	0	0	20	8
	Zr	182	177	39	63
	Sr	48	56	163	168
	Rb	11	16	13	15
	Zn	10	7	79	104
	Cu	36	24	37	95
	Ni	5	0	29	50
Total		99.56	98.42	92.21	92.10

(1) Ottawa University analysis of LU1

(2) Analysis of LU1 provided by J.M. Franklin

LEGEND

INTRUSIVE ROCKS

Late Mafic Intrusions

- 8 a. Fine to coarse grained diorite.
b. Plagioclase porphyritic andesite.

intrusive contact

Felsic Synvolcanic Intrusions

- 7ob a. Flow banded, microspherulitic rhyolite.
b. Massive, aphanitic white rhyolite ± albite and quartz phenocrysts.
c. Quartz-feldspar porphyry, brecciated and silicified.

Mafic Synvolcanic Intrusions

- 6a a. Aphanitic, brown basalt.
bc b. Massive, fine to medium-grained andesite-dacite.
c. Amygdaloidal, "pitted" andesite-dacite.

intrusive contact

METAVOLCANIC and METASEDIMENTARY ROCKS

Tuffaceous Metasediment

- 5 a. "C" contact tuff. Pyritic, thin bedded to laminated cherty, andesitic ash tuff.

Amulet (Millenbach) Andesite

- 4a a. Massive, medium to fine-grained, plagioclase porphyritic flows ± amygdules.
b. Massive, medium to fine-grained, plagioclase porphyritic pillowed flows ± amygdules.
c. Pillow-flow brecciated andesite. Angular andesite blocks in a chert matrix.

Tuffaceous Metasediment

- 3 a. Main contact tuff. Pyritic, thin bedded to laminated cherty, andesitic ash tuff.

Amulet "Rhyolite"

- 2a a. Ribbon to blocky white fragment breccia. Hybrid breccia of variably silicified angular, white, amygdaloidal andesite blocks and ribbon forms in a chlorite-quartz and/or andesite matrix.
b. Angular white fragment breccia. Discordant zones of

LEGEND

Intrusive Rocks

- ☐ Diorite
- ☐ Rhyolite
- ☐ Quartz-feldspar porphyry

Volcanic Flow Rocks

- ☐ Amulet Andesite
- ☐ Amulet Rhyolite
- ☐ Rusty Ridge Andesite

☐ Dalmatianite

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Dalmatianite

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Amulet "Rhyolite"

- ☐ 2a a. Ribbon to blocky white fragment breccia. Hybrid breccia of variably silicified angular, white, amygdaloidal andesite blocks and ribbon forms in a chlorite-quartz and/or andesite matrix.
- ☐ b b. Angular white fragment breccia. Discordant zones of silicified, angular, amygdaloidal andesite fragments in a matrix of fine andesite fragments, chlorite and quartz.
- ☐ c c. Massive, white to grey-green weathered, silicified andesite. Commonly plagioclase porphyritic, quartz amygdaloidal and weakly flow laminated.
- ☐ d d. Massive, brown to green weathered, amygdaloidal, plagioclase porphyritic andesite. Commonly mottled.
- ☐ e e. Massive, aphanitic, brown, chlorite-quartz amygdaloidal intermediate flow(s). Chloritized and locally silicified.
- ☐ f f. Brown, rubble breccia.
- ☐ g g. Quartz amygdaloidal, microspherulitic rhyolite. Chloritized, sericitized and locally microbrecciated.
- ☐ h h. Flow banded to massive, quartz amygdaloidal, microspherulitic rhyolite. Chloritized, sericitized and microbrecciated.
- ☐ i i. Beecham breccia. Thick bedded to laminated reworked volcaniclastic. Silicified.

Rusty Ridge Andesite.

- ☐ a a. Massive, brown, fine-grained, quartz amygdaloidal flows. Cooling units RR1, RR3, RR5.
- ☐ b b. Pillowed andesite. Densely packed irregular pillows with radial quartz amygdules and fractures. Cooling units RR2, RR4.
- ☐ c c. Quartz amygdaloidal, pillowed andesite. Silicified polygonal fractures, pillow rims and interpillow hyaloclastite. Cooling unit RR6.
- ☐ d d. Pillowed, quartz amygdaloidal andesite. Silicified concentric cooling laminations and pillow margins. Cooling unit RR7.
- ☐ e e. Massive to laminated, weakly amygdaloidal flows and flow breccia. Cooling unit RR8.
- ☐ f f. Pillow-flow breccia, weakly silicified.

MAP SYMBOLS

- Lineation
- Joint
- Schistosity, fracture cleavage
- Strike and dip of beds or geologic contact

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[] Quartz-feldspar porphyry

Volcanic Flow Rocks

[] Amulet Andesite

[] Amulet Rhyolite

[] Rusty Ridge Andesite

Dalmatianite

Dalmatianite

Duprat Twp

Dufresnov Twp

Corbett
Mine

RRI

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Dalmatianite

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- ☐ d. Massive, weakly amygdaloidal, concentric cooling laminations and pillow margins. Cooling unit RR7.
- ☐ e. Massive to laminated, weakly amygdaloidal flows and flow breccia. Cooling unit RRB.
- ☐ f. Pillow-flow breccia, weakly silicified.

MAP SYMBOLS

- Lineation
- Joint
- Schistosity, fracture cleavage
- Strike and dip of beds or geologic contact
- Pillow lava, strike and top direction
- Shear zone
- Fault, located, approximate
- Geologic boundary, defined and assumed
- Flow contact
- Spherulite or amygdale zone
- Silicified and chloritized, autobrecciated vitrophyre
- Breccia
- Flow breccia, intrusive breccia

Alteration Symbols

- Insta breccia, chlorite vein, vein network, with quartz envelopes.
- Mottled texture. Carbonate-epidote-quartz alteration, weak and intense.
- Shear or fault with chloritic or sericitic-quartz envelope.

Abbreviations

a amygdale

Buttercup Hill

..... Spherulite or amygdale zone

//// Silicified and chloritized, autobrecciated
vitrophyre

△△ Breccia

--- Flow breccia, intrusive breccia

Buttercup Hill

Alteration Symbols

▲▲ In situ breccia, chlorite vein, vein network,
with quartz envelopes.

○ ○ ○ ○ Mottled texture. Carbonate-epidote-quartz
○ ○ ○ alteration, weak and intense.

~~~~~ Shear or fault with chloritic or sericitic-
quartz envelope.

Abbreviations

a amygdale

s spherulite

CJ columnar joint

py pyrite

ccp chalcoppyrite

CH chert

CHL chlorite

Sil silicified

Sources of Information

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