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# Geology of the Timber Top Volcanic Subgroup (Featherbed Volcanic Group) and Associated Rocks, Mount Mulligan Area, North Queensland



by

*B. S. Oversby, I. P. Rienks, & D. E. Mackenzie*

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B.S. Oversby[1], I.P. Rienks[2], and D.E. Mackenzie[3]

[1] Australian Geological Survey Organisation, Canberra (now retired).
[2] Geological Survey of Queensland, Department of Mines and Energy, Brisbane.
[3] Australian Geological Survey Organisation, Canberra.

*A contribution to the National Geoscience Mapping Accord*
*NORTH QUEENSLAND PROJECT*

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# SUMMARY

The Mount Mulligan area is underlain by a basement of Silurian-Devonian turbiditic sedimentary rocks, a suite of Late Carboniferous to Early Permian volcanic and intrusive rocks, and coal-bearing Late Permian to Early Triassic terrestrial sedimentary rocks. The distribution and relationships of these units have been reassessed in detail, and the results are illustrated in Plate 1.

The Hodgkinson Formation in the Mount Mulligan area consists mostly of turbiditic arenite and argillite, with minor rudite, chert, and mafic extrusive rocks. These rocks are multiply deformed and are cut by several north-northwesterly trending mylonite and breccia zones, some of which have localised Au ± Sb mineralisation.

Volcanic and intrusive rocks of the Late Carboniferous-Early Permian Timber Top Volcanic Subgroup range in composition from andesite and granodiorite to predominant rhyolite/granite. They are intimately associated with one another, and are all of similar age. Some units contain recognisable variations or subunits, and some units may be distal or proximal equivalents of others; all are described in detail. The environments of deposition of the volcanic units are constrained, where possible, using lithology, distribution, grainsize, clast characteristics, and depositional structures. Significantly, several units appear to be extrusive in some parts but intrusive in others, so that the eruptive sources of some strata are probably exposed. Remobilised welded ignimbrites and intrusive pyroclastic bodies have been recognised in the area for the first time. Parts of some units may have been emplaced by pyroclastic surges. Rocks at several localities appear to have been deposited in a near-vent environment; locations of eruptive vents show a strong strucural control, notably by major faults. The major intrusive units appear to have been emplaced with "bell-jar" geometry - disc-like bodies with peripheral feeder dykes.

The local structure of the igneous rocks closely reflects the regional structure, in particular a set of major north-northwesterly trending faults, and is strongly rectilinear. This contrasts with the circular structures in the adjacent volcanic sequences of similar age (Djungan and Wakara Cauldrons). Post-eruption juxtaposition due to displacement along faults and differences in relative syn-eruption volcanic subsidence are considered as explanations of this anomalous character. The northeastern segment of the fracture system bounding the Mount Mulligan Cauldron is marked by exposed dykes. The base of the eruptive sequence varies little from 600 m, there is little marginal oversteepening of strata, and much basement is exposed. This evidence suggests that relative subsidence was probably much less than in the adjacent Wakara Cauldron, for example. The western margin of the Mount Mulligan Cauldron is overprinted by the Wakara Cauldron, indicating an age greater than ~280 Ma.

The terrestrial sedimentary rocks consist of two previously recognised formations, the Mount Mulligan Coal Measures and Pepper Pot Sandstone. New type and auxiliary sections are defined, a previously documented subdivision has been extensively revised, and all units and subunits have been described in detail. The stratigraphy is more complex than previously documented, principally because many of the previously recognised lithological changes are gradational, both laterally and vertically. Depositional environment for the lowest part of the sequence was juvenile alluvial (fans, debris flows). This was succeeded first by a period of lacustrine deposition, then one of mature (meandering) alluvial deposition. Detritus during these stages was derived from the north and northeast. A period of drainage rejuvenation followed, with deposition in alluvial fan and/or proximal braidplain environments, during which some detritus was derived from the Featherbed Cauldron Complex, which had become elevated, to the west. The final phase saw deposition of detritus, derived mainly from the east, in a distal braidplain or sheet-floodplain environment.

Re-activated movement on pre-existing north-northwesterly trending faults was the dominant mechanism of basin formation and sediment accommodation. Distribution and thickness variations of various units and subunits of the sequence indicate periodic disturbance by syn-depositional faulting. Post-depositional oversteepening has occurred along some of the major north-northwesterly trending faults, but the main folding episode was probably due to post-Triassic uplift and warping.

Coal resource potential is very low, because of the thinness and low quality of the four seams present. There may be some potential for Au-Sb deposits along the Retina and Kondaparinga fault sysems. Extensive areas of sericitic, kaolinitic, and brecciation-related siliceous hydrothermal alteration along and adjacent to major faults are potentially prospective for Au and/or base metals.

# INTRODUCTION

Mount Mulligan is a prominent mesa located about 60 km northwest of Mareeba, in northeast Queensland, and has scenic, historical, archaeological and geological features which make it unique in the region. Mount Mulligan also has the unfortunate distinction of being the site of Australia's worst coal-mining disaster when in 1921, 75 workers perished underground after an explosion (*e.g.* Bell, 1980). Further interest derives from the position of Mount Mulligan, near the northeastern extremity of the Featherbed cauldron complex, a series of volcanic rocks of unusual character and of uncertain origin.

Access is by unsealed roads from the townships of Dimbulah or Mount Carbine to the former township of Mount Mulligan or to "Kondaparinga" homestead respectively (Plate 1). However, access to the area immediately west of Mount Mulligan requires cross-country traversing.

The Mount Mulligan massif is 18 km long, reaches 6.5 km wide at its northern end, and trends north-northwest. The summit plateau occupies about 50 km$^2$; most of this area appears to represent an old land surface, at an elevation of approximately 700 m, whereas the surrounding country averages about 500 m. The mesa has been incised by the north-northwest flowing Gorge Creek, a tributary of the Hodgkinson River.

Mount Mulligan is bounded by spectacular red cliffs and steep, benched slopes along all but its central western portion, and commonly comprises two tiers. The lower tier typically rises between 100 and 200 m sheer above a narrow pediment, and commonly extends laterally for several uninterrupted kilometres.

The objectives of this investigation are threefold: to re-evaluate relationships between the sedimentary rocks of Mount Mulligan and the late Palaeozoic igneous rocks; to clarify the affinity of these igneous rocks; and lastly to establish constraints on the contribution of these rocks and of the nearby Featherbed Volcanic Group to the Mount Mulligan sedimentary sequence. This investigation forms part of an ongoing AGSO/GSQ strategy aimed at elucidating the Late Palaeozoic tectono-magmatic evolution of northeastern Queensland, and at developing a predictive understanding of associated mineralisation (Mackenzie, 1993; Mackenzie, in prep.). In this context, the Mount Mulligan area was recognised as potentially containing an important record of events between the main phases of Late Palaeozoic igneous activity and later Mesozoic-Cainozoic cratonic sedimentation.

While this report is designed to be read with the figures provided, reference to the published map of Mackenzie & others, (1993) will allow the reader to gain a better appreciation of the regional geological context, particularly the structural environment and magmatic history. All grid references in the following text refer to the Australian Map Grid (AMG), are prefixed by GR and apply to the Mount Mulligan 1:100 000 sheet area, Sheet 7864. Topographic names which do not appear on this map or that of Mackenzie & others (1993) are from the map of Ball (1912).

# ACKNOWLEDGMENTS

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## HODGKINSON FORMATION

Basement to the Mount Mulligan sequence consists of the multiply deformed (to intensely deformed locally), but weakly metamorphosed Hodgkinson Formation (de Keyser & Lucas, 1968; Arnold & Fawckner, 1980). The Hodgkinson Formation was not studied as part of this investigation, but has been examined in detail during GSQ remapping of the area (Halfpenny & others, 1987), and the following data have been drawn from this source.

Hodgkinson Formation exposure in the Mount Mulligan area is dominated by turbiditic arenite and argillite, with subordinate rudite, chert, and basic extrusives, better developed east and southeast of the massif. Three units have been mapped on the basis of the relative proportions of the arenite and argillite.

The clastic components of the Hodgkinson Formation appear to be of diverse provenance, including scattered carbonate. Some clasts were clearly deformed or metamorphosed prior to deposition.

A notable feature of the Hodgkinson Formation is that it is traversed by north-northwest to northwest trending linear mylonite and breccia zones, spaced at intervals of 5 to 10 km. Important vein-type Au ± Sb deposits appear to occur in these zones at Thornborough and Kingsborough, about 20 km southeast of Mount Mulligan township, and elsewhere (*e.g.* de Keyser & Lucas, 1968; Murray, 1975). Other parts of the Hodgkinson Formation are marked by barren quartz stringers, veinlets, and scattered substantial reefs, mostly with arenite hosts.

## FEATHERBED VOLCANIC GROUP

The volcanic rocks which form extensive, rugged and inaccessible terrain west, southwest and south of Mount Mulligan were previously referred to as the "Featherbed Volcanics" (Branch, 1966; de Keyser & Lucas, 1968), but have been subdivided and raised in status to Featherbed Volcanic Group (Mackenzie & others, 1993; Mackenzie, 1993). The Featherbed Volcanic Group has been deposited in a succession of overlapping subsidence structures, within each of which is a distinct assemblage of volcanic rocks, and which together comprise the Featherbed Cauldron Complex. Each of these assemblages has been assigned subgroup status (Mackenzie & others, 1993; Mackenzie, 1993). One of the component subsidence structures of the Featherbed cauldron is the Mount Mulligan Cauldron, which hosts the Timber Top Volcanic Subgroup.

## Timber Top Volcanic Subgroup (Mount Mulligan Cauldron)

Outliers of volcanic and subvolcanic rocks which rest unconformably on Hodgkinson Formation west of the northern portion of Mount Mulligan have been assigned to the Timber Top Volcanic Subgroup. These rocks, previously assigned to the "Featherbed Volcanics", crop out within a discrete volcano-tectonic subsidence structure, the Mount Mulligan Cauldron (Mackenzie & others, 1993; Mackenzie, 1993). They are overlain by, and petrologically and geochemically distinct from, rocks of the Early Permian Yongala Volcanic Subgroup within the nearby Djungan Cauldron (Mackenzie & others, 1993; Mackenzie, 1993; see below). Formation of the Mount Mulligan Cauldron is believed to have been later than that of the Boonmoo Sag (306-308 Ma) and the Wolfram Cauldron (~300 Ma), and before subsidence of the Featherbed Cauldron (290 Ma) and Djungan Cauldron (280 Ma; geochronology reported in Mackenzie & others, 1993 & Mackenzie, 1993; geochronology by Black & Mackenzie, in prep.). Hence, a Late Carboniferous to Early Permian age for these rocks is most likely.

The Timber Top Volcanic Subgroup consists of the named and unnamed units described below.

### Unnamed Andesite (CPa)

**Distribution.** Andesite crops out over a very small area south of Controversy Hill, and in association with the Controversy Hill Rhyolite near the Gipps Hills (GR 715 294).

**Thickness and stratigraphic relationships.** The stratigraphic base of the andesite does not appear to be exposed, hampering thickness estimates. Outcrop relief suggests a minimum of 20 m, and concordance with overlying pyroclastic units suggests a thickness of approximately 80 m. The andesite appears to be one of the lowermost units in the Subgroup. Outcrops in the Gipps Hills area appear to be of a small, faulted-bounded slice.

**Lithology.** The andesite is grey-green or brownish-purple, and sparsely to moderately porphyritic. It contains up to 3% corroded quartz phenocrysts about 2 mm across; and 5 - 10% conspicuous white to pink or buff feldspar phenocrysts up to 3 mm, rare <1 cm subangular microdiorite rock fragments, and rare 1cm calcite-filled amygdales in a pilotaxitic groundmass. The apparent concordance with overlying rocks and the presence of amygdales are consistent with extrusive emplacement.

**Structure.** The andesite is in a structurally disturbed setting, and is invariably moderately to intensely fractured and altered.

## Unnamed Clastic Rocks (CPu)

**Distribution.** This unit has been mapped over about 1 $km^2$ in the northwest of the study area, near Little Watson Creek, and to the southwest of Controversy Hill.

**Lithology.** CPu includes a variety of clastic, pyroclastic, fragmental and primary volcanic rocks. Rudite or breccia is the most abundant lithology: It is pale green, commonly sericitised, and consists of subangular to subrounded sparsely porphyritic rhyolite clasts in a felsic fine-sand sized matrix. Clast sizes range from a few centimetres to boulders 0.8 m diameter.

Vitric tuff exposed at or near the base of the unit in the northwest is fine grained, poorly stratified, contains very sparse quartz crystals, and is of rhyolitic composition. Rare clasts of sparsely porphyritic rhyolite and Hodgkinson Formation arenite are present in a few localities. This tuff may be equivalent to unit CPt, described below.

In the eastern part of the study area, patchily distributed rudite is overlain by rhyolite. The rhyolite is pinkish-, reddish- or purplish-buff, moderately porphyritic, and contains 7-10% white to brownish-pink or pale orange-red feldspar phenocrysts up to 4 mm long, less abundant quartz phenocrysts (up to 1mm), and scattered grains and clumps of chlorite (after biotite?). A crude planar flow banding is apparent in places, as are spherulites. The rhyolite may be intrusive in part.

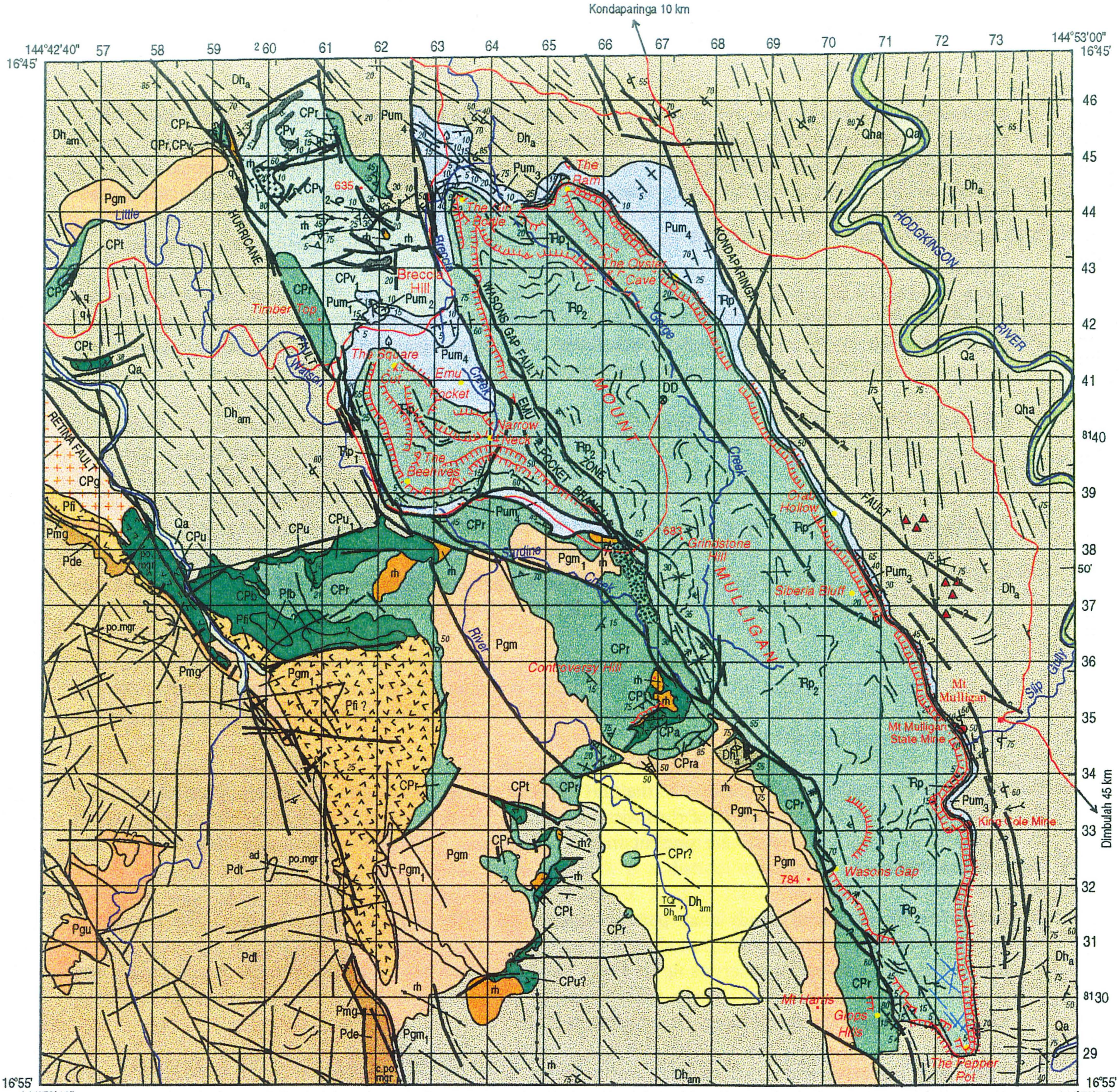
**Thickness, intrusive and stratigraphic relationships.** Total thickness reaches about 50 to 80m. The unit dips gently southward, and overlies Hodgkinson Formation unconformably. Unit CPb and the Controversy Hill Rhyolite appear to overlie CPu unconformably or disconformably; $CPu_1$ appears to grade laterally and downward into CPu. The Mancater Granodiorite and microgranite associated with the Djungan Cauldron ring dyke (Pmg) intrude CPu. Controversy Hill Rhyolite is partly intrusive (see discussion below), and also intrudes CPu.

## Unnamed rudite and rhyolite ($CPu_1$)

**Distribution.** Unit CPu gives way laterally to this unit in the northwest of the Mount Mulligan Cauldron, about 4 km south of Timber Top (Plate 1).

**Lithology.** $CPu_1$ consists mostly of massive clast-supported rudite, with clasts dominated by sparsely porphyritic rhyolite from 3cm to several metres across. Sparsely porphyritic rhyolite similar to that of the clasts forms outcrops of several hundred $m^2$ in the central portion of the unit, but it is unclear whether these are exceptionally large clasts or partially exposed lava flows. The rudite is better stratified in the west, where it overlies CPu, consisting of pebbly lenses, boulder-rich horizons, and a stratum of pebbly volcanogenic arenite.

**Stratigraphic relationships and thickness.** This unit is up to 140m thick, and forms a subhorizontal to gently south to east-northeast dipping sheet, which is unconformable on the Hodgkinson Formation and




0 4 km

Geological boundary

Fault

Fault showing relative horizontal displacement

Intrusive boundary along pre-existing fault

Dyke or vein; ad - andesite, c.po.mgr - coarse-porphyritic microgrtanite, da - dacite, gr - granite, po.mgr - porphyritic microgranite, q - quartz, rh - rhyolite

Syncline, showing plunge

Where location of boundaries, folds and faults is approximate, line is broken; where inferred, queried; where concealed, boundaries and folds are dotted, faults are shown by short dashes

Strike and dip of strata

Vertical strata

Strike and dip of inverted strata

Strike and dip of strata, facing not known

Vertical strata, facing not known

Strike and dip of strata; dip 5° to 15°

Strike and dip of strata; dip 15° to 45°

Strike and dip of strata; dip greater than 45°

Trend-line

Trend-line showing dip 5° to 15°

Trend-line showing dip greater than 45°

Joint pattern

Lineament

airphoto interpretation

Facing of beds

Strike and dip of cleavage

Strike and dip of platy alignment

Vertical platy alignment

Plant fossil locality

DD Diamond-drill hole

Au+Sb, coal mines, abandoned

Escarpment

Minor road

Vehicle track

Walsh Homestead

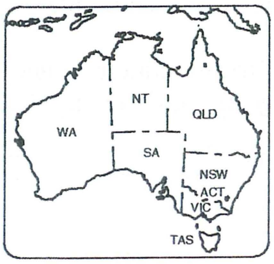
Building

Yard

498 Elevation in metres

All watercourses on this map are intermittent

LOCALITY MAP

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## QUATERNARY (HOLOCENE)

Qha — *Channel alluvium: sand, gravel, silt, mud; soil*

## QUATERNARY

Qa — *Overbank/flood plain alluvium: sand, gravel, silt, mud; soil*

## TERTIARY - QUATERNARY

TQr — *Dissected terrace/flood plain alluvium: sand, gravel, silt, mud; soil; partly consolidated*

## LATE PERMIAN - EARLY TRIASSIC

PEPPERPOT SANDSTONE

$Rp_2$ — *Mid-purple to pale grey, medium to thick-bedded, medium to coarse, commonly gritty or pebbly, lithic-quartz arenite; minor coarse siltstone to fine arenite and massive fine-pebble conglomerate; rare laminated lutite*

$Rp_1$ — *Mid to dark purple or brick-red, poorly sorted, clast- supported polymictic pebble to boulder conglomerate; lesser medium to very coarse lithic-quartz arenite; silicified wood*

## LATE PERMIAN

MOUNT MULLIGAN COAL MEASURES

$Pum_4$ — *Grey to pale brown, massive, polymictic, clast-supported, pebble to cobble conglomerate; very minor medium-bedded to massive lithofeldspathic arenite to lithic arkose*

$Pum_3$ — *Pale to mid-grey, laminated to thin-bedded, micaceous, commonly carbonaceous, siltstone to fine arenite; rare coarser arenite and pebbly arenite; coal; silty coal; medium quartz siltstone with normal grading*

$Pum_2$ — *Pale to mid buff or greyish to greenish-buff, laminated to thin-bedded, fine to medium quartz siltstone with normal grading, carbonaceous detritus, plant remains rare pebbles*

$Pum_1$ — *Mid-grey to buff, medium to thick-bedded, poorly sorted, coarse, pebbly vitric-crystal lithic arenite to fine rudite; nonwelded ignimbrite with charcoal clasts at base*

## EARLY PERMIAN

Pmg — *Pale grey, pink, green-grey, or brown, strongly porphyritic ±hornblende-biotite microgranite*

BUSTLEM MICROGRANITE (280 ±4 Ma)

Pgu — *Medium-pale grey to pink-grey, strongly porphyritic augite?-fayalite-hypersthene (micro)granite*

### FEATHERBED VOLCANIC GROUP

#### DJUNGAN CALDERA - DJUNGAN VOLCANIC SUBGROUP

LUMMA RHYOLITE (281 ±2 Ma)

Pdl, Pdt — *Medium to very dark grey or greenish-grey, intensely welded, lithics-free to very lithics-poor, very crystal-rich to to crystal-rich rhyoliticignimbrite with rare garnet, and pale "coarse-porphyritic" pumice clasts 2-20 cm. Pdt - Tuffisite*

LIGHTNING CREEK RHYOLITE

Pde — *Pale-medium to very dark grey, moderately to intensely welded, lithics-poor to very lithics-poor, crystal-rich to extremely crystal-rich, rhyolitic ignimbrite; clasts of fine, sparsely porphyritic rhyolite 1-5 cm*

#### YONGALA VOLCANIC SUBGROUP

FISHERMAN RHYOLITE

Pfi — *Buff to pink crystal-poor to rich rhyolitic ignimbrite, extensively rheomorphosed, locally brecciated; flow-banded sparsely porphyritic rhyolite, extensively brecciated; lithic-bearing crystal-poor vitric tuff*

MANEATER GRANODIORITE

Pgm — *Pale to medium-dark grey, fine to medium-grained, sparsely porphyritic to equigranular, granophyric biotite-hornblende granodiorite, contains combinations of hypersthene and/or augite, very rare garnet, and enclaves of arenite ( Dh ) and granite ( CPg )*

$Pgm_1$ — *Dark grey to reddish or greenish-grey, very fine to medium-fine, sparsely porphyritic, two (?)-pyroxene-biotite hornblende granodiorite grading into sparsely porphyritic dacite*

## LATE CARBONIFEROUS - EARLY PERMIAN

#### TIMBER TOP ( "MULLIGAN") VOLCANIC SUBGROUP (includes intrusive units)

Plb — *Grey, coarse to very coarse, matrix-supported volcanogenic rudite or lithics-rich, moderately crystal-rich, rhyolitic ignimbrite or co-ignimbrite ground leg deposit*

CPb — *Pink or pink and green, coarse, clast-supported volcanogenic rudite, lithic-rich ignimbrite, or co-ignimbrite lag deposit containing clasts of pink rhyolite up to 30 cm in pink or green matrix*

CPu — *Pale grey to cream, coarse to extremely coarse, proximel(?) lithic-rich rhyolitic ignimbrite and/or volcanogenic rudite with clasts up to several m; minor finer, lithic-rich ignimbrite*

CPu — *Buff to pale green, sparsely porphyritic rhyolite volcanogenic feldspathic-quartz arenite or crystal tuff; poorly welded, lithics-rich, crystal-poor, rhyolitic ignimbrite*

CPa — *Grey-green or brown-purple, sparsely to moderately porphyritic andesite; locally amygdaloidal at top; rare microdiorite enclaves*

CPt — *Pale green to greenish-buff, massive to thin-bedded commonly lithic-rich, rhyolitic fine-ash vitric tuff or volcanogenic siltstone; cross-stratified in places; partly a pyroclastic surge deposit?*

CONTROVERSY HILL RHYOLITE

CPr — *Medium buff to brown, green-grey, or dark grey, sparsely to moderately porphyritic, rhyolite to dacite with well-developed planar lamination,contorted in part, and rare rhyolite to andesite enclaves; where altered*

CPra — *Dark grey, moderately porphyritic biotite rhyolite with common enclaves of porphyritic andesite and microdiorite up to 5 cm*

BRECCIA CREEK RHYOLITE

$CPv_2$ — *Medium purple-red, medium to thick-bedded, poorly sorted, pumice clast-bearing, rhyolitic fine-ash crystal-vitric pyroclastic surge deposit or volcanogenic siltstone*

*Medium buff to grey, unwelded to (locally) intensely welded, lithics-rich to (upward) moderately lithics-rich, crystal-poor to moderately crystal-rich rhyolitic ignimbrite with lithic clasts to 50 cm, rarely 2 m; rare volcanogenic rudite or breccia*

*Intensely altered (sericite and/or kaolinite) and quartz-veined rhyolitic ignimbrite*

*Dark grey to brown-grey, moderately lithics-poor with clasts of black, colourless, brown, or grey obsidian up to 1 m long*

#### OOTANN SUPERSUITE - OOTANN SUITE?

LITTLE WATSON GRANITE

CPg — *Pale pink to white, medium-, even-grained, biotite granite to leucogranite*

## EARLY DEVONIAN - LATE DEVONIAN?

HODGKINSON FORMATION

$Dh_a$ — *Pale to medium grey or brown, thin to very thick-bedded, fine to coarse, feldspathic-quartz arenite, rarely pebbly; minor mudstone*

$Dh_{am}$ — *Pale to medium grey or brown, thin to very thick-bedded, fine to coarse, feldspathic-quartz arenite, pebbly in places; interbedded with mudstone*

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grades laterally and downward into unit CPu. Controversy Hill Rhyolite overlies and/or intrudes $CPu_1$, and it is intruded by two unnamed rhyolite plugs.

## Unnamed Pyroclastic Rocks (CPt)

**Distribution.** A mappable unit of non-welded pyroclastic rocks crops out within 2 km south and southeast of Controversy Hill, and up to 5 km to the southwest. A small inlier of rocks that may be correlated with this unit crops out at GR 648 381.

**Lithology.** The unit consists mainly of stratified, pale green to greenish-buff or rarely mid-buff to brown coarse tuffaceous (vitric) siltstone, probably of rhyolitic composition. Much of the siltstone is rich in pumice and/or lithic clasts, but some lacks larger clasts.

Pumice clasts are angular to subangular, range from subequant to distinctly discoidal, and from coarse sand to small pebble in size. Lithic clasts constitute up to 50% of the rock by volume; most are granule to (sparse) cobble-size clasts of Hodgkinson Formation arenite. Aphyric rhyolite clasts become increasingly abundant higher in the unit, taking the place of clasts of Hodgkinson Formation arenite in places. A silicified matrix is developed in some rhyolite clast-rich rocks. Crystal fragments are typically sparse and small. However, in local arenaceous intervals, crystal fragment up to 3 mm long form up to 20% of the rock. Original vitric-clast and feldspar components of the silty matrix appear at most localities to have been pervasively argillised.

**Depositional structures and their significance.** Stratification where present tends to be diffuse, thin to medium in scale, and tabular to lensoidal. Laminae were observed locally, as were very low-angle cross strata. In the Controversy Hill area, massive siltite is overlain by stratified siltite. Size grading of clasts is apparent in some outcrops, and is predominantly normal, although reverse grading is present at some localities. Discoidal pumice clasts commonly show alignment, but because the adjacent matrix appears to be undeformed, this alignment is likely to be the result of compaction rather than welding.

The lensoidal and low-angle cross strata, and local reverse-grading, suggest that deposition took place from pyroclastic surges, rather than by an air-fall mechanism. However, massive siltite may represent nonwelded low-volume ignimbrite deposits.

**Thickness and intrusive relationships.** Preserved thickness in the Controversy Hill area appears to be 60m. The small inlier to the southwest may represent siltite which has been compacted, welded, recrystallised and sheared during emplacement of the Maneater Granodiorite, rhyolite plugs, and perhaps the Controversy Hill Rhyolite.

## Controversy Hill Rhyolite (CPr, CPra)

**Distribution and type area.** Controversy Hill Rhyolite crops out over a wide area to the west of Mount Mulligan. A proposed type area is about 1 km south of Controversy Hill, immediately north of Grainers Gully, where the unit crops out in two southwest-trending ridges, the highest of which attains an elevation of 675m at GR 679 347. A small area 1 km south-southeast of Controversy Hill is included as CPra.

**Subdivision.** A distinct rock-type of restricted distribution (CPra) tentatively correlated with Controversy Hill Rhyolite because it appears to grade laterally and vertically into rocks typical of the latter is described separately below.

**Lithology.** CPr Consists dominantly of rhyolite to dacite which typically are mid-buff, brownish- or greyish-green, or dark grey in colour, and contain 5-10% of evenly distributed quartz grains; a slightly to distinctly lesser amount of white, buff or pink altered feldspar (mostly 2 mm; up to 4mm), rare augite (up to 2 mm; mostly in more melanocratic rocks), and sparsely scattered subrounded fragments of rhyolitic to andesitic rocks. A wispy, discontinuous foliation is commonly developed, as described below.

 

North of the central dyke zone in the Breccia Creek Rhyolite, the eastern part of that unit is cut by a series of 25° westerly-dipping concordant rhyolitic to dacitic sheets included in Controversy Hill Rhyolite. The sheets are 2-3 m thick, consist of mid to dark greenish-grey rhyolite to dacite, and are sparsely porphyritic. They contain up to about 7% of quartz to 2 mm, subsidiary white feldspar phenocrysts to 5 mm, accompanied by rare sub-millimetre aegirine. The rocks are contortedly flow banded, and contain scattered to locally concentrated clasts of rhyolite and Hodgkinson Formation arenite up to about 5 cm across. These sheets are thinner than typical elsewhere in the Mount Mulligan area.

In the southwestern part of the elongate mass north of Breccia Hill, a gently-dipping sheet of lithic clast-bearing crystal-rich rhyolitic ignimbrite is associated with Controversy Hill Rhyolite. It contains scattered concentrations of coarsely recrystallised "blebs" and irregular patches which may be collapsed and/or recrystallised pumice clasts, and quartz-filled amygdales. The amygdales (or lithophysae) are mostly a few millimetres long, but reach 9 cm long and are locally elongated, with a steep southerly plunge. A rounded clast, about 60 cm across, of abundantly porphyritic (20% quartz, 20% feldspar to 4 mm) microgranite was also observed. This ignimbrite apparently forms a steeply dipping sheet of intrusive origin.

<u>CPra:</u> Consists of dark grey, moderately lithic-rich, welded rhyolitic to dacitic ignimbrite, which contains 20% quartz crystals to 2.5mm; 5% plagioclase and plagioclase aggregates to 2mm; about 3% biotite to 1mm; and 10-15% of lithic clasts. The lithic clasts are dark green-grey, subrounded to angular andesite and microdiorite, containing white feldspar and feldspar aggregates up to 6mm across. This subunit may represent ash-flow material which either has failed to escape from or has collapsed back into a fissure vent.

**Texture and mode of emplacement.** A well-developed fine lamination characterises much of the Controversy Hill Rhyolite. The lamination is locally planar, but is most commonly undulating to intensely contorted, and is generally rather discontinuous, with a wispy to streaky appearance. The lamination typically resembles the extremely attenuated and deformed eutaxitic foliation of intensely welded, subsequently remobilised "rheoignimbrite" or "rheomorphosed ignimbrite" (*cf.* Ekren & others, 1984).

Parts of the Controversy Hill Rhyolite have clear ignimbrite textures, including shards, pumice *fiamme*, pressure "shadows", and broken crystals:

(1) a small inlier south of Controversy Hill (GR673343);
(2) the eastern side of a fault-bounded block north of Controversy Hill (GR664372);
(3) the southwestern side of a steep-sided, dyke-like body 2 km north of Breccia Hill (GR619444); and
(4) a dyke crossing Little Watson Creek at GR559422.

The last two sites, particularly the dyke on Little Watson Creek, have intrusive character and ignimbrite textures, and thus appear to be examples of fissure vents from which the pyroclastic material was not completely expelled, or fissure vents filled as pyroclastic material collapsed back into them.

In other parts of the unit, the foliation is apparently of viscous flow origin, because broken crystals are rare or absent. Rhyolite apparently of flow origin was observed at several localities, the most extensive and notable being in a body that extends east-west between Sardine and Little Watson Creeks. This body appears to be a subhorizontal sheet about 200 m thick, and this part of the Controversy Hill Rhyolite at least lacks any evidence of a pyroclastic origin. However, in many outcrops, especially those intensely recrystallised, the origin of the lamination and the mode of emplacement are uncertain, although some form of intrusive emplacement is probable for the parts of the unit that appear to be steep-sided, and unequivocal intrusive contacts crop out in some places (see below).

**Relationships.** Controversy Hill Rhyolite is intimately associated with Maneater Granodiorite, and in places appears to be intruded by it. In some areas, such as the dyke crossing Little Watson Creek and the ~6.5 km-long Mount Harris dyke south of Mount Mulligan, the two units occupy the same fault-bounded dyke (ring-dyke?) system. Some rocks correlated with Controversy Hill Rhyolite, especially to the south of Sardine Creek, appear to grade almost imperceptibly into intrusive dacite which apparently is a marginal variant of Maneater Granodiorite. This similarity in appearance is due partly to contact metamorphism, which has recrystallised the fine microequigranular "snowflake"- textured Controversy Hill Rhyolite groundmass to a very fine saccharoidal appearance, and partly due to alteration or contact metasomatism by the granodiorite.

 

Controversy Hill Rhyolite appears to incorporate portions of the underlying unnamed pyroclastic rocks (CPt, described above). At GR 659341, about 2 km southwest of Controversy Hill, flow-banded Controversy Hill Rhyolite is interfingered with disturbed highly irregular, locally diffuse pyroclastic rocks. This relationship suggests interaction between intrusive rhyolite and older subjacent unlithified pyroclastic material, implying, in turn, a minimal age difference between the two units.

The Controversy Hill Rhyolite intrudes the Breccia Hill Rhyolite. In the northern part of a dyke-like body north of Breccia Hill (GR 613455), clearly intrusive apophyses of Controversy Hill Rhyolite project upward into adjacent Breccia Creek Rhyolite. Two small (750 m, 350 m in diameter), plug-like bodies of rhyolite correlated with Controversy Hill Rhyolite intrude Hodgkinson Formation 3-4 km south of Controversy Hill.

## Unnamed ignimbrite

Slightly to moderately welded, mid-buff, rhyolitic ignimbrite forms an isolated fault slice, too small to show at map scale, at GR 622387, to the southwest of The Beehives. The ignimbrite contains about 10-12% quartz (up to 4 mm) and 8-10% pale orange-red feldspar (up to 2 mm), is moderately rich in pumice clasts, and contains scarce, small (up to 8 mm) clasts of Hodgkinson Formation rocks and rhyolite. Relict glass shards have been completely pseudomorphed, and have slightly to mildly deformed, robust shapes.

The rock appears to have been faulted into position before intrusion of adjacent Controversy Hill Rhyolite, although it may nevertheless be equivalent to part of the Controversy Hill Rhyolite. However, its moderately crystal-rich, lithics- poor nature is not typical of the Timber Top Volcanic Subgroup, whereas it is similar to the Aroonbeta and Lightning Rhyolites of the Djungan Cauldron (Mackenzie, 1993; Mackenzie & others, 1993).

## Unnamed unit CPb

This unit crops out over an area of about 2 km$^2$ near Little Watson Creek, in the northwest of the Mulligan Cauldron. It consists entirely of coarse, clast-supported rhyolitic breccia which forms a gently southward-dipping sheet up to 100 m thick. Clasts are subangular to angular, pink, buff, or brown-grey, sparsely porphyritic rhyolite up to 30 cm across, and are set in a fine, felsic matrix. In one area, disruption of the breccia appears to be slight, because clasts show only slight relative rotation. The matrix is variably altered, and ranges in colour from pale pink (slight to moderate potassic or phyllic alteration) to dark green (intense chlorite-dominated propylitic alteration) depending on the type and intensity of alteration. It is likely that the unit represents brecciated rhyolite lava flow or flows.

The breccia overlies CPu, and apparently also overlies Controversy Hill Rhyolite, disconformably or unconformably. It is overlain conformably or paraconformably by Pfb, and is inferred to be overlain disconformably by rhyolite tentatively assigned to Fisherman Rhyolite.

## Breccia Creek Rhyolite (CPv$_1$, CPv$_2$)

**Distribution and derivation of name.** Breccia Creek Rhyolite is restricted to an area of about 8 km$^2$ immediately north of The Square Cut at the northwestern end of Mount Mulligan. The unit has been named from Breccia Creek, which drains Emu Pocket below the northwestern part of Mount Mulligan, and flows north to join the Hodgkinson River opposite "Kondaparinga" homestead.

**Type section.** The type section of the Breccia Creek Rhyolite extends downstream along Breccia Creek from its inferred contact with subunit Pum$_1$ of the Mount Mulligan Coal Measures (below) at GR 620425 for about 200m to GR 620427, and then north-northwest for 1.5 km across a series of rounded rock pavements and locally benched ridges (in which vitrophyre intervals, described below, crop out) to the limit of exposure at GR 614441. There is probably some repetition of the lower part of the sequence between east-striking faults and dykes which intersect the type section at GRs 616433 and 615436.

 

**Lithology.** Clast-rich ignimbrites ($CPv_1$). This subunit consists mainly of mid-buff to mid-grey rhyolitic ignimbrite which is typically crystal-poor to (less commonly) moderately crystal-rich, containing up to 20% quartz and less abundant feldspar crystals (up to ~2 mm). Ubiquitous pumice clasts reach a few centimetres long, but are mostly less than 1 cm. The matrix originally comprised vitric shards and dust, but both pumice and shards appear to have been pseudomorphed during devitrification.

A eutaxitic foliation defined by deformed pumice clasts and devitrified glass shards is confined to scattered zones of moderate to intense welding reaching a few metres thick. The eutaxitic foliation is locally irregular or distinctly contorted at outcrop scale, which suggests a degree of post-depositional rheomorphic, lava-like, flow (*cf.* Ekren & others, 1984). The presence of several welded intervals suggests that the sequence contains several cooling units. Indeed, at several localities in non-welded intervals, clast-size variations that coincide with topographic benches appear to delimit flow units about 10m thick. Welded intervals of Breccia Creek Rhyolite contain appreciably fewer lithic clasts than typical non-welded material, an inverse relationship which may be interpreted to indicate that the clasts were relatively cold during pyroclastic flow emplacement.

Lithic clasts are distributed throughout the Breccia Creek Rhyolite; they are mostly angular to subrounded, and their abundance and size tends to decreases upwards through the sequence. Most clasts are less than 50 cm in diameter, although scattered blocks that were probably emplaced ballistically are up to 2 m across. A large proportion of the clasts are Hodgkinson Formation arenite: the remainder are predominantly crystal-poor welded rhyolitic ignimbrite, similar to that in non-vitrophyric welded intervals within the Breccia Creek Rhyolite, which locally are more abundant than Hodgkinson Formation arenite. Grey crystal-poor welded rhyolitic ignimbrite of uncertain provenance is a less common clast type. The unit also contains rare clasts of sparsely porphyritic dark purplish-brown andesite(?), which contain feldspar phenocrysts up to about 2 mm. These clasts cannot readily be correlated with any exposed rock-type in the area.

Outcrops of the subunit located about 2.5 km north-northwest of Timber Top (Plate 1: stippled screen in Mackenzie & others, 1993) show intense sericite and/or kaolinite alteration, and are cut by quartz veins.

Vitrophyric clast-rich ignimbrites ($CPv_1$ with cross-hatch screen). Vitrophyre appears to form lenticular intervals, up to about 30 m thick, at perhaps two stratigraphic levels within the mainly nonwelded bulk of the Breccia Creek Rhyolite: it crops out at GRs 619429, 618430, and 616435, but the outcrop at the last locality is probably a repetition of one of the other horizons.

The vitrophyre is rich in undevitrified to slightly devitrified rhyolitic glass which is present in lithic clasts as well as the matrix. The clasts, which range in form from irregular and angular to more equidimensional and rounded, are up to 1 m across. Most are black (dark brown in thin section), and resemble obsidian, but all contain crystals and most lack the typical conchoidal fracture; some vitric clasts are colourless or pale to mid brown, and a few are pale to mid grey. Some clasts have an intricate, irregular shape, suggesting that that they were incorporated into the flow while hot and plastic. The glassy clasts appear to have originated as crystal-poor/sparsely porphyritic rocks (or magmas) including poorly-expanded pumice, moderately to intensely welded ignimbrite, and perhaps lava. They are accompanied by a small proportion of clasts of Hodgkinson Formation arenite, and rare clasts of andesite up to (exceptionally) about 15 cm across.

The matrix of the vitrophyre consists of shards and dust, and up to about 15% quartz, much less abundant feldspar, and rare augite crystals up to about 2 mm long. Parts of at least one of the obsidian-rich intervals have moderately- to well-developed macro- and micro-eutaxitic foliation defined by flattened pumice clasts and deformed groundmass shards respectively. Matrix glass is mostly colourless to pale brown.

Devitrification is localised, and affects mainly the glass in the matrix: the clasts have developed no more than a 3 cm-thick rind, usually adjacent to rare quartz stringers, or to some joints.

These vitric-rich rocks appear to be either the result of atypically hot and dry pyroclastic flows, or are the lowermost parts of originally much thicker flow units.

Nonwelded pyroclastic surge(?) deposit ($Cpv_2$) makes up approximately the top 10 m of the Breccia Creek Rhyolite at the north- northeastern extremity of the type section. It consists of poorly sorted mid purplish-red pumiceous crystal-vitric siltite grading to coarse arenite. The crystal content is dominated by quartz fragments. Pumice clasts and shards are pseudomorphed, but appear to be undeformed, indicating that welding was poor or lacking. Stratification is moderately well defined, and medium to thick. Bedding appears to be planar at outcrop scale, although slight convergence between some upper and lower surfaces was observed, and may indicate large-scale lenticularity and/or very-low-angle cross-stratification; no grading was observed. These bedding characteristics suggest that they were deposited by pyroclastic surge rather than by pyroclastic flow or by air-fall.

**Thickness, environment of deposition, and eruptive source.** The Breccia Creek Rhyolite has an estimated minimum preserved thickness of about 250 m. Of this, all but the uppermost 10 m or so consists of rhyolitic ignimbrite, most of which was originally unwelded.

The abundance of large lithic clasts throughout much of the Breccia Creek Rhyolite indicates that it was deposited near-vent, although no voluminous lag-fall deposit, which might be expected in such environments (Wright & Walker, 1977), was observed. At least one source vent can be identified within the outcrop area of Breccia Creek Rhyolite, whereas none is known from outside its outcrop area, suggesting that the unit was erupted locally and buried its own vents.

A locality 1.5 km west of The Gin Bottle at GR 619440 appears to represent a very-near vent environment. The contact zone between Breccia Creek Rhyolite and underlying Hodgkinson Formation has an irregular vertical relief of several metres. Lowermost Breccia Creek Rhyolite contains very large irregular and angular blocks of Hodgkinson Formation arenite, and less common argillite, reaching at least 5 m, about the size of the local outcrops. The blocks are penetrated by and separated by apophyses of ignimbritic material extending downwards from the overlying sheet. Blocks persist in about the lower 10 m of the sheet, becoming progressively more intensely fractured and disaggregated upward. Detached fragments show variable rotation and become subrounded locally. The blocks represent shattered and gas-streamed basement of strictly local surface or near-surface derivation rather than blocks emplaced ballistically or entrained from a deeper substrate, and must indicate proximity to, if not coincidence with, a vent.

A second possible vent locality is at GR 613455, 1.6 km north-northwest of the locality described above. An irregular north-northeast trending subvertical sheet about 1 m wide, and consisting mainly of subrounded Hodgkinson Formation arenite blocks, cuts nonwelded ignimbrite of the lower Breccia Creek Rhyolite. The nonwelded ignimbrite contains markedly fewer, more varied clasts of Hodgkinson Formation and other lithologies than the dyke-like body.

Northwest of The Gin Bottle, Breccia Creek Rhyolite contains blocks of deformed Hodgkinson Formation (predominantly arenite). These blocks range from shattered to partly disaggregated, and reach 1m across. The matrix of the rhyolite also contains local concentrations of angular to subangular quartz and feldspar crystal fragments, and angular to rounded coarse sand- to granule-size clasts.

A significant proportion of the sand to granule-sized clasts are quartzose; most probably represent deformed and metamorphosed Hodgkinson Formation, although a few clasts contain some feldspar and/or altered biotite, and could be granite-derived. Quartz in these quartzose clasts typically shows undulose extinction, deformation banding, serration of boundaries (subgrain growth), and polygonisation-recrystallisation (*cf.* Bell & Etheridge, 1973) of constituent grains, and some also show a well developed foliation. These observations suggest that the local basement had undergone ductile and probably mylonitic deformation. This degree of deformation is more intense than in the typical Hodgkinson Formation exposed in the vicinity of Mount Mulligan. The observations described above strongly imply that at least some Breccia Creek Rhyolite vented *via* a discrete pre-existing mylonite zone.

Elsewhere, intrusions which may relate to the Breccia Creek Rhyolite also appear to have been emplaced along pre-existing structures. In the vicinity of GR 603448, locally haematitic, coarse, crystal- and lithic-rich nonwelded rhyolitic rocks of arenite to rudite grainsize appear to intrude a west-trending high-angle fault zone, which cuts the Breccia Creek Rhyolite proper. Clasts in these rocks are sorted on a local scale into dominantly fine and dominantly coarse phases, reaching 30 cm in diameter in the latter, implying either multiple or repeated differentiation events, probably driven by gas-streaming. Quartzite clasts at this locality have a "mortar" microtexture, perhaps reflecting incipient mylonitisation. Larger constituent grains have very variable, partly discordant ductile deformation textures, and a few are well foliated. These textural relationships are consistent with a history of multiple deformation events in the local basement, with grains recording an earlier phase than the aggregates as a whole.

A pebbly to cobbly volcanic arenite at GR 628344 is possibly of similar, intrusive, origin.

 

**Relationships and correlation.** The unit lies unconformably on Hodgkinson Formation and is overlain with less obvious unconformity by rocks assigned to the Mount Mulligan Coal Measures (mostly subunit $Pum_1$, locally $Pum_4$). It has been intruded by miscellaneous rhyolitic to dacitic rocks, and by rocks which probably belong to Controversy Hill Rhyolite (below).

Ball (1912) noted the coarsely fragmental nature of the Breccia Creek Rhyolite and inferred that it represented an extrusive vent. Subsequently, the rocks were assigned with varying degrees of uncertainty to Nychum Volcanics (*cf.*. Branch. 1966; de Keyser & Lucas. 1968). Breccia Creek Rhyolite is here tentatively assigned to the Featherbed Volcanic Group, although it cannot be correlated directly with any member within the Group's main outcrop area. This assignment is mainly based on the large volume of rhyolitic ignimbrite present, and on relationships between the unit and the Maneater Granodiorite and Controversy Hill Rhyolite, which together form an irregular ring-dyke peripheral to the Mulligan Cauldron.

Unnamed pyroclastic rocks regarded as part of the Featherbed Volcanic Group (CPt; described above) are possibly distal equivalents of the Breccia Creek Rhyolite. Rocks of the unit that crop out in the Little Watson Creek area are of lag-fall type, and may be evidence of such a relationship. This possibility is further supported by:

- the abundance of Hodgkinson Formation lithic clasts in both units,
- by the presence of typical CPt in a fault slice near the confluence of Little Watson and Sardine Creeks, not far south of outcrops of typical Breccia Creek Rhyolite, and
- the presence of rocks of transitional character in fault slices on the western side of the outcrop area of Breccia Creek Rhyolite.

### Unnamed unit Pfb

Breccia assigned to this unit forms two small outliers, with a total area of less than 1 km², in the northwest of the Mulligan Cauldron, near Little Watson Creek. The breccia is massive, clast-supported, and composed of clasts of flow-banded, sparsely porphyritic rhyolite set in a grey, fine-grained felsic matrix. As in the case of $CPu_1$, extensive areas (hundreds of square metres) of flow-banded rhyolite may be very large clasts, and like $CPu_1$ and CPb, Pfb may be a brecciated lava flow. It overlies CPb with apparent conformity (or disconformity), and forms a distinctive outcrop pattern of very large boulders, clearly visible on 1:25 000-scale aerial photographs, whereas a smoother texture is developed on CPb. However, its exact relationship to CPb is uncertain, and the two may be parts of the same extrusive unit.

## Yongala Volcanic Subgroup (Djungan Cauldron)

The Yongala Volcanic Subgroup is a major component of the Featherbed Cauldron (Mackenzie & others, 1993; Mackenzie, 1993), west of Mount Mulligan. The Featherbed Cauldron is composed of a series of overlapping Cauldrons, the northeasternmost of which, the Djungan Cauldron, is a few kilometres west of Mount Mulligan. Rhyolite which overlies the Timber Top Subgroup east of the main Djungan Cauldron is similar to that in the Fisherman Rhyolite, a unit at the base of the Djungan Cauldron sequence, and has been tentatively assigned to that unit.

### Fisherman Rhyolite (Pfi) (?)

**Distribution.** About 10 km² of rhyolite adjacent to the eastern margin of the Djungan Cauldron, 5 km west of Controversy Hill (Plate 1), has been tentatively included in this unit.

**Lithology.** Fisherman Rhyolite in the Mount Mulligan area consists of an apparently subhorizontal sequence of rhyolitic ignimbrite and lava flows. A discontinuous lower horizon of extensively brecciated, strongly flow-banded, sparsely porphyritic rhyolite is overlain by locally brecciated, extensively rheomorphosed, crystal-poor rhyolitic ignimbrite. In a few places, non-welded pyroclastic rocks, including a probable lithics-bearing, crystal-poor vitric tuff, also crop out.

Brecciation of the basal rhyolite is most extensive in its lower parts, but is also common in the upper portions: in places, only cores of rhyolite up to a few metres across remain intact. The breccia is mostly clast-supported, with subrounded to angular clasts ranging up to 40 cm set in a fine "sandy" matrix. The distribution and morphology of the clasts suggest that the breccia is mostly of flow-carapace origin, although some breccia near the margin of the Djungan Cauldron, along the extension of the Retina Fault, may be tectonic.

The ignimbrite includes a fine, crystal-poor, vitric variety, and a lithic-bearing, moderately crystal-poor to crystal-rich variety. The latter contains clasts (up to 2 cm) of flow-laminated rhyolite that are variably devitrified, recrystallised, and altered. Evidence of rheomorphism is widespread: the foliation commonly grades from extreme attenuation of lenticular pumice *fiamme* to a continuous, intensely and complexly convoluted banding strongly resembling flow banding. Brecciation of the ignimbrite is localised and irregularly distributed, and is closely associated with areas of intense rheomorphic overprinting of the eutaxitic foliation.

These rocks closely resemble rhyolitic ignimbrite and lava in the southeastern extremity of the Djungan Cauldron, and both groups of rocks are similar in lithology, and sequence of lithologies, to Fisherman Rhyolite in the type area near the Walsh River (Mackenzie & others, 1993; Mackenzie, 1993).

**Relationships.** The lava, breccia, and ignimbrite overlie, or are faulted against, the Timber Top Volcanic Subgroup, and are faulted against the Djungan Volcanic Subgroup. They are intruded by dykes of porphyritic microgranite (Pmg) similar to that which forms a discontinuous ring dyke around the margin of the Djungan Cauldron.

## LATE CARBONIFEROUS-EARLY PERMIAN INTRUSIVE ROCKS

### Maneater Granodiorite (Pgm, $Pgm_1$)

Maneater Granodiorite appears to be the youngest of the late Palaeozoic igneous units preserved in the Mount Mulligan area. The unit consists of a number of partly interconnected, steep-sided to gently-dipping, sheet-like bodies: these are interpreted as an incomplete, north-south-elongated, "bell-jar" pluton (*cf.* Pitcher, 1978), truncated along its western side and southern end(?) by the Featherbed Cauldron. Gently-dipping portions of Maneater Granodiorite, which are probably at least 200m thick locally, are underlain and/or overlain in many places by Controversy Hill Rhyolite.

Maneater Granodiorite contains two unnamed subunits, Pgm and $Pgm_1$.

**Pgm** is the dominant subunit of Maneater Granodiorite, and consists of pale to moderately dark greenish-grey, sparsely porphyritic, medium to fine-grained granodiorite. It contains approximately 1% very pale green plagioclase phenocrysts up to 7 mm, and rare quartz phenocrysts; quartz phenocrysts are more abundant and much more prominent in $Pgm_1$. Partly chloritised biotite and subsidiary hornblende mostly form interstitial intergrowths and subhedral prisms disseminated in the groundmass, but also form scattered aggregates up to 1 cm across. The aggregates are particularly conspicuous in paler and more felsic parts of the subunit. The groundmass typically has an incipient to well developed granophyric texture. Irregular pegmatitic segregations and vuggy quartz stringers and veinlets, some with selvedges of bleached appearance, were observed in a few places.

Enclaves, mostly of dark, equigranular microdiorite, are ubiquitous in paler variants of Pgm, but are much less common in the darker varieties. They range from irregular and angular to near-equant and rounded in shape, and from 1 cm to 3 cm across: some have and orbicular appearance.

Xenoliths are also largely confined to paler variants of the granodiorite. Subangular to rounded fragments of hornfelsed Hodgkinson Formation arenite are relatively common, and are mostly similar in size to the enclaves. Larger xenoliths also occur in a few localities. Micaceous arenite xenoliths up to several metres across occur at a locality 2.7 km west of Controversy Hill, and a dyke 4 km northwest of Timber Top contains xenoliths of arenite and siltstone, and of coarse biotite granite, ranging up to tens of metres across. A body of pink, coarse, biotite leucogranite about 200 m long and 100 m wide crops out 2.7 km west of Controversy Hill (a few hundred metres north of the locality mentioned above), and is probably also a large xenolith. Xenoliths of white to pink, medium to coarse, equigranular biotite leucogranite up to about 1 m across are scattered elsewhere in the unit. Some of these leucocratic xenoliths contain miarolitic cavities. Biotite leucogranite similar to that observed in many of the xenoliths crops out near Little Watson Creek, between the Retina Fault and the northeastern margin of the Djungan Cauldron.

The morphology and appearance of Maneater Granodiorite appear to depend on the country rocks it has intruded. It tends to be darker where it cuts other late Palaeozoic units than where it intrudes Hodgkinson Formation, and tends to be sheet-like in the former and dyke-like in the latter.

**Pgm$_1$** is essentially a chilled marginal phase of Pgm, although relationships with Pgm are discordant in places, and contacts are predominantly sharp. It is well developed adjacent to gently to moderately steeply-dipping margins of the Maneater Granodiorite near Mount Mulligan and in the Maneater Creek area, in the southwestern portion of the Mulligan Cauldron.

Pgm$_1$ consists of mid- to dark green, variably porphyritic microgranodiorite to dacite. About 6 km southwest of Controversy Hill, a steep-sided body of sparsely porphyritic dacite which grades into medium-grained granodiorite has been assigned to Pgm$_1$. This body appears to cut across the southern end of the main mass of Pgm. Dacitic Pgm$_1$ appears in a few areas to grade *via* mid greenish-buff to greenish-pink microgranodiorite into coarser-grained granodiorite (Pgm), although contacts appear to be sharp elsewhere.

Pgm$_1$ is predominantly sparsely porphyritic, with 3-5% phenocrysts, up to 3 mm, of plagioclase and subsidiary to subequal quartz. The groundmass is fine-grained, mostly equigranular to graphic, and commonly shows "snowflake" or "felted" (pilotaxitic) textures. A diffuse, discontinuous lamination, similar in appearance parts of the Controversy Hill Rhyolite, is present in some rocks near the margins of bodies of Pgm$_1$.

Xenoliths are generally less abundant than in Pgm, but enclaves of pink biotite granite up to several metres across were observed in the discordant body southwest of Controversy Hill.

Dykes subparallel to the main body of Maneater Granodiorite to the west and south of Mount Mulligan are also included in subunit Pgm$_1$, and may represent an early, chilled phase of the granodiorite. The dykes consist of pale greenish grey, moderately porphyritic dacite to microgranodiorite containing about 7% white to pale green plagioclase phenocrysts (up to ~7 mm), and subsidiary quartz phenocrysts (up to ~1 mm). Dark green spots and irregular patches up to 5 mm across of chloritised biotite and/or hornblende occur both within feldspar phenocrysts and in the groundmass.

## Unassigned intrusive rhyolite and dacite (rh)

Bodies of rhyolite and dacite crop-out in Breccia Creek Rhyolite and Controversy Hill Rhyolite to the north and west of Mount Mulligan, but have not been assigned to specific units. Some intrusions are steeply- to gently dipping, but some may have been emplaced as lava flows. Most appear to be older than the Controversy Hill Rhyolite and Maneater Granodiorite, but a few may be younger.

A dyke cutting Controversy Hill Rhyolite in the area to the <u>west of Sardine Creek</u> consists of dark green-grey sparsely porphyritic rhyolite and pale greenish-grey and pink aphyric rhyolite. The aphyric rhyolite typically contains abundant autoliths up to 20 cm across, most of which are angular to subangular, although a few of the larger clasts are subrounded to rounded. This rounding suggests some milling took place. Rarely, diffuse, undulating flow bands are present in coherent portions of the rhyolite.

Intrusive rhyolite distinct from nearby Controversy Hill Rhyolite crops out in the <u>Controversy Hill area</u>. This rhyolite is poorly columnar-jointed, pale purplish-grey to purplish- buff, sparsely to moderately porphyritic and slightly but pervasively sericitised. It contains about 30% phenocrysts, comprising buff feldspar to 3 mm, slightly less quartz to 1.5 mm, and biotite flakes (<1%), pseudomorphed by opaque minerals, up to about 1.5 mm wide. The rock has a somewhat streaky texture in places, but is not flow banded. Local brecciation gives rise to mostly subangular fragments up to 25 cm across.

The <u>Upper Sardine Creek area</u> contains rhyolite similar to that in the Controversy Hill area. Most bodies are more intensely altered, and crudely or diffusely flow banded in part. These bodies are also brecciated in places, but clast size reaches a few cm at most. This rhyolite is probably older than adjacent Controversy Hill Rhyolite.

A west-trending dyke of unaltered, moderately porphyritic, biotite-bearing rhyolite crops out in the upper Grainers Gully area. This rock is mid grey, and contains about 30% white feldspar phenocrysts mostly up to 4 mm (rarely up to 1 cm) long, subsidiary quartz phenocrysts up to 4 mm, mostly smaller. The dyke appears to mark the contact between Hodgkinson Formation and Controversy Hill Rhyolite, but does not appear to cut nearby Maneater Granodiorite.

Several dykes and fault-bounded remnants of intensely fractured to brecciated, sparsely to moderately porphyritic rhyolite, some of which grade to microgranite, crop out on the western side of the Mount Mulligan massif. Most of these bodies are parallel to the fault zone along the western side of the Mount Mulligan massif, but some are transversely oriented. The bodies are spatially associated with Controversy Hill Rhyolite. Transverse bodies in the upper Grainers Gully area are probably older than Maneater Granodiorite. Faulting obscures original relationships with Controversy Hill Rhyolite.

Rhyolite bodies southwest of the Controversy Hill area are sparsely to moderately porphyritic, commonly flow-banded, and altered. They form small, mainly steep, sheets and plugs intruding CPt, CPu, and Controversy Hill Rhyolite(?). Soft-sediment-style deformation is evident in adjacent pyroclastic rocks (CPt, CPu) and clastic material of up to medium pebble size has been incorporated into the rhyolite in places, suggesting that the rhyolite was emplaced prior to lithification of the pyroclastic rocks.

A swarm of predominantly westerly-trending dykes intrude the Breccia Creek Rhyolite to the north of Mount Mulligan. The dykes are composed of mid to dark buff, locally green, sparsely porphyritic rhyolite transitional to microgranite, flow banded in places. Some of these rocks are similar to the Controversy Hill Rhyolite, and they may be related. The rhyolite contains up to about 5% phenocrysts of white to pink feldspar (up to 3 mm) and slightly less abundant quartz (up to 1.5 mm); some contain minor biotite. Breccia Creek Rhyolite adjacent to these dykes is locally reddened and silicified. The dykes are cut in a few outcrops by rare north-striking stringers of quartz. A north-trending dyke of similar, but altered, rhyolite cuts Breccia Creek Rhyolite 4 km northwest of Breccia Hill.

The central part of the Breccia Creek Rhyolite also contains dykes of mid-green, sparsely to moderately porphyritic dacite containing up to 5% quartz phenocrysts (up to 2 mm) and 1-2% pale green feldspar phenocrysts (up to 4 mm), as well as abundant prismatic to irregular chlorite-carbonate-epidote aggregates, containing rare remnant biotite, less than 1 mm across. Quartz and feldspar in the groundmass are irregularly intergrown in a micrographic-like texture. These features are reminiscent of the Maneater Granodiorite, and may indicate that the latter is younger than the Breccia Creek Rhyolite.

## MOUNT MULLIGAN SEQUENCE

Previous studies of the Mount Mulligan sequence are summarised by Matheson (1995).

**Thickness.** The Mount Mulligan massif comprises a sequence of terrestrial clastic rocks with a maximum preserved thickness of more than 1200 m. The maximum thicknesses of an individual section exceeds 545 m, measured in a coal-exploration well drilled at GR 671407, approximately 1 km from the eastern edge of the mesa. This well is at the northern end of the mountain, and did not reach the base of the sequence. Section thicknesses decrease irregularly but consistently southwards.

**Gross stratigraphy, relationships, and age.** The sequence consists of the Mount Mulligan Coal Measures, which is overall upwards-coarsening, overlain by the upward-fining Pepper Pot Sandstone. Lower parts of the Mount Mulligan sequence are exposed around the eastern and northern sides of the massif, but are concealed in the west; data from exploration drillholes are available for some of the concealed interval. Mount Mulligan Coal Measures wedge out about 1 km south of the King Cole Mine, so that the Pepper Pot Sandstone rests directly on Hodgkinson Formation at the southern end of the mountain.

The Mount Mulligan Coal Measures are known to be of Late Permian age (*e.g.* Matheson, 1995), and the Pepper Pot Sandstone is inferred to be Early Triassic.

## Mount Mulligan Coal Measures

**Derivation of name and synonymy.** The Mount Mulligan Coal Measures ("productive measures" of Ball, 1912) were named from Mount Mulligan. The name was first used in its current formal stratigraphic sense by de Keyser & Lucas (1968).

**Type and auxiliary section.** The type area of the unit was originally defined as "the Mount Mulligan coalfield" (de Keyser & Lucas, 1968, p. 61). However, to allow detailed reference and comparison, a type section is proposed here extending up Slip Gully from the contact with underlying Hodgkinson Formation at GR 725347, about 150 m south of the collapsed adit of Mount Mulligan mine, to the base of conglomerate assigned to the lower Pepper Pot Sandstone at GR 724346.

An auxiliary section is also proposed, at the northern end of the mesa. It extends from the inferred basal contact with Breccia Creek Rhyolite in Breccia Creek at GR 620425, upstream along Breccia Creek for about 300m to GR 618423, then almost due south up slope for about 0.8 km to the base of overlying Pepper Pot Sandstone in the lower part of a steep pediment beneath cliffs of The Square Cut (GR 620415).

**Subdivision and internal relationships.** The Mount Mulligan Coal Measures were divided into three units by Whitby (1975), and although we have used similar nomenclature, we have defined four subunits. Each subunit is a lithotope, differentiated from the others by sedimentary facies, and is an association of rock-types, or, in the case of $Pum_2$, consists of a single, distinctive rock type. Lithological associations or lithologies are mostly lenticular, and interfinger with and/or grade laterally into one another, or are repeated up-section; they are not stacked in a straightforward, "layer-cake" fashion as previous descriptions (*e.g.*, Ball, 1912; Whitby, 1975) implied.

### Unnamed subunit $Pum_1$

**Distribution & relationships.** The lowermost part of the Mount Mulligan Coal Measures ($Pum_1$) overlies Breccia Creek Rhyolite at the northern end of Mount Mulligan, where it is poorly and discontinuously exposed. It occurs in the auxiliary section between its base at GR 620425 and its contact with overlying subunit $Pum_2$ (below) at GR 620424, and again between GRs 619421 and 619420, but has not been recognised in the type section.

The main rock-types included in $Pum_1$ are irregularly distributed, and one is difficult to distinguish from the nonwelded ignimbrite which dominates the underlying Breccia Creek Rhyolite. This compositional similarity may be explained by the probable initial accumulation of $Pum_1$ in depressions in an irregular palaeosurface on ignimbrite. This inference is supported by the presence, in parts of the Breccia Creek Rhyolite immediately below the contact, of a silicified groundmass which may be a palaeoweathering feature.

**Thickness.** Most of subunit $Pum_1$ is probably about 10 to 20 m thick, but it may reach 40 m thick locally.

**Lithology.** Subunit $Pum_1$ is characterised by crudely medium to thick-bedded to locally massive, poorly-sorted, mid grey to buff fine to coarse-grained, pebbly, vitric-crystal-lithic arenite and fine rudite. The subunit is exposed only in Breccia Creek, at and near its confluence with an unnamed southeastern tributary at GR 620424. Clasts include angular quartz, angular to subangular sparsely porphyritic rhyolite (including nonwelded ignimbrite and intrusive types), Hodgkinson Formation arenite, fine-grained amphibolite, and pumice. Small carbonaceous fragments are also common.

**Relationships and boundary criteria.** The boundary between subunit $Pum_1$ and underlying Breccia Creek Rhyolite is not easily recognised. Stratified intervals of subunit $Pum_1$ in Breccia Creek are underlain by essentially massive clastic debris superficially similar to nonwelded ignimbritic deposits that have elsewhere been assigned to Breccia Creek Rhyolite. This "ignimbritic" material appears to be locally pumice-enriched, but is otherwise unstratified and unsorted. However, in this location it contains rare carbonaceous fragments, which resemble charcoal, and clasts of laminated to mottled mid to dark-grey siltstone. Both of these clast types are absent from the Breccia Creek Rhyolite, and are regarded as diagnostic of basal $Pum_1$; however, Breccia Creek Rhyolite locally contains clasts of black graphitic argillite that are superficially similar to charcoal. The siltstone appears to have been incorporated by disruption of an unlithified stratum.

 

The "ignimbritic" material underlying clearly sedimentary $Pum_1$ may be interpreted as incipiently reworked Breccia Creek Rhyolite, and as such is regarded as its base. The outcrop pattern of $Pum_1$ appears to represent eroded palaeohills of Breccia Creek Rhyolite surrounded by the sedimentary rocks, further exacerbating the difficulty of recognising the lower boundary of $Pum_1$.

The presence of carbonaceous clasts also allows basal $Pum_1$ to be recognised farther north along Breccia Creek and farther east at the northern end of Emu Pocket. In the latter area, matrix-supported rudite forms a section about 40 m thick, which also has similar appearance and petrography to nonwelded ignimbrite. However, the following characteristics indicate that the rocks are $Pum_1$: local very poor stratification and sorting; carbonaceous clasts up to about 1 cm across; diffusely-bounded irregular intercalations of massive to laminated mid-grey and buff, fine to medium siliciclastic siltite with a few thick beds of poorly-sorted mid greenish-buff, medium-grained quartzofeldspathic sublithic arenite containing carbonaceous granules.

**Depositional environment.** The observed features of rocks assigned to the lowermost Mount Mulligan Coal Measures as developed in the Breccia Creek area suggest that they represent reworked deposits derived initially from immediately subjacent Breccia Creek Rhyolite. Such reworked material may have accumulated as small-scale alluvial fans and scattered debris flows in palaeotopographic depressions until local relief was eliminated, at which time they could have been succeeded by well stratified alluvial deposits of more distal derivation.

## Unnamed subunit $Pum_2$

**Relationships.** $Pum_2$ overlies $Pum_1$ sharply and probably concordantly, near GR 620424.

**Thickness.** Total thickness may reach 50 m, although lateral extent appears limited.

**Auxiliary section.** This subunit is absent from the type section, but well developed in the auxiliary section, where it consists of near-continuous strike-parallel exposure in the southern bank of Breccia Creek between GRs 620424 and 620415.

**Lithology.** $Pum_2$ consists of pale to mid buff and greyish- or greenish-buff, rhythmically laminated to thin-bedded, fine- to medium-grained, siliciclastic siltite. Laminae and beds are normally-graded. Lenticular bedding and cross stratification were not observed

The unit contains sparse finely-divided carbonaceous material throughout, although this is characteristically most conspicuous in the finer-grained upper parts of laminae and beds. Scattered plant remains are preserved on some bedding surfaces, and include relatively complete impressions of large *Glossopteris* leaves. The unit also contains rare subrounded to rounded clasts of Hodgkinson Formation arenite, up to 30 cm across, which have probably been reworked.

**Depositional environment.** The fine-grained and evenly laminar-bedded nature of these rocks (interrupted only by rare pebbles and cobbles), the large unbroken leaf impressions, and sparse but unmodified carbonaceous material, suggest that accumulation took place in an oxygenated (shallow?) but quiet lacustrine environment. This environment was probably never widespread, but confined to transitory depressions into which there was only sporadic and minor coarse alluvial sediment input from an adjacent low-relief terrain.

## Unnamed subunit $Pum_3$

**Relationships.** This part is separated from the sequence containing subunits $Pum_1$ and $Pum_2$ to the west by a fault zone (below). Subunit $Pum_3$ commonly lies directly on Hodgkinson Formation, and is the only subunit represented in the type section of the Mount Mulligan Coal Measures.

Subunit $Pum_3$ probably interfingers diagonally(?) upwards with subunit $Pum_4$ (described below). This is suggested by the presence of lenses, up to about 30m thick, of $Pum_4$ rock types within $Pum_3$. There is also a degree of local intergradation between rock types of the two subunits to the northwest of the confluence of

 

Breccia and Gorge Creeks, although the coarsest facies of $Pum_4$ probably has an at least partly erosional base in many localities.

**Distribution and thickness.** The basal Mount Mulligan Coal Measures in and to the north of the lower reaches of Breccia Creek east of Emu Pocket have been assigned to this subunit. Subunit $Pum_3$ is thickest between Crab Hollow and the area of King Cole mine, where it forms essentially the whole thickness, about 50 m, of the Mount Mulligan Coal Measures. A minimum thickness of about 65 m is indicated in the exploration drillhole at GR 671407. The subunit forms a lens up to about 40 m thick between subunit $Pum_4$ and Pepper Pot Sandstone below The Ram. No outcrop of the subunit has been observed along the edge of the Mount Mulligan mesa due east of the exploration drillhole at GR 671407, and it is absent in the area south of King Cole mine. There is no exposure of $Pum_3$ on the western side of the Mount Mulligan mesa, and if present, it is down-faulted along the Wasons Gap/Hurricane Fault Zone (Fig. 1) and concealed.

**Lithology.** Subunit $Pum_3$ of the Mount Mulligan Coal Measures is distinguished by an association of lutite and fine arenite, in about equal proportions, accompanied by a minor proportion of coarser-grained rocks. Up to four coal-dominated intervals, each reaching 3 m thick, are distributed throughout the subunit. These intervals were worked in the State (Mount Mulligan) and King Cole mines.

The rocks of subunit $Pum_3$ are typically pale to mid grey, and made up of angular to subangular grains, invariably including abundant small flakes of muscovite, rare biotite, and very rare tourmaline. Carbonaceous fragments and plant fossils are locally common, and with increasing carbonaceous content, lutite grades into impure "ashy" coal. The rocks are highly fissile, with a platy to flaggy appearance.

**Sedimentary structures.** Stratification ranges from poorly to well-developed laminae in lutite or thin beds in arenite. Carbonaceous material is commonly concentrated on stratification planes. Small-scale, low-angle, planar to slightly upward-concave ripple cross-stratification is commonly present, but no steep and/or curved cross-stratification was observed. Some strata have undergone soft-sediment deformation, possibly as a consequence of loading by coarser clastic material. Some sandstone intervals have sharp, probably erosional, lower contacts with underlying finer-grained rocks, and the subunit may represent a series of fining-upward cycles.

**Clasts.** Some arenaceous intervals, particularly in the basal part of the subunit (which is purple in a few areas), contain scattered to moderately concentrated subrounded to rounded, small pebbles to small cobbles, within a matrix-supported fabric. Clasts appear to have a dominantly intraformational origin, with subsidiary weathered(?) Hodgkinson Formation and scattered rhyolite clasts. The rhyolite is not distinctive, and of indeterminate provenance, and there does not appear to be any systematic variation in proportions of clast lithologies, or in the size or roundness of clasts. These rudaceous rocks may be the "puddingstone" observed by earlier workers (*e.g.*, Ball, 1912; Connah, 1953), reported to attain a maximum thickness of about 10 between the State and King Cole mines (Ball, 1912).

Other rudaceous rocks included in subunit $Pum_3$ are similar to those which dominate subunit $Pum_4$, and may be regarded as thin tongues and lenses of that subunit.

**Depositional environment.** The association of carbonaceous lutite and fine arenite, with local coal-rich intervals, in possible fining-upward cycles is most consistent with deposition in a meandering alluvial setting (*cf.* Walker & Cant, 1984). In this case, the lutite and coal-rich intervals represent vertical accretion floodplain accumulations, and arenite represents point-bar and other channel-associated lateral-accumulation bodies. However, the large-scale trough and planar cross-stratification which commonly characterise these lateral accretion deposits have not been observed. Relationships between coal-rich and coal-poor intervals observed in the mine workings (Ball, 1912) suggest that the sedimentary source was to the north and/or northeast.

## Unnamed subunit $Pum_4$

**Auxiliary section.** Subunit $Pum_4$ of the Mount Mulligan Coal Measures crops out in the auxiliary section between GR 619420 and 620415.

**Lithology.** The subunit consists mainly of interfingering, in part intergrading, lenses of bench-forming rudite, and a minor proportion of arenite.

The rudite contains clasts of mostly very large pebble to small cobble size, or smaller. Imbrication of pebbles was observed locally, but insufficient measurements could be made to infer flow directions. The rudite is clast-supported, and massive to very poorly bedded at typical outcrop scale. Contacts with associated arenite horizons are locally slightly discordant, probably as a reflection of large-scale, low-angle planar cross stratification. Finer-grained rocks are rare. Overall, the subunit fines southwards, particularly beyond Crab Hollow, but there does not appear to be any consistent trend of upward fining or coarsening.

Arenite of subunit $Pum_4$ is pale grey to buff, locally pink, and medium bedded to massive; bedded varieties tend to be flaggy. Most of the arenite is lithic-feldspathic, grading to lithic arkose. Carbonate cement is evident in some parts.

The arenite contains scattered clastic muscovite flakes and subsidiary biotite flakes in a few places. The mica flakes are in similar relative proportions and grainsize to those in nearby Hodgkinson Formation, from which they are likely to have been derived. The arenite also contains sparse carbonaceous fragments, and subrounded to rounded granules and pebbles are locally common as scattered individuals and in clast-rich layers. Most clasts are probably derived from Hodgkinson Formation, although others, such as recrystallised corroded quartz grains and sparse rhyolitic clasts, are clearly of volcanic origin. Rare rounded grains of micrographic quartz-feldspar intergrowth indicate a granitic source. Matrix grains are mainly angular to subrounded.

Clasts. The subunit contains abundant, locally dominant, subangular to rounded, commonly silicified rhyolite clasts, minor dacite clasts, and rare, banded, brecciated and recemented chalcedony clasts. Most clasts are not distinctive, although some rhyolite and dacite clasts can be tentatively correlated with source units in the Featherbed Volcanic Group (Table 1).

**Table 1. Tentative source units for various clast-types in subunit $Pum_4$ of the Mount Mulligan Coal Measures. References are to the lithology of the correlative units.**

| *Clast Lithology* | *Correlation* | *Comments* | *References* |
|---|---|---|---|
| Mid-grey crystal-rich welded rhyolitic ignimbrite | Lightning and Aroonbeta Rhyolites, Djungan Cauldron NE Featherbed Cauldron | Particularly common in lens of $Pum_4$ enclosed by $Pum_3$ near confluence of Breccia and Gorge Creeks | Mackenzie & others, 1993; Mackenzie, 1993 |
| Variably altered pale-green to buff crystal- poor rhyolitic ignimbrite and sparsely porphyritic flow rhyolite | Fisherman Rhyolite, central and northeastern Featherbed Cauldron | | Mackenzie & others, 1993; Mackenzie, 1993 |
| Pale green or buff to mid grey crystal-poor to moderately crystal-rich welded rhyolitic ignimbrite | Beapeo Rhyolite and other units in the Wallaroo and Maneater Creek areas on the eastern side of the Featherbed Cauldron | | Mackenzie & others, 1993; Mackenzie, 1993 |
| Suite of mid-green, crystal-rich welded dacitic ignimbrite, mid-purple, moderately porphyritic intrusive(?) dacite, pale green and buff sparsely and moderately porphyritic intrusive(?) rhyolite, and rare dark greenish-grey medium diorite | Equivalent to the intrusive-extrusive assemblage preserved in the Nightflower mine-Elizabeth Creek area of the northern Featherbed Cauldron | | Mackenzie & others, 1993; Mackenzie, 1993 |
| Refer to earlier, this report | Breccia Creek Rhyolite | Moderately common, mostly small: <<1 cm | This report |

**Sedimentary structures.** Medium to large-scale, low to medium-angle planar cross stratification is widespread in subunit $Pum_4$.

**Relationships, distribution and thickness.** In the main, subunit $Pum_4$ succeeds one of the other Mount Mulligan Coal Measures subunits, or rests directly on Hodgkinson Formation. It also forms a mappable lens up to about 30 m thick enclosed by subunit $Pum_3$ near the confluence of Breccia and Gorge Creeks. Subunit $Pum_4$ is overlain by Pepper Pot Sandstone.

Subunit $Pum_4$ is the only component of the Mount Mulligan Coal Measures which extends across the full width of the northern part of the outcrop area, where it is mainly about 60 m to 80 m thick. The thickness near The Ram is reduced to about 15 m due to a faulted basement high. Southward from The Ram, $Pum_4$ thickens progressively to a maximum of about 400 m opposite The Oyster Cave, then thins again farther southward, not persisting as a mappable entity beyond Crab Hollow.

With the exception of the distribution of Lightning and Aroonbeta Rhyolite ignimbrite clasts noted in Table 1, no evidence of systematic vertical or lateral variation in the proportions, sizes, or roundness of various clast types was observed in subunit $Pum_4$.

Angular chips and flakes of coal, up to about 2 cm long, but mostly smaller, are concentrated in thin intervals low in subunit $Pum_4$,where it interfingers with $Pum_3$. Angular and irregular lutite clasts accompany the coal, and were probably incorporated while soft.

**Depositional environment.** The coarse clastic and overall poorly sorted and stratified nature of subunit $Pum_4$ of the Mount Mulligan Coal Measures suggest that it accumulated in a coarse-sandy and gravelly, low-relief alluvial fan and/or a proximal braidplain environment. This interpretation is supported by the intergradational to erosional relationships between rudite and arenite, scattered low-angle planar cross-stratification, and the absence of an *in situ* mudstone component. The possibility that accumulation took place in a high-angle proximal fan environment (*cf.* Rust & Koster, 1984) may be discounted because of the apparent lack of debris-flow or hyperconcentrated flood-flow (Smith, 1986) deposits. The gradual rather than sharp lateral grainsize/facies changes observed in the subunit are also inconsistent with a high-angle proximal fan environment.

The outcrop dimensions of subunit $Pum_4$ are inadequate to confidently evaluate its original distribution and palaeotopography. However, there is no indication that its deposition was confined to narrow zones, which may indicate a relatively broad and uniform physiography, such as in a piedmont plain, as opposed to a narrow variable physiography, such as in a riverine valley with discrete channels. Sparse palaeocurrent measurements indicate a generally northward depositional current direction.

## Pepper Pot Sandstone

**Derivation of name and synonymy.** Pepper Pot Sandstone, the "non-productive measures" of Ball (1912), takes its name from The Pepper Pot at the extreme southern end of Mount Mulligan (de Keyser, *in* Amos & de Keyser, 1964; de Keyser & Lucas, 1968).

**Type and auxiliary sections.** The type area of the formation has been given previously only as "Mount Mulligan" (de Keyser & Lucas, 1968, p. 93). A type section is thus proposed here continuing up Slip Gully from the top of the Mount Mulligan Coal Measures (GR 724346), for 400 m west-southwest, *via* a double cliff succeeded by a series of benches, to GR 719344. The cliffs in this section are accessible from above and below, but unscaleable without advanced rock- climbing techniques.

An auxiliary section, in which cliffs can be avoided, is on the western side of Mount Mulligan, 1.2 km northwest of The Pepper Pot. This section extends from the unconformity between Hodgkinson Formation and Pepper Pot Sandstone at GR 715296, roughly north-northwest and northeast for about 600 m to a gently southwest-dipping series of pavements at GR 715300.

**Thickness.** The maximum preserved thickness of the Pepper Pot Sandstone is estimated here to be in the order of 800 m between The Oyster Cave and Narrow Neck fault zone, whereas approximately 300 m was inferred by de Keyser & Lucas (1968) from cliff heights, and nearly 400 m were intersected in the exploration well from GR 671407.

**Age.** The formation has yielded Mesozoic plant fossils (Ball, 1917), and is commonly inferred to be mainly or wholly of Lower Triassic age.

**Relationships.** The base of the Pepper Pot Sandstone is rarely exposed, and consequently difficult to characterise. Relationships to Mount Mulligan Coal Measures are probably erosional in part, but with very low angle discordance at most. Matheson (1995) reports the contact to be a low-angle unconformity, but it appears to be gradational in core from the exploration drillhole at GR 671407. The wedging out of Mount Mulligan Coal Measures in the southeastern part of the Mount Mulligan massif appears to represent onlap of the Pepper Pot Sandstone onto a palaeohigh composed of Hodgkinson Formation. The unconformity between Pepper Pot Sandstone and Hodgkinson Formation is well exposed adjacent to the auxiliary section of the former, at GR 717295.

Characterisation of relationships between Pepper Pot Sandstone and Mount Mulligan Coal Measures is also made difficult by arenite near their mutual contact being routinely assigned to the lowermost Pepper Pot Sandstone. It may actually have closer sedimentological and depositional affinities with the Mount Mulligan Coal Measures (*cf.* de Keyser & Lucas, 1968), as discussed further below.

**Subdivision, and distribution of subunits.** The Pepper Pot Sandstone was subdivided by McElroy & Bryan (1981) into two, a lower and upper unit, separated by a south-southwest trending boundary traversing the central portion of the Mount Mulligan mesa. This subdivision appears to have been made on the basis of a change of colour, which we interpret as reflecting a change of cement type, which we interpret, in turn, as transgressing the stratigraphy. However, a twofold subdivision is recognised here also, although the upper surface of the mesa is dominated by the second subunit. The subunits crop out in intergradational vertical succession. The lower subunit is absent in the exploration well at GR 671407. This subunit cannot be portrayed in the south at map scale because of its occurrence in or immediately below a vertical cliff line developed mainly on the upper subunit. Also, the lower subunit, if developed, is below the current level of exposure around most of the western edge of the Mount Mulligan mesa.

The Pepper Pot Sandstone may contain two fining-upward sequences, the contact between which occurs in the upper subunit.

## Unnamed subunit ₠p$_1$

**Correlations and distinguishing criteria.** The lower subunit of the Pepper Pot Sandstone has an overall similarity to subunit Pum$_4$ of the Mount Mulligan Coal Measures, and may be part of the same depositional cycle. The reasons for placing the Mount Mulligan Coal Measures - Pepper Pot Sandstone contact at the base of ₠p$_1$ are only that it is almost everywhere coarser than *immediately underlying* rocks; and it is commonly (but not invariably) purple in colour. "Red tuff" has been reported as defining the base of the Pepper Pot Sandstone (Matheson, 1995), but no tuff was observed during this study, and red arenite with a hematitic cement may have mistakenly been identified as tuff (see below).

**Lithology, distribution and thickness.** Subunit ₠p$_1$ is dominated by clast-supported rudite, with subsidiary arenite. The subunit mostly gives rise to steep slopes with short intervening benches. It varies in thickness from about 30 to 50 m in most parts of Mount Mulligan, including about 30 m in the type section, although lower thicknesses of about 10 m are common in the south, where Pepper Pot Sandstone overlaps Mount Mulligan Coal Measures, such as in the auxiliary section.

The subunit commonly has a hematitic cement which imparts a mid to dark purple or brick-red colour, particularly to arenite horizons.

Rudite horizons in the lower parts of the subunit typically contain well-rounded clasts up to small boulder size. In the thicker northern part of ₠p$_1$, which contains several rudite intervals, clast sizes decrease upwards to medium or large pebbles. There is also an upward increase in the proportion and/or thickness of arenite intervals, which become dominant as the subunit passes into subunit ₠p$_2$. Medium to large-scale, low to moderate-angle planar cross-stratification is conspicuous in this gradational interval.

**Clast lithology.** Clasts derived from the Hodgkinson Formation are ubiquitous and dominant. Rhyolite clasts derived from the Featherbed Volcanic Group, together with minor dacite and other rock-types, are also common in the rudite horizons and locally exceed in abundance the Hodgkinson Formation-derived material. Igneous clasts commonly appear to be more friable than clasts of similar lithology in the underlying Mount Mulligan Coal Measures rudites, possibly because they were derived from a more weathered source. If this were the case, lower Pepper Pot Sandstone could belong to the same depositional cycle as coarser upper Mount Mulligan Coal Measures, despite the grainsize difference emphasised above.

**Table 2. Source units (in addition to those listed in Table 1) for clasts in subunit Ꞧp$_1$ of the Pepper Pot Sandstone. References are to lithology of correlative units.**

| *Clast Lithology* | *Correlation* | *Comments* | *References* |
|---|---|---|---|
| Mid greenish-grey moderately crystal-rich welded rhyolitic ignimbrite | Arringunna Rhyolite and Lumma Rhyolite of the central and northern Featherbed Cauldron | | Mackenzie, 1993; Mackenzie & others, 1993 |
| Mid buff crystal-poor verging on moderately crystal-rich welded rhyolitic ignimbrite | Combella Rhyolite of the central Featherbed Cauldron | | Mackenzie, 1993; Mackenzie & others, 1993 |
| Agate | Spherulites from Fisherman Rhyolite, Combella Rhyolite or amygdales from the Nychum Volcanics | Rare | Mackenzie, 1993; Bultitude & Domagala, 1988. |

The range of possible sources of rhyolitic-dacitic material is essentially the same as that tentatively identified for equivalent material in subunit Pum$_4$ of the Mount Mulligan Coal Measures (Table 1), with some additions, as given in Table 2.

Rare clasts of medium-grained diorite are also present in subunit Ꞧp$_1$, and are associated with equally rare pink sparsely porphyritic microgranite, porphyritic medium-grained granitoid, and white fine to medium-equigranular muscovite granitoid and pegmatoid. The pegmatoid has a graphic texture, and some clasts contain quartz-tourmaline intergrowths. Other notable but rare clast types include: banded chalcedony; cockscomb-textured vein quartz, like that in the reef adjacent to the northwestern limit of the Breccia Creek Rhyolite; brecciated quartz; pyritic dacite; and pumiceous "sediment" possibly derived from Breccia Creek Rhyolite or subunit Pum$_1$ of the Mount Mulligan Coal Measures.

**Relationships and distinguishing features.** Most arenite horizons in subunit Ꞧp$_1$ of the Pepper Pot Sandstone are closely comparable to those in subunit Pum$_4$ of the Mount Mulligan Coal Measures, particularly in the sparseness of recognisable volcanic quartz grains, and in their relationship to associated rudite horizons. The main features used to distinguish Pepper Pot arenites, other than colour, are higher quartz, lower lithic, and much lower clastic muscovite contents, and a lack of carbonate cement. The higher quartz content is reflected most conspicuously in a population of scattered but ubiquitous, commonly well-rounded, quartz granules and some larger clasts.

However, arenite that crops out in places at the southern end of Mount Mulligan, between Hodgkinson Formation and the sharp (erosional?) base of the lowest rudite horizon of subunit Ꞧp$_1$, is lithic-rich and planar cross-stratified. These observations may indicate that the depositional regime of at least the lowermost part of Ꞧp$_1$ was similar to that of the uppermost Mount Mulligan Coal Measures.

**Fossils.** Silicified wood, including segments of logs up to about 50 cm in diameter and length, forms abundant float in dissected debris flows on north-facing slopes between The Square Cut and the upper reaches of Breccia Creek. Silicified wood is also moderately common in Breccia Creek itself. The float can be traced to a debris-covered interval in the lowermost part of subunit Ꞧp$_1$. Rare float of silicified wood was also observed on slopes below The Gin Bottle, farther to the northeast.

**Depositional environment.** Observations made in the lower subunit of the Pepper Pot Sandstone suggest accumulation in a fluvial and probably proximal braidplain environment broadly similar to that inferred for subunit Pum$_4$ of the Mount Mulligan Coal Measures. The combination of renewed input of very coarse detritus along with southward progradation indicates a rejuvenated drainage system. Rejuvenation was probably the result of relative uplift of source areas due to tectonic activity. The dominantly hematitic cement in the Pepper Pot Sandstone suggests an arid climate, with reduced rainfall and run-off relative to conditions during deposition of the upper Mount Mulligan Coal Measures.

### Unnamed subunit ₮p₂

**Distribution, thickness and topographic expression.** Subunit ₮p₂ makes up the bulk of the estimated maximum preserved 800 m of Pepper Pot Sandstone capping the Mount Mulligan massif. The subunit is expressed as spectacular sheer cliffs around all but the southwestern side of the mountain, where it forms benches and more subdued cliffs.

**Lithology.** Subunit ₮p₂ is dominated by medium to thick-bedded, medium to coarse-grained, commonly granule to pebble-bearing, variably lithic, feldspathic sandstone with angular to subangular grains. The sandstone is rich in detrital biotite, but mostly muscovite-poor to locally almost muscovite-free; tourmaline is a rare component. Coarse siltstone grading to fine sandstone, and massive, mostly small-pebble, rudite are uncommon. Thin and discontinuous, poorly to moderately laminated, lutite is a rare component.

An interval between about 150 and 200 m above the base of the upper Pepper Pot Sandstone consistently forms slopes rather than cliffs, and is probably dominated by fine sandstone and fossiliferous mudstone.

The subunit commonly has a hematitic cement, which gives it a mainly mid purple colour. However, rocks in the upper parts of the subunit are pale grey and tend to lack such cement, although they are apparently otherwise identical to the purple rocks. The contact between purple and grey rocks appears to transgress bedding, and is probably a consequence of groundwater movement and weathering, rather than sedimentation.

**Clasts.** Diffuse stringers and lenses of mostly matrix-supported granule to pebble-size clasts are distributed throughout subunit ₮p₂. The most conspicuous component in this coarser fraction is subangular to well-rounded white vein quartz, but clasts of Hodgkinson Formation arenite, chert, and jasper are also common. Small, variable amounts of granule to pebble-size rhyolitic clasts derived from the Featherbed Volcanics Group are also present; rhyolitic clasts of smaller size are not distinctive, but are probably derived from the Featherbed Volcanic Group or associated intrusive rocks.

**Sedimentary structures.** Individual sandstone beds in the upper Pepper Pot Sandstone are of remarkably constant thickness and lateral persistence, although a few beds are very elongate and lenticular. Individual beds tend to fine-upwards, and commonly contain low-angle planar cross-stratification; trough cross-stratification is uncommon. Large-scale channel structures can be seen in some cliff faces.

**Depositional environment.** Observations in the upper Pepper Pot Sandstone are consistent with it having accumulated in medial or distal reaches of an unconfined, mainly sandy, braidplain and/or sheetflood plain (*cf.* Blair, 1987; Rust & Jones, 1987; Walker & Cant, 1984; Young & Winston, 1990). This inference is supported by:

- the grading in, and laterally continuous sheet-like and highly attenuated lenticular nature of, bedding in the sandstone intervals;
- the local stacked sets of low-angle planar cross-stratified beds with erosional bases;
- the paucity and limited thickness of *in situ* mudstone; the existence of large-scale channel structures; and the lack of evidence for lateral restriction of the subunit at the scale of the Mount Mulligan massif.

**Fossils.** Mudstone in the interval 150 to 200 m above the base of the upper Pepper Pot Sandstone, in Geraldine Creek, is reported to have yielded Mesozoic plant fossils (Ball, 1917).

## Provenance of the Mount Mulligan sequence

Clearly, the Hodgkinson Formation has been the source of much of the clastic material represented by the Mount Mulligan sequence. However, because of the wide distribution and uniformity of constituent rock-types in the Hodgkinson Formation, and lack of detailed palaeocurrent data, it is difficult to constrain the input from this source other than in a general way. De Keyser & Lucas (1968) infer derivation from the west and southwest for the Mount Mulligan Coal Measures, whereas input from a new source to the south and east is preferred for the Pepper Pot Sandstone. Support for this provenance for the Pepper Pot Sandstone comes from its higher content of detrital biotite relative to muscovite, and its coarseness relative to the immediately subjacent Mount Mulligan Coal Measures. A change of climate coincident with this provenance change is indicated by a change from dominantly carbonate cement to hematitic cement.

The eastern source inferred to have contributed late in the deposition of the sequence is likely to have contained Mareeba-type (*cf.* Richards, 1980) or similar biotite-rich granitoid, in order to give rise to the increase of detrital biotite relative to muscovite in arenite horizons of the upper Pepper Pot Sandstone. Since lower units generally show a predominance of muscovite over biotite, such an igneous source need not be invoked for them. No clasts of either the Maneater Granodiorite or Controversy Hill Rhyolite were observed in the Mount Mulligan sequence, so that neither of these potential igneous sources was likely to have been exposed during the period of sedimentation. High-grade metamorphic detritus is also lacking, suggesting that the Georgetown Inlier and easternmost Hodgkinson Province were not significant contributors of clastic material.

Given that the coarse molasse-like material in subunit $Pum_4$ of the Mount Mulligan Coal Measures and in subunit $Ꞧp_1$ of the lower Pepper Pot Sandstone was derived from unstable elevated regions close to Mount Mulligan, it is difficult to constrain such sources to specific areas with any confidence. The presence of Featherbed Volcanic Group clasts, from a range of subgroups other than the Timber Top Subgroup (Tables 1 & 2), indicates that the Featherbed Cauldron Complex was elevated. However, such clasts are not as abundant nor as large as those in the current drainage, so that this source was of only moderate significance, and the palaeo-relief was not as great as at present. Likely loci for some of the uplift of the Featherbed Cauldron Complex include the Retina Fault and its subsidiaries, situated adjacent to and within the eastern part of the main outcrop area of Featherbed Volcanic Group.

## STRUCTURE

### Regional Structural Context

In the Mount Mulligan and adjacent areas, components of the Palmerville Fault System evidently interacted with more localised intrusion-induced concentric and radial fractures to exert significant influence on the structural framework of the late Palaeozoic Featherbed Cauldron Complex.

The Palmerville Fault and associated faults probably acted predominantly as thrusts until mid- Palaeozoic time (Shaw & others, 1987). Subsequent wrenching is strongly implied by the close association of the faults with the Featherbed Volcanic Group and penecontemporaneous passively-emplaced intrusive rocks in a composite volcano-tectonic cauldron structure. The location of these subsidence structures on the concave eastern side of a marked bend in the *Palmerville Fault*, together with their rhomboid shape, are strongly suggestive of a setting in the transtensional "releasing bend" of a sinistral wrench system. The entire Featherbed Cauldron Complex could be an extremely large "negative flower structure" (*cf.* Harding & others, 1985), with the Mount Mulligan area lying in an outer, eastern, part.

Fault morphologies in the Mount Mulligan area are consistent with their having undergone wrenching at least at some stage of their development, because they are braided and have varied dips. Further, a local tectonic model involving translation of the Mount Mulligan area relative to the Featherbed Cauldron complex after eruption helps explain the absence from the Mount Mulligan Cauldron of a thick and varied volcanic sequence typical of the Featherbed Volcanic Group. It also helps to explain the lack of good evidence for high palaeotopography, comparable to that which can be inferred for the adjacent part of the Featherbed Cauldron. This lack of evidence is exemplified in the absence of clasts of either the Maneater Granodiorite or Controversy Hill Rhyolite in the Mount Mulligan sedimentary sequence.

## Structure of Late Palaeozoic igneous rocks

### Intrusive Rocks

A near-orthogonal system of high-angle fractures appears to have strongly influenced the emplacement of the late Palaeozoic intrusive rocks in the Mount Mulligan area. This rectilinear geometry is anomalous in the context of volcanic subsidence structures of the Featherbed Volcanic Group, the remainder of which are ovoid.

The distribution of the Maneater Granodiorite and to a lesser extent the Controversy Hill Rhyolite show rectilinear geometry to advantage. The steeper contacts of these units with their country-rocks trend dominantly north-northwest, while an east-northeast trend is subordinate.

Displacement along some representatives of both sets of fractures appears to have been dip-slip, and to have taken place pre- and syn-emplacement. Brittle shearing is also evident on at least the north-northwest set.

*"Bell-jar" plutonism.* Broadly, the morphology of the late Palaeozoic intrusive rocks in the Mount Mulligan area can be described in terms of disrupted and incomplete, rectilinear, "bell-jar"-type plutons (*e.g.*. Pitcher, 1978). For example, the flat-lying roof of the Maneater Granodiorite lies within Featherbed Volcanic Group remnants outside of the Djungan Cauldron proper, whereas its steep margins form part of the Mount Harris Dyke, described further below; there is continuous granodiorite outcrop between these two portions. Controversy Hill Rhyolite can be included as part of this same body.

This "bell-jar" geometry is perhaps also shared by some of the unassigned intrusive rhyolite bodies intruding the Maneater Granodiorite, notably in the northern part of the volcanics, where both flat-lying and sheet-like geometry is apparent in similar rock-types. Similarly, intrusive rhyolite in the Controversy Hill area, perhaps of pre-Maneater Granodiorite age, and rhyolite in the upper Sardine Creek, may respectively comprise the flat-lying and steep portions of a "bell-jar' body. A gently north-dipping sheet up to about 50 m thick crops-out at the contact between unnamed pyroclastic rocks in and overlying Controversy Hill Rhyolite. Apparently identical rhyolite, in the area of upper Sardine Creek immediately west of Mount Mulligan, which is largely fault-bounded and nearly 2 km long, appears to have been emplaced as a steep body.

*Mount Harris Dyke.* The contacts of the compound north-northwest-striking *Mount Harris Dyke*, made up of the portions of Maneater Granodiorite and Controversy Hill Rhyolite which strike through Mount Harris (*ca.* GR 700 300), have local moderate westerly dips. The eastern contact between Grainers Gully and Wasons Gap is notable in this respect. This part of the dyke consists entirely of Maneater Granodiorite, and passes north of Grainers Gully into a gently- to moderately-dipping sheet probably at least 200 m thick. The site of a precursor fracture beneath the sheet may be marked by a lineament west of Sardine Creek. The transition from steep to gentle attitude is abrupt, and coincides with the change northwards and to higher altitude from Hodgkinson Formation to Timber Top Volcanic Subgroup country rocks. The moderate to gentle attitude and sheet-like form appears to be maintained wherever the Timber Top Volcanic Subgroup is the host.

*Little Watson Creek.* Near the confluence of Sardine and Little Watson Creeks, Maneater Granodiorite constitutes a steep east-northeast-striking body intruding Hodgkinson Formation. The eastern portion of this body includes scattered small plugs separated by Hodgkinson Formation, rather than a single coherent body. This style of intrusion suggests that the present exposure in that area approximates the roof or the side of the Maneater Granodiorite pluton.

### Tectono-magmatic interpretation

The Mount Harris Dyke and the dyke near the confluence of Sardine and Little Watson Creeks may be regarded as intrusions along the peripheral fractures of a system delimiting the northeastern boundary of the Featherbed Cauldron. These fractures evidently were not the locus of substantial amounts of subsidence and infilling as were other more centrally located fracture systems. Orthogonal fracture sets and intrusions may indicate an irregular segmentation of basement rocks inside the peripheral fracture system.

 

The main fracture system around the Mount Mulligan Cauldron appears to have been overprinted by that associated with the Djungan Cauldron, suggesting that the rocks contained in the latter are younger than the Timber Top Volcanic Subgroup and associated intrusive rocks. Relative subsidence in the Mount Mulligan Cauldron appears to have been slight, so that with erosion, the volcanics have been partly stripped, and Hodgkinson Formation basement exposed. The stratigraphic base of preserved Timber Top Volcanic Subgroup in the Mount Mulligan Cauldron lies at an elevation of about 600 m, and is fairly constant. Parts of the sequence adjacent to the peripheries are not greatly oversteepened, supporting the suggestion of slight subsidence.

Breccia Creek Rhyolite probably marks the position of a vent, the only vent which can be located with some confidence in the Timber Top Volcanic Subgroup. This inferred vent is located in the vicinity of the northeastern corner of the peripheral fracture system of the Mount Mulligan Cauldron. The local sequence has the form of a north-northwest-elongated basin, only partly bounded and segmented by faults and intrusions subsidiary to those associated with the peripheral fractures. Since no evidence of an independent fracture and intrusion system is developed around this inferred vent, subsidence there is likely to have taken place in concert with subsidence over a broad area, as opposed to having been localised above a separate small magma chamber as it was evacuated. Further support for this model of broadly-based subsidence comes from the subsurface environment, where there is the combination of the inferred "bell-jar" style of plutonism, discussed above, and the presence of widespread, relatively uniform, sheet-like eruptive deposits.

## Structure of the Mount Mulligan sequence

### Broad structural setting

The Mount Mulligan sequence represents an asymmetrical north-northwest-elongated basin. Reactivation of pre-existing faults probably had a far more profound influence on basin development than did the development and motion of new structures.

The major axis of the basin is parallel to the three major local structures. The western boundary in the south coincides with a substantial fault zone, the Wasons Gap Fault Zone, and the Hurricane and Kondaparinga Faults delimit the western and eastern margins of the exposure respectively. The basin may have formed in response to east-side-down motion on the Wasons Gap and Hurricane structures, and west-side-down motion on the Kondaparinga Fault. However, the basin is probably too large to be entirely accommodated for by fault drag, and significant contributions from increments of drag on concealed faults, from active basement downwarping, and from post-Pepper Pot Sandstone compressional folding should also be considered (*e.g.* Matheson, 1995).

The basement topography beneath the Mount Mulligan Coal Measures, as indicated by the distribution of its lower subunits, appears to have been irregular as a result of pre- and perhaps syn-depositional fault movements. Later fault movements resulted in local steepening and over-steepening of beds. An open syncline is developed parallel to the major structures, and has been related to post-Triassic uplift (Whitby, 1975).

### Subunit distribution & thickness variation as evidence of pre- and syn-depositional faulting

The nature of basement directly below Mount Mulligan Coal Measures, and the distribution of subdivisions within the lower part of the sequence, contrast markedly across the Emu Pocket Branch of the Wasons Gap Fault Zone. This suggests significant faulting immediately before accumulation of the sequence, although some degree of syn-depositional activity cannot be ruled-out.

West of the Emu Pocket Branch fault, the Mount Mulligan Coal Measures rest on Breccia Creek Rhyolite. The latter has not been observed to the east, where the coal measures lie on Hodgkinson Formation instead. This relationship strongly suggests that an episode of faulting took place prior to deposition of the coal measures. Such faulting would have been dominantly west-side-down relative displacement, presumably of at least the 200 m sufficient to completely erode the Breccia Creek Rhyolite, and/ or have involved lateral wrenching.

*$Pum_1$, $Pum_2$*. The restriction of subunits $Pum_1$ and $Pum_2$ to the area west of the Emu Pocket Branch fault may indicate additional relative west-side-down movement on the structure during the time of their accumulation. However, coarse clastic sediments were not observed adjacent to the fault, suggesting that a marked palaeotopographic scarp was not developed, perhaps indicating that any fault was a blind, growth-type, structure.

*$Pum_3$*. The confinement of subunit $Pum_3$ to the east side of the Emu Pocket Branch may indicate a short-lived reversal of movement to east-side-down during or shortly after its accumulation, but again without production of coarse clastic material.

Localisation of coal-rich intervals in subunit $Pum_3$ may also have been influenced by contemporaneous or penecontemporaneous fault movements.

*$Pum_4$*. Most faulting had evidently ceased by the time that subunit $Pum_4$ was deposited, as this unit appears to have prograded across the structures. Nevertheless, western branches of the Kondaparinga Fault Zone may have remained active as a broad zone, with east-side-down relative movement, in the vicinity of The Oyster Cave, where $Pum_4$ attains its maximum preserved thickness. The southern limit of the subunit (as a mappable entity) in the Crab Hollow area, may in part coincide with splays diverging from the Kondaparinga Fault Zone.

*Pepper Pot Sandstone*. Lateral thickness or facies variations consistent with pre- and syn-depositional fault activity were not observed in the Pepper Pot Sandstone. However, an episode of source structural reactivation may be indicated by the probable second fining-upward cycle recorded by subunit $\text{Ꝛ}p_2$.

## Post-depositional faults

The pre-existing system of brittle-fractures and fault zones in the Mount Mulligan area are probably outlying components of the Palmerville Fault system, with similar origin, essential attributes, and early evolution (*cf.* Shaw & others, 1987). Steep reactivated brittle faults appear to be the dominant type of structure cutting the Mount Mulligan Coal Measures and Pepper Pot Sandstone. These faults are mainly north-northwest- to northwest-striking, and are expressed at outcrop scale as narrow zones of granulation and perhaps clast rotation. Sympathetic and reverse-sense oversteepening of beds adjacent to individual faults within the main fault zones was observed locally. The fault zones are commonly collinear with the older fracture/intrusion system discussed above, and thus can readily be regarded as reactive of them.

Faults which are approximately orthogonal or oblique to these main fault systems have not been observed.

There has, however, been a degree of disruption along the basal unconformity of the Mount Mulligan sequence. Gently-dipping faults have also been recorded from early coal workings at about the site of King Cole mine (Ball, 1912).

## Fault descriptions & interpretations

*Wasons Gap Fault Zone*. Most of the present western boundary of the Mount Mulligan sequence is marked by the Wasons Gap Fault Zone, a braided series of faults which extends from the southern Gipps Hills to the southern side of Narrow Neck. For much of this distance the zone is subparallel to, although offset slightly from, the eastern edge of the Mount Harris dyke. The south of the fault zone apparently represents a preferential development of a south-southeast-striking conjugate shear system.

At Narrow Neck the Wasons Gap Fault Zone splits into two branches. The eastern *Emu Pocket Branch* extends from Narrow Neck past The Gin Bottle into Emu Pocket essentially as an extrapolation of the main fault zone. It continues into the area of confluence of Breccia and Gorge Creeks, but farther north its course is uncertain. It may trend northwesterly and rejoin the western branch (below).

The *western branch* of the Wasons Gap Fault Zone follows Sardine Creek to opposite The Square Cut; north of there it defines the western boundary of Breccia Creek Rhyolite, and equates with the *Hurricane Fault* of Halfpenny & others (1987).

 

The braided nature of the Wasons Gap Fault Zone may be modelled by the development of oblique bridging across the overlap between two originally separate left-stepping *en echelon* faults. These in turn may have been the successors of a single, gently east-flexed, structure whose southern part was intruded and stitched by the late Palaeozoic intrusions. Post-intrusion movement would thus have had to be accommodated by a new fault alongside (east) of the stitched segment, and thus offset from the northern segment, which remained at its original site and was reactivated. Given this model, zones of milled breccia within Maneater Granodiorite in Sardine Creek at GR 643378, indicate that reactivation of the southern segment may have commenced soon after its intrusion and the resultant stitching, while waning magmatism was still able to give rise to explosive hydrothermal activity.

The Wasons Gap Fault Zone appears broadly subvertical, but component faults in both the main zone and its branches vary in their dips, and perhaps in their relative displacements also.

*Kondaparinga Fault Zone.* The eastern boundary of the Mount Mulligan sequence coincides with, or is a short distance west of, a west-northwest-striking fault zone, the Kondaparinga Fault of Halfpenny & others (1987). This fault zone is mostly less well marked and less well known than those to the west of Mount Mulligan.

Several component faults of the Kondaparinga Fault Zone appear to diverge markedly from its overall trend, to trend southeasterly. This may indicate a series of "horsetail" splays, and mark an approach to the southern termination of the fault as a single structure.

The Kondaparinga Fault Zone may show similar complexity at the component fault scale to the Wasons Gap Fault Zone.

*Gorge Creek.* The crudely linear north-northwest course of most of Gorge Creek on the Mount Mulligan plateau may indicate a concealed fault or one which incompletely penetrates the Mount Mulligan sequence. No distinct evidence for a continuation of such a structure was observed north of the Mount Mulligan massif. However, variations in the thickness of the Mount Mulligan Coal Measures between Gorge Creek and The Ram could relate to basement faulting along such a structure.

The timing of the last episode(s) of post-Pepper Pot Sandstone brittle fault reactivation is not known - it could have been late Mesozoic to Cainozoic. Observed slickensides associated with the *Wasons Gap Fault Zone* at GR 714296, which are presumably related to this late activity, plunge 65° north, 30° east, and 25° northwest on surfaces dipping 80° to azimuth 095°, 30° to azimuth 090°, and 50° to azimuth 255° respectively; slickensides on a horizontal surface at the same locality strike 045°.

### Folding

Folding of the Mount Mulligan sequence has been ascribed to post-Triassic warping (Whitby, 1975) and, at the local scale, to fault-drag. A syncline is developed along the western boundary of the sequence in the south, striking north-northwest, and is termed the Grindstone Hill Syncline (Whitby, 1975). A monocline was also observed in Emu Pocket, but no clear evidence for such a structure was observed here. No folds with east or north-east trending axes were observed in the Mount Mulligan sequence.

## MINERAL DEPOSIT AND COAL POTENTIAL

The mineral deposit potential of the Mount Mulligan area has been considered briefly by Oversby (1987) and by Garrad (1993), and will be dealt with briefly here. Garrad (1993) provides a comprehensive summary of available data from mineralisation in the Mount Mulligan 1:100 000 sheet area.

The potential for exploitable coal resources in the Mount Mulligan sequence is extremely limited, because even though coal development may be widespread, it is confined to four thin seams which reach a maximum intersected thickness of about 2 m (Ball, 1910; 1912; 1917), and is of relatively low quality (Matheson, 1995). Coal resource potential will not be discussed further.

 

## Gold-antimony

Vein-type gold-antimony deposits hosted by Hodgkinson Formation occur in and adjacent to the Mount Mulligan area (*e.g.*, Gregory *et al.*, 1980). Significant historical gold production is recorded from the General Grant and Tyrconnel Mines at Kingsborough, a main centre of the former Hodgkinson Goldfield (*e.g.* Garrad, 1993). These mines are associated with the Retina and Kingsborough Faults and with what may be splays of the Kondaparinga Fault.

## Alteration

Intensely sericitised-kaolinised, and less commonly silicified and quartz-veined late Palaeozoic igneous rocks of all types excluding the Maneater Granodiorite, occur locally along and adjacent to some of the major fault zones. This observation supports the potential for late Palaeozoic mineralisation.

The most conspicuous altered localities observed in the area are: along the northern part of the Wasons Gap Fault Zone, opposite Grindstone Hill, where mainly unnamed intrusive rhyolite is altered, and; in the southern Hurricane Fault Zone to the north of Timber Top, where Hodgkinson Formation, Breccia Creek Rhyolite ($CPv_1$), and Controversy Hill Rhyolite, as well as unnamed intrusive rhyolite, are altered. At the latter locality, quartz-veining is more common than elsewhere. There is also a substantial north-northwest-striking reef of quartz, with textures indicating open-space filling, occupying a breccia zone in Hodgkinson Formation.

Less notable altered localities observed include: south of Controversy Hill, where mainly Controversy Hill Rhyolite and unnamed pyroclastic rocks are altered, adjacent to what may be an early northeast-striking fault zone; pyroclastic and associated intrusive rhyolite in the southwestern part of the area described in this report; near the confluence of Little Watson and Sardine Creeks, where a site south of the intrusive boundary of the compound dyke is marked by a north-northwest-striking quartz reef in Hodgkinson Formation. The reef extends discontinuously into a fault-slice of altered unnamed pyroclastic rocks, where it forms scattered northwest-striking stringers and veins. The second locality listed does not appear to be linked to a known structure.

## Deep lead-style deposits

In view of the proximity of coarse fluvial-alluvial sedimentary rocks in the Mount Mulligan Coal Measures and the Pepper Pot Sandstone to exposed Hodgkinson Formation hosted vein-type gold deposits, it is plausible that palaeo-alluvial concentrations could occur in appropriate settings within the Mount Mulligan sequence. This possibility was apparently investigated, without success, by Ball (1912).

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