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RESEACH ARTICLE

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Large phreatomagmatic vent complex at Coombs Hills, Antarctica: Wet, explosive initiation of flood basalt volcanism in the Ferrar-Karoo LIP

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Abstract The Mawson Formation and correlatives in the Transantarctic Mountains and South Africa record an early eruption episode related to the onset of Ferrar-Karoo flood basalt volcanism. Mawson Formation rocks at Coombs Hills comprise mainly ($\geq$80% vol) structureless tuff breccia and coarse lapilli tuff cut by irregular dikes and sills, within a large vent complex ($>$30 km^2). Quenched juvenile fragments of generally low but variable vesicularity, accretionary lapilli and country rock clasts within vent-fill, and pyroclastic density current deposits point to explosive interaction of basalt with groundwater in porous country rock and wet vent filling debris. Metre-scale dikes and pods of coherent basalt in places merge imperceptibly into peperite and then into surrounding breccia. Steeply dipping to sub-vertical depositional contacts juxtapose volcaniclastic rocks of contrasting componentry and grainsize. These sub-vertical tuff breccia zones are inferred to have formed when jets of debris + steam + water passed through unconsolidated vent-filling deposits. These jets of debris may have sometimes breached the surface to form subaerial tephra jets which fed subaerial pyroclastic density currents and fall deposits. Others, however, probably died out within vent fill before reaching the surface, allowing mixing and recycling of clasts which never reached the atmosphere. Most of the ejecta that did escape the debris-filled vents was rapidly recycled as vents broadened via lateral quarrying of country rock and bedded pyroclastic vent-rim deposits, which collapsed along the margins into individual vents. The unstratified, poorly sorted deposits comprising most of the complex are capped by tuff, lapilli tuff and tuff breccia beds inferred to have been deposited on the floor of the vent complex by pyroclastic density currents. Development of the extensive Coombs Hills vent-complex involved interaction of large volumes of magma and water. We infer that recycling of water, as well as recycling of pyroclasts, was important in maintaining water supply for phreatomagmatic interactions even when aquifer rock in the vent walls lay far from eruption sites as a consequence of vent-complex widening. The proportion of recycled water increased with vent-complex size in the same way that the proportion of recycled tephra did. Though water recycling leaves no direct rock record, the volcaniclastic deposits within the vent complex show through their lithofacies/structural architecture, lithofacies characteristics, and particle properties clear evidence for extensive and varied recycling of material as the complex evolved.

Keywords LIP · Flood basalt · Peperite · Pyroclastic · Phreatomagmatic · Gondwana · Continental break-up

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Introduction

Although flood basalt eruptions are traditionally viewed as overwhelmingly effusive, a new picture of composite large igneous province (LIP) volcanism, which recognizes a range of magma compositions and eruptive styles, is emerging (e.g., Mahoney and Coffin 1997). The importance of large igneous provinces lies in their temporal association with continental break-up (Dalziel et al. 2000), in the radical effects their eruptions had on landscapes, and in the impact of large volume eruptions on climate through injection of volcanic aerosols into the atmosphere (Rampino and Self 1984; Thordarson and Self 1996; Thordarson et al. 2003). Climate change coincident with flood basalt eruptions has been implicated in mass extinctions, such as the Permian extinction (Siberian Traps) and the extinction at the Cretaceous-Tertiary boundary (Deccan Traps) (Renne et al. 1995; Wignall 2001). Explosive volcanism provides a much more efficient vehicle for injection of climate-modifying ash and aerosols such as sulphur and chlorine into the atmosphere than purely effusive volcanism (Thordarson et al. 2003). This work describes one type of volcano formed during an explosive flood basalt eruption and extends our understanding of the possible styles of explosive flood basalt eruptions and the structure of the volcanoes that form during such eruptions; by describing the physical form and evolution of one such volcano, it can inform future studies of how flood basalt volcanism might have contributed to past climate change.

Recent work has established that effusion of flood basalt is preceded and accompanied by explosive volcanism, both basaltic and silicic (Pankhurst et al. 2000; Elliot and Hanson 2001; Marsh et al. 2001; Ross et al. 2005). Development of a rift system during Jurassic-Early Cretaceous fragmentation of Gondwana created a setting in which rising Ferrar-Karoo flood basalts intercepted a water-saturated terrestrial sedimentary succession to form large hydrovolcanic fields represented along thousands of outcrop kilometres in the Transantarctic Mountains (Fig. 1). Volcaniclastic rocks deposited during formation of this volcanic field include massive to bedded tuff and tuff breccia, with some widespread, thick, accretionary lapilli-bearing units (Hanson and Elliot 1996; Elliot and Hanson 2001).

At Coombs Hills, South Victoria Land, Antarctica (Fig. 1) interaction of Ferrar Group magmas with water-bearing sedimentary material is recorded in the Mawson Formation by extensive peperite, hyaloclastite and irregular intrusive masses intermixed with tuff, coarse lapilli tuff and tuff breccia. The Coombs Hills provide extensive (>30 km^2) and excellent exposure of these basaltic volcaniclastic rocks, along with syn-volcanic intrusive complexes. The deposits represent a vent complex inferred to have formed by coalescence of many single phreatomagmatic centres, and include features that inform us about processes of vent coalescence and transport of debris within debris-filled vents generally. This complex also represents a volcanic centre of a size and type capable of producing the huge volumes of volcaniclastic debris preserved at the base of many LIP successions worldwide (Ross et al. 2005), the volcanic centres from which they derive having been enigmatic until now. This paper examines the physical volcanology and sedimentology of the Coombs Hills vent complex, and provides an interpretation of the eruption processes by which it was formed.

Regional geology

The Gondwana sequence in the Transantarctic Mountains comprises a flat-lying, relatively thin (ca. 2 1/2 km) succession of Beacon Supergroup sedimentary rocks (Barrett 1970) atop the early Paleozoic Ross orogenic belt, intruded and capped by tholeiitic Ferrar-Karoo LIP sills, dikes, flows and volcaniclastic rocks (Elliot 2000). The Ferrar-Karoo LIP in Antarctica consists mainly of the Dufek intrusion (Fig. 1) (0.6×10^6 km^3) and Ferrar Dolerite sills (1.1–1.7×10^6 km^3), plus locally preserved Kirkpatrick flood basalts and volcaniclastic rocks of the Carapace Sandstone, and Mawson, Exposure Hill and Prebble Formations (Fig. 1) (Elliot 2000). U/Pb and Ar/Ar dating indicate that the Ferrar-Karoo igneous event took place over a short interval in the Middle Jurassic at ca. 180 Ma (Riley and Knight 2001).

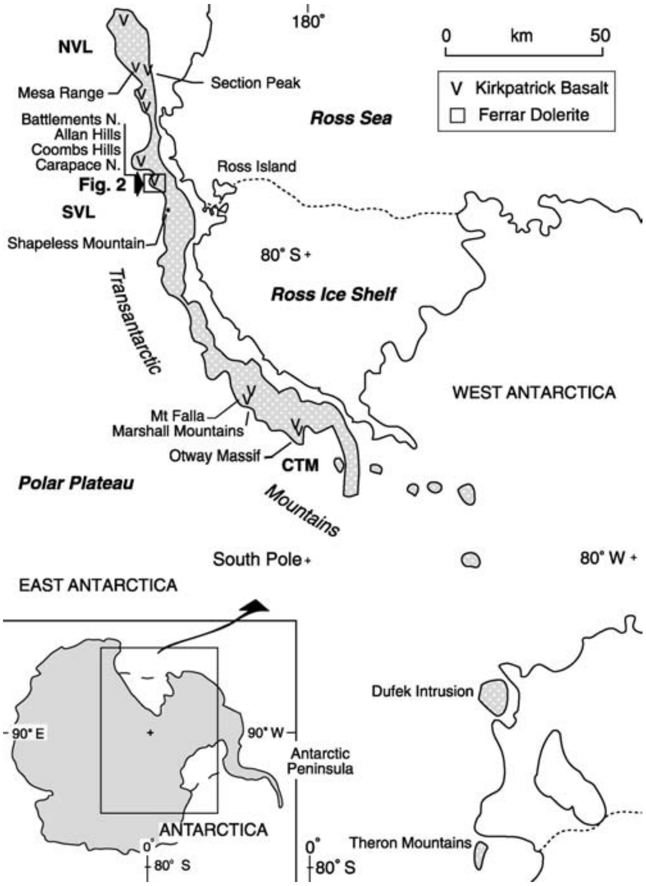


Fig. 1 Ferrar Large Igneous Province (Ferrar Supergroup) in Antarctica, after Elliot (2000). Note linear trend of Ferrar Supergroup rocks along the Transantarctic Mountains (mainly thick Ferrar Dolerite sills), and scattered remnants of Kirkpatrick flood basalt. Co-magmatic basaltic volcaniclastic rocks crop out in the Central Transantarctic Mountains (*CTM*) at Otway Massif, Marshall Mountains, and Mt Falla (Prebble Formation), in South Victoria Land (*SVL*) at Battlements Nunatak, Allan Hills, Coombs Hills, Carapace Nunatak, and Shapeless Mountain (Mawson Formation), and in the Mesa Range in North Victoria Land (NVL) (Exposure Hill Formation). Silicic tuff immediately underlies Ferrar Supergroup at Section Peak (*NVL*), Mt Falla (*CTM*) and Coombs Hills (Elliot et al. 2004)

Organisation and terminology

In this paper, country rock and coherent igneous rock units present are first introduced briefly, then volcaniclastic lithofacies of the Mawson Formation are elaborated based on rock type, grainsize, structure and componentry of deposits (Table 1). Codes defined in Table 1 are used subsequently in the text. Rock descriptions are derived from field and thin section observations. We describe these rocks using a modified form of the IUGS classification for volcaniclastic rocks (Schmid 1981). All volcaniclastic rocks are named according to grainsize (ash, <2 mm, lapilli, 2–64 mm, and block (lithic) and bomb (juvenile), >64 mm), and variations within grainsize classes are noted by prefixing rock names with modifiers that describe componentry, deposit texture and structure, chemical composition of volcanic clasts, and depositional process. Bed thickness follows Ingram (1954): laminated, <1 cm; very thinly

Table 1 Lithofacies divisions and lithofacies associations within the Mawson Formation at Coombs Hills

Deposit characteristics	Tuff breccia 25–75% block	Lapilli tuff 25–75% lapilli	Tuff >75% ash	Lithofacies association
Polymict, non-bedded		L0	T0	Bedded tephra lithofacies association (LAbt)
Juvenile-rich, non-bedded		L0j		
Block-rich, weakly coarse-tail normal graded	TB1			
Weakly stratified beds	TB2			
Normally graded beds		L3	T3	
Beds with crude internal stratification	TB4j	L4	T4	
Thinly stratified, alternating coarse & fine layers in thicker bedsets		L5	T5	
Laminated beds			T6	
Low angle cross-stratified beds			T7	
Polymict, non-bedded	TB0u			Cross-cutting breccia lithofacies association (LAcb)
Juvenile-rich, non-bedded	TB0j			
Lithic-rich, non-bedded	TB0l			
Peperite				
Hyaloclastite				
Dikes				
Megablocks of Victoria Group				
Volcaniclastic rafts				
Clastic dikes				

Divisions (tuff breccia, lapilli tuff, and tuff) are based on grainsize, componentry and structure. Lithofacies codes indicate grainsize (TB = tuff breccia, L = lapilli tuff, T = tuff) and deposit structure (0 = non-bedded, with higher numbers indicating increasing deposit structure). Subscript 'j' denotes ≥75% juvenile content ('juvenile-rich'); subscript 'l' denotes ≥75% lithic content ('lithic-rich'). Unoccupied fields in the table represent rock types not observed in the field. Recurring lithofacies assemblages led us to define two lithofacies associations: Lithofacies in the lightly shaded division collectively form the bedded tephra facies association, and lithofacies in the heavily shaded division make up the cross-cutting breccia lithofacies association. Table 2 describes each lithofacies in detail and provides an interpretation of fragmentation and transport processes

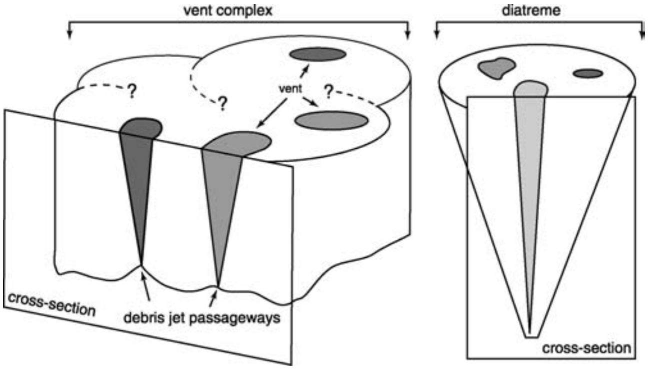


Fig. 2 Cartoon showing how closely spaced vents, each the surface expression of a debris jet passageway, together form the Coombs Hills vent complex. Clusters of vents (different *grey shades* represents subtle contrasts in composition of vent fill) that were active at the same time (*left*) might otherwise be described as diatremes if isolated as a single structure (*right*) (e.g., Lorenz 1986); because the boundaries between single active centers are not clearly defined at Coombs Hills, we describe the cluster of vents as a vent complex

bedded, 1–3 cm; thinly bedded, 3–10 cm; medium bedded, 10–30 cm; thickly bedded, 30–100 cm; very thickly bedded, >1 m. Percentages of volcaniclastic components, vesicularity (<15% vesicles-dense; 15–50% vesicles-moderate; >50% vesicles-highly vesicular) and sorting of Mawson Formation deposits are visually estimated.

Twenty-two lithofacies, grouped into two lithofacies associations, are defined for the Mawson Formation at Coombs Hills (Tables 1, 2). Lithofacies associations are defined for groups of lithofacies on the basis of (1) spatial association; (2) contact relationships, including both bedding contacts and crosscutting ones, and; (3) inferred genetic relationships. Two broad associations arise, with one representing deposits formed on subaerial depositional surfaces (bedded tephra lithofacies association, LAbt), and the other an amalgam of vent-filling deposits with diverse histories (cross-cutting breccia lithofacies association, LAcb). The cross-cutting breccia lithofacies association (LAcb) comprises a range of largely structureless coarse lapilli tuff and tuff breccia characterised by complex cross-cutting contacts, large blocks and rafts of other material, and numerous penecontemporaneous intrusions. Bedded volcaniclastic rocks are confined to the stratigraphically highest parts of the Mawson Formation and make up the bedded tephra lithofacies association (LAbt).

Each lithofacies description is accompanied by interpretation of transport and depositional processes (summarised in Table 2). The lithofacies associations within the Mawson Formation are then characterised and the range of transport and deposition processes inferred to have been important in their formation discussed before concluding with an overall interpretation of the Mawson Formation in the context of all rock units at Coombs Hills. We think that the operation

Table 2 Summary of lithofacies characteristics and inferred fragmentation and transport modes for lithofacies and lithofacies associations of the Mawson Formation at Coombs Hills

Lithofacies	Description	Fragmentation	Transport
Lithofacies association bedded tephra (LAbt)	*Localized successions of bedded tuff and lapilli tuff (up to $\geq$30 m thick) resting on cross-cutting breccia lithofacies association (LAcb) deposits on the upper slopes of the Pyramid and on the North Ridge (Fig. 4, Fig. 7) or forming discrete, steeply dipping tabular bodies a few metres thick within tuff breccia now part of the cross-cutting breccia lithofacies association (see " volcaniclastic rafts" below; Fig. 7). The North Ridge exposures are of bedded volcaniclastic rocks isolated within Ferrar Dolerite intrusions or Mawson Formation tuff breccia. Bed contacts are mainly depositional with some channeling and scours, and dips range from sub-horizontal to $\geq 30^\circ$*	*Dominantly phreatomagmatic*	*PDC + fall*
L0 Structureless lapilli tuff	Poorly to moderately sorted lapilli in coarse ash matrix. Locally shows openwork, matrix-free fabric or partially clast-supported fabric with minor interstitial ash. Tuff, mudstone, siltstone, & quartz sandstone lithics (up to 15 mm) abundant. Sub-equant and blocky or ribbon-like juvenile ($<$5–40% vesicles) clasts, isolated accretionary & armoured lapilli (Fig. 8). Clast orientation and imbrication defines weak sub-horizontal fabric. Poorly defined internal layers separated by diffuse contacts. Thin to thick, plane-parallel beds bounded by well-defined, sharp to irregular contacts; some large clasts occupy impact sags. Broad, shallow (0.5–2 m wide by $\leq$0.5 m deep) channels form some basal contacts	Phreatomagmatic	Damp, dense PDC
T0 Structureless tuff	Moderately to poorly sorted, medium to coarse ash-sized juvenile, lithic & composite clasts (Fig. 8). Accretionary lapilli to ash common, volumetrically dominant in some layers. Gradational contacts with under- & overlying beds	Phreatomagmatic	Fall or damp, dense PDC?
L0j Structureless juvenile-rich lapilli tuff	Amoeboid to blocky juvenile (20–40% vesicles) lapilli & rare bombs ($\geq$80%), composite (10%) & lithic lapilli (10%). Matrix comprises blocky or ragged juvenile ash & fine lapilli (75–85%), & subangular lithic clasts (15–25%). Up to 20% openwork texture (now cemented). Coarser-grained than L0, with higher lapilli:ash ratio. Closely packed juvenile clasts show accommodation to adjacent lapilli, with localised clast-support. Majority of juvenile grain margins irregularly fluidal; some smoothly curving clast margins. Some L0j lithofacies mainly elongate, attenuated, highly irregular juvenile clasts with ragged terminations; preferred orientation of flattened clasts defines diffuse planar fabric. Limited lithic diversity; basalt lithic clasts rare to absent	Magmatic to phreatomagmatic	Fall or dry, dense PDC?
TB1 Coarse-tail normal-graded block-rich tuff breccia	Matrix- to locally framework-supported, unbedded, weakly coarse-tail normal-graded block-rich tuff breccia of TB1 lithofacies forms sub-horizontal ($\leq 5^\circ$), 2–3 m thick pinching-and-swelling beds (Fig. 7, Fig. 9) on the Pyramid (Fig. 3). Contacts with underlying TB0u or L0 lithofacies are defined by abrupt (cm scale) or diffuse (dm-m scale) increase in proportion of blocks, particularly feldspar and pyroxene-phyric basalt and country rock lithics (Fig. 10). Angular to sub-angular, non-vesicular to incipiently vesicular, glassy to finely crystalline dark brown or black basalt blocks contrast with light brown, fluid-form once-glassy basalt bombs. Includes composite clasts. Country rock lithics comprise sub-angular sandstone clasts, blocky to globular coal clasts and silicic tuff plus sub-angular to sub-spherical quartz (75%), feldspar (20%), and accessory biotite, hornblende and garnet grains. Basal contacts undulate on dm-m scale, with common impact sags. Crude alignment of flat or elongate clasts defines a weak sub-horizontal fabric. The poorly sorted lapilli tuff matrix comprises juvenile, country rock lithic and composite clasts with rare microcrystalline basaltic clasts. Blocky to amoeboid, dense to moderately vesicular ($\leq$30% vesicles) juvenile clasts (up to 75% vol) show smoothly curving margins. Weakly vesicular blocky clasts predominate, and some amoeboid clasts have weakly aligned trains of elongate vesicles; blocky clasts contain sub-spherical vesicles	Phreatomagmatic	Fall and/or dense PDC?

Table 2 Continued

Lithofacies	Description	Fragmentation	Transport
TB2 Weakly bedded tuff breccia	Componentry as for nonbedded TB0u lithofacies (see below). Crude, metre to tens of metre scale normal grading and weakly developed bedding. Stratification defined by crude orientation of lapilli or blocks, broad, shallowly dipping scours, diffuse, laterally impersistent lapilli trains, or plane-parallel, gradational contacts with interbedded lenses and layers of lapilli tuff	Phreatomagmatic	Damp, dense PDC
L3 Normally graded lapilli tuff	Componentry, sorting & clast orientation as for L0 lithofacies. Basal lapilli grades into lapilli plus coarse ash to coarse ash at tops of beds (1–15 cm thick). Gradational contacts with laminated or wavy bedded ash. Rare attenuated, ribbon-like juvenile fragments deformed against adjacent clasts. Locally brittly fractured lithics, some jigsaw-fit. Includes accretionary lapilli-rich bed with lapilli folded or flattened parallel to base of the bed; some smeared or plastered against adjacent clasts, forming densely packed aggregates of overlapping lapilli. Rare loading structures, asymmetric basal bedding plane sags (Fig. 8)	Phreatomagmatic	Damp, dense PDC
T3 Normally graded tuff	Componentry, sorting & clast orientation as for L3 lithofacies. Basal coarse to medium tuff grades into fine tuff at tops of 3–10-cm-thick beds (Fig. 8). Sharp to gradational contacts with over- and underlying beds	Phreatomagmatic	Damp, dense PDC
TB4j Crudely stratified juvenile-rich tuff breccia	Componentry as for structureless TB0j lithofacies. Attenuated, highly irregular ribbon bombs and ragged clasts common, some ≥1.5 m in length. Bombs show accommodation to underlying blocks. Alignment of flattened or elongate fluidal clasts defines a weak sub-horizontal fabric. Forms poorly defined beds 1–7 m thick showing diffuse, highly irregular, gradational contacts with adjacent units; beds laterally persistent for ≥15 m	Magmatic to phreatomagmatic	Fall or dry, dense PDC?
L4 Crudely stratifed lapilli tuff	Poorly sorted lapilli tuff: vague planar bedding (dm- to m-scale) defined by clast orientation or diffuse, laterally persistent lapilli trains. 35–75% amoeboid to ribbon-like juvenile clasts in matrix and coarse fractions. Tuff matrix incl. sub-spherical to sub-angular juvenile, lithic and composite clasts. Contacts are diffuse, irregular and gradational. Some broad, shallow U-shaped channels within the sequence scour underlying beds	Phreatomagmatic	Dense PDC
T4 Crudely stratifed tuff	Structureless to weakly-bedded coarse tuff. Crude stratification defined by diffuse bands of outsize clasts, or by discontinuous, locally clast-supported coarse ash or lapilli trains. Diffuse, gradational contacts	Phreatomagmatic	Dense PDC and/or fall
L5 Thinly stratified, alternating coarse and fine layers in thicker bedsets	Thin-bedded lapilli tuff (1–2 cm) interbedded with thin- to very thin-bedded coarse tuff (3–4 cm), and rare very thin beds of laminated dark-grey ash. Lapilli tuff incl. juvenile & lithic blocks up to 10 cm. Laterally continuous (≥25 m) beds c. 1 m thick: sharp basal contacts with massive lapilli tuff, gradational upward into T5 lithofacies tuff	Phreatomagmatic	Dilute PDC
T5 Thinly stratified, alternating coarse and fine layers in thicker bedsets	Coarse tuff & fine lapilli tuff interbedded with fine to medium tuff. Coarse layers include moderately sorted, locally clast-supported, amoeboid to blocky juvenile clasts, and sub-angular composite and lithic clasts. Contacts with underlying medium to fine tuff planar and abrupt. Massive coarse layers show normal grading upward across diffuse, gradational contacts into fine layers. Fine layers include accretionary lapilli composed of fine-ash rims plastered around a medium-ash aggregate core. Diffuse planar fabric defined by discontinuous coarse ash and fine lapilli trains, and by diffuse lenses of coarse ash and accretionary lapilli within medium ash. Accretionary lapilli are sub-spherical to flattened; some broken lapilli along contacts with coarse-grained lenses	Phreatomagmatic	Damp, dilute PDC

Table 2 Continued

Lithofacies	Description	Fragmentation	Transport
T7 Low-angle cross-stratified beds	Cross-bedded ($\lambda \geq 10$ cm, $A \geq 1.5$ cm), moderately to well-sorted coarse tuff gradational upward, via normally graded lapilli tuff, into very thinly bedded, weakly cross-bedded medium tuff. Cross-beds truncate underlying beds. Includes shallow-dipping wavy lamination mm in amplitude (ca. 4 mm thick), with slight thickening of beds toward wave crests. Bedding defined by alternating layers of dark, fine tuff and light-coloured coarse tuff; coarse tuff incl. scattered juvenile and lithic clasts up to 2 mm. Sharp, ~planar contact with overlying lapilli tuff. Gradational contacts between lapilli tuff and overlying coarse tuff are marked by accretionary lapilli layer <5 mm thick which passes upward into series of ripples ($\lambda \sim 5$ mm, $A \sim 1$ mm)	Phreatomagmatic	Dilute PDC
Lithofacies association cross-cutting breccia (LAcb)	*Comprises the bulk of volcaniclastic rocks at Coombs Hills, ≥350 m thick and exposed more-or-less continuously over ≥25 km^2. Characterized by steeply dipping contacts between different lithofacies of the TB0 family, and between different TB0-family lithofacies and other lithofacies. Rocks within these steeply dipping tuff breccia zones comprise individual occurrences of subfacies TB0j and TB0l, and many include peperite and localised intrusive hyaloclastite tangled with nonbedded TB0u tuff breccia. Megablocks and volcaniclastic rocks also lie among these lithofacies. Lithofacies at all structural levels are intruded by dikes. Many dikes show a transition from coherent basalt to peperite to volcaniclastic rock*	*Phreatomagmatic to magmatic, granulation due to shearing and shockwaves*	*Debris jets, gravitational collapse, mass movement, PDC, fall*
TB0u Structureless undifferentiated tuff breccia and coarse lapilli tuff	TB0u is the most abundant and widespread lithofacies at Coombs Hills. Its main characteristic is diversity without being either very rich or poor in juvenile fragments (see lithofacies TB0j and TB0l, respectively; below) (Fig. 6). The juvenile component of the TB0u deposits consist of fluidal, blocky or amoeboid glassy basaltic clasts (now altered). Dense (≤5% vesicles) to moderately vesicular (≤40% vesicles) juvenile fragments are elongate or ribbon-like. Accommodation of juvenile fragments to adjacent clasts is common. Abundant composite clasts comprise fluid-form glassy basalt mingled with Victoria Group sandstone and/or Mawson Formation volcaniclastic debris. Lithic clasts are angular to sub-round and some, including rare jigsaw-fit clasts, are intruded by dikelets of matrix tuff or lapilli tuff. Most lithic clasts have curved to embayed outlines; composite clasts and blocks of crystalline basalt are angular to sub-round. Clasts of Victoria Group sedimentary rock, crystalline basalt or composite mingled basalt-sediment clasts enclosed in a shell of glassy or microcrystalline basalt form sub-spherical to flattened cored bombs. The enclosing basalt generally shows a light coloured, differentially altered (possibly quenched) contact with the cores, which themselves often show a thin altered (inferred baked) rind at the contact. Vuggy calcite or zeolite is common in the glassy rims The matrix of TB0u lithofacies comprises moderately to poorly sorted lapilli mixed with medium to coarse ash. Single grains of quartz and minor plagioclase, alkali feldspar, biotite, muscovite, clinopyroxene and garnet comprise up to 75% of the lithic component (Fig. 6). Lithic clasts and grains are sub-angular to sub-round; many coal clasts show globular shapes with highly irregular margins. Jigsaw-fit clasts are rare. Composite clasts mainly comprise altered glassy basalt with a "swirly" pattern enclosing grains of quartz, feldspar and mica; cored lapilli comprising rock fragments encased in coherent basalt are also present. Composite clast shapes are generally highly irregular, with amoeboid to ragged margins. The juvenile component of the matrix is mainly non-vesicular to incipiently vesicular (≤20% vesicles), ragged to blocky fragments of palagonite with rare (≤2% volume) highly vesicular clasts (≥60% vesicles). Margins of the dense to moderately vesicular juvenile clasts range from highly irregular to smooth and curviplanar. Vesicles are predominantly sub-spherical, but some clasts host trains of elongate, aligned vesicles. Some TB0 matrix was openwork and grain-supported, with abundant interstitial space now occupied by calcite and zeolite cements	Repeated cycles of phreatomagmatic fragmentation, plus minor magmatic fragmentation	Transport within debris jets, slumping and sliding into craters (diatremes?), fall and PDC deposition

Table 2 Continued

Lithofacies	Description	Fragmentation	Transport
TB0j Structureless juvenile-rich tuff breccia	Juvenile-rich TB0j lithofacies ($\geq$75% vol juvenile clasts) occupies irregular, steep-sided zones within other lithofacies, and is the dominant rock type on the West Ridge and Windy Ridge (Fig. 4). It consists of poorly to moderately sorted tuff breccia, comprising up to 80% juvenile clasts, ca. 5–10% composite clasts, and 10–20% basalt and country rock lithic clasts in a coarse ash to lapilli tuff matrix (Fig. 12). Juvenile clasts are mainly dense to poorly vesicular ($\leq$30% vesicles), with occasional scoria-like tachylitic clasts. Juvenile clast shapes include: (1) fluidal, ragged, amoeboid or elongate ($\geq$75% of clasts); and (2) blocky equant to sub-equant, bounded by planar or curviplanar surfaces. Vesicularity is similar for both clast types. Ragged, fringed terminations of clasts are often well preserved (Fig. 12), and some juvenile clasts enclose thin, irregular stringers of coarse ash and lapilli matrix In thin section, fine lapilli- to coarse ash-sized juvenile clasts are highly irregular and ragged, with irregular bulges and tendrils that extend from clast margins into the heavily cemented (>20% vol) ash matrix. Blocky clasts are relatively rare, comprising <25% of typical TB0j tuff breccia. Vesicles are spherical to highly irregular, fluidal elongate (teardrop) shapes, which, with feldspar microlites, are aligned within individual clasts. Some clasts show thin rims of dense glass. Juvenile clasts in this lithofacies are crystal-rich relative to juvenile fragments in other Mawson Formation volcaniclastic rocks, containing up to 15% feldspar microlites. Composite clasts are mainly composed of grains of quartz and feldspar enclosed in amoeboid juvenile clasts. Clasts of silicic tuff, sandstone, coal plus single grains of feldspar, quartz, biotite and garnet comprise the remainder of the matrix fraction	Magmatic to weakly phreatomagmatic	Transport within debris jets, slumping and sliding into craters, fall and PDC deposition
TB0l Structureless lithic-rich tuff breccia	Lithic–rich TB0l lithofacies ($\geq$75% vol lithic clasts) outcrops (1) in close association with Victoria Group country rock contacts and megablocks, where it marks the transition from them to polymict lapilli tuff and tuff breccia, and (2) within and defining steeply dipping zones with approximately elliptical cross-sections metres to tens of metres in diameter, and cutting nonbedded TB0u breccia kilometres from Victoria Group contacts or megablocks. In the first case, the transition from country rock to TB0u lithofacies via TB0l lithofacies may be localised, with both TB0l and TB0u tuff breccia along different parts of the same contact, or TB0l rocks may form aureoles several metres wide around country rock megablocks isolated in TB0u lithofacies. TB0l lithofacies grades outward from country rock contacts into more polymict TB0u tuff breccia. In the second case, the steeply dipping TB0l zones have abrupt contacts with host tuff breccia, and have no contacts with megablocks or in situ country rock	(1) Granulation in response to shaking, shocks and shearing within crater fill	(1) Slumping and sliding into crater fill
	Abundant lithic clasts lend TB0l rocks a distinctive light to dark grey colour on fresh surfaces. Juvenile clasts are markedly sparse ($\leq$10% vol) in typical TB0l, which mostly comprises a poorly sorted mixture of elongate, sub-angular to equant ash- to block-sized fragments of fine- to medium-grained sandstone, siltstone and coal, including some jigsaw-fit clasts. Juvenile fragments comprise $\leq$25% of the matrix and are rare in the coarse size fraction. Blocky, sub-equant juvenile clasts predominate over fluidal shapes, and $\geq$80% of the juvenile clasts comprise dense ($\leq$10% vesicles) glass. The great majority of juvenile clasts contain lithic inclusions. TB0l lithofacies matrix is dominated by medium to fine ash-sized angular to sub-angular grains of quartz with accessory feldspar, biotite, hornblende, and garnet mixed with coherent country rock clasts. Country rock clasts include carbonaceous and quartzose sandstone and coal, plus rare clasts of microcrystalline basalt	(2) Fragmentation by phreatomagmatic explosions	(2) Transport within debris jets

Table 2 Continued

Lithofacies	Description	Fragmentation	Transport
Peperite	The Mawson Formation at Coombs Hills includes outstanding exposures of fluidal peperite, at metre- to sub-millimetre scale (McClintock and White 2002). Peperite includes basalt intimately mingled with sandstone, siltstone, coal, tuff, lapilli tuff, and tuff breccia. The basaltic component of these peperites comprises glassy, highly irregular intrusive ribbons and elongate rags contiguous with coherent basalt in larger intrusive bodies (e.g., dikes, sills), and nearby clasts fully enclosed within the clastic host (Fig. 13). The margins of intrusive ribbons may show fluidal or blocky textures; fluidal-textured intrusions often show subsidiary finger-like extensions. Ribbons and subsidiary extensions show highly irregular, amoeboid terminations. At many scales coherent basalt encloses, or partially encloses, domains of host sediment, or discrete lithic, and even composite, clasts. Similarly, ragged or wispy fragments of basalt irregularly distributed in volcaniclastic rock define the gradational outer edge of these peperites. Peperite margins of coherent basalt intrusions often include a zone of dense altered glass adjacent to the intrusion that includes many isolated clasts of host sediment, transitional into a zone characterized by elongate, swirly ribbons of basalt extending outward into the host. Ribbons splay out into the host rock, diverging from adjacent ribbons with increasing distance from the intrusion. Individual ribbons may merge with and diverge from adjacent ribbons a number of times along their length before terminating in the host domain. Ribbons merge seamlessly into intrusion margins, and into adjacent ribbons. These ribbons may be widely separated from one another or closely packed; in the latter case, ribbons are separated by narrow host domains, which may be reduced to discontinuous pinch-and-swell stringers of sediment where two or more ribbons of basalt are incompletely joined (Fig. 13). Tracing host domains into intrusion margins reveals a progressive loss of continuity until discrete host domains become 'trains' of isolated host clasts surrounded by basalt, and then discrete, isolated clasts irregularly distributed within the inclusion-rich intrusion margin. In many cases, peperite is gradational into the glassy-fragment-rich TB0j with composite blocks, itself in cryptic contact with TB0u lithofacies lapilli tuff and tuff breccia (Fig. 14). The outer edges of these peperites are commonly cryptic because the host itself has a component of ragged clasts identical to the basalt clasts in the outer peperite	Shear, quenching, weak to strong phreatomagmatic explosions, magma-sediment density contrasts, mechanical stress	Intrusion
Intrusive hyaloclastite	Intrusive hyaloclastite occurs as a transitional lithofacies between coherent basalt and the surrounding clastic host in localised zones adjacent to intrusions. Angular, closely packed ash- to lapilli-sized fragments of altered glass (now palagonite) are cemented by large crystals of calcite (max. 10 mm), or are scattered within a finer-grained tuff matrix. Jigsaw-fit clasts are common. Juvenile clasts in intrusive hyaloclastite have curviplanar to irregular shapes and are mostly non-vesicular; where present, vesicles are ovoid and transected by clast surfaces. In detail, single clasts comprise a 0.1–0.2 mm thick rim of clear, pale brown altered glass enclosing a dense, dark brown cryptocrystalline core. Rim thickness is similar for large and small clasts. Hyaloclastite typically grades from monomict hyaloclastite (glassy shards + cement), to hyaloclastite with a supporting matrix of finely fragmented basalt glass, and then to peperite of lapilli-tuff grade in which blocky glassy fragments are mixed with quartz and feldspar grains in a polymict matrix	Quench-cooling granulation	Intrusion

Table 2 Continued

Lithofacies	Description	Fragmentation	Transport
Dikes	Dikes within the Mawson Formation are characterized by irregular, swirly shapes, by association with peperite and hyaloclastite, and by discontinuous or en-echelon outcrop patterns. Dikes range in thickness from ≤ 10 cm to more than 2 m. Dikes with marginal peperite or hyaloclastite comprise dense to moderately vesicular ($\leq 30\%$ vesicles) holohyaline to porphyritic tholeiitic basalt, composed of plagioclase (up to 0.5 mm) + clinopyroxene + opaque microphenocrysts + zeolite ± calcite ± olivine in a groundmass of altered glass. Vesicles (≤ 2 mm) are infilled by platy or prismatic zeolites or calcite. Swallow-tail texture and weak normal zoning is common in plagioclase. The largest dikes comprise coarsely porphyritic (average grainsize ≥ 0.5 cm) basalt of the same phenocryst assemblage; these lack peperite and hyaloclastite. These coarser-grained basalts show a mixture of intersertal and intergranular texture, with space between feldspars in the latter occupied by subhedral to anhedral clinopyroxenes. Olivine forms small (≤ 0.2 mm) crystals in intergranular basalt; no olivine was observed in the glass-rich basalts	Intrusion	
Megablocks of Victoria Group	The contact between in situ Victoria Group north and east of continuous Mawson Formation outcrop is characterised by large ($10 - 100+$ m long and thick) tilted but coherent megablocks of Victoria Group enclosed within Ferrar Dolerite. These megablocks are progressively replaced over about 250 m to the south and west by smaller blocks (<20 m long and thick) of country rock surrounded by peperite and TB0 tuff breccia, and then by Mawson Formation with few or no megablocks. Throughout this transition zone, megablocks have contacts with irregular intrusions of basalt and/or with volcaniclastic rocks; most megablocks are in contact with both	Fragmentation by phreatomagmatic explosions, granulation in response to gravitational (wall-rock) collapse plus shaking, shocks and shearing within crater fill	En masse slumping and sliding into craters
	Tilted Victoria Group megablocks have no preferred orientation (strike), and oppositely dipping strata occur in adjacent blocks. Bedding within and along the margins of these floating blocks is commonly distorted and buckled at both the metre and tens of metres scale, with local preservation of centimetre- to decimetre-scale cross-bedding but deformation of metre-scale bedsets. Some megablocks have brecciated margins gradational outward into lithic-rich TB0l tuff breccia, and then into polymict TB0u lithofacies. Along dikes basalt-sandstone peperite shows gradational contacts with breccia composed of angular fragments of sandstone mixed with fluidal to angular clasts of basalt (Fig. 5). Highly irregular contacts are characterized by basalt-sandstone peperite and irregular intrusive lobes and finger-like domains of tuff and basalt choked with composite and juvenile clasts (≤ 1 m wide) extending into coherent Victoria Group sedimentary rock or into isolated Victoria Group blocks. Isolated lapilli-sized clasts locally define diffuse trains running from Victoria Group block margins into block centres. Broad, continuous trains of clasts separate small Victoria Group blocks from larger blocks, forming breccia composed of large clasts of Victoria Group sandstone in a polymict lapilli tuff or tuff breccia matrix		
Volcaniclastic rafts	Roughly tabular but gently folded, steeply dipping, rafts of bedded to unbedded tuff and lapilli tuff lie isolated within TB0u lithofacies at all structural levels and without systematic orientation (cf. Bradshaw 1987). Some volcaniclastic rafts are in excess of 20 m thick, and ≥ 200 m in exposed length (Fig. 15), with down-dip continuation in places demonstrably several times thickness. They are composed of interbedded poorly to moderately sorted tuff and lapilli tuff containing a mixture of juvenile and lithic clasts. Bedding contacts may be sharp or gradational (Fig. 7); contacts between rafts and host rock are sharp (Fig. 15). Accretionary lapilli are present in some well-bedded rafts but block-sized clasts are rare. The rafts generally include more lithic clasts than host TB0u tuff breccia, with coal especially prominent. Bedding and other sedimentary structures may or may not be present, although some rafts show well-defined internal bed divisions and bedforms (Figs. 7, 15).	Fragmentation by phreatomagmatic explosions, granulation in response to gravitational (wall-rock) collapse plus shaking, shocks and shearing within crater fill	Initial formation as tuff ring and cone deposits (PDC and fall); undermining of crater rims led to en masse slumping and sliding into craters

Table 2 Continued

Lithofacies	Description	Fragmentation	Transport
	Bedding can be continuous for ≥20 m along strike, beyond which beds begin to pinch-and-swell and anastomose. Individual beds become increasingly difficult to distinguish along strike, merging to form homogeneous tuff in the centre of the block bracketed by laminated tuff margins; the raft finally narrows and pinches out completely. Loss of internal structural continuity along strike, often coupled with buckling of layers and increasingly irregular raft shapes toward terminations, is characteristic of all volcaniclastic rafts		
Clastic dikes	Clastic dikes form larger, proportionally thin, vertically dipping tabular bodies of tuff relative to volcaniclastic rafts (see above). The vertically dipping bodies of tuff form more or less structureless, homogeneous tuff bracketed by laminated margins. They are up to 70 m wide and extend for tens to many hundreds of metres along strike, locally bending, anastomosing, or separated into en echelon segments. Because they crosscut all other lithofacies at Coombs Hills, they must have formed after the main phase of Mawson Formation activity had ceased	Intruded as clastic dikes (Ballance and Watters 1971; Grapes et al. 1974; Bradshaw 1987; Ross and White 2005)	

PDC-pyroclastic density current; λ-bedform wavelength; A-bedform amplitude. Dense PDC = ≥10% solids by volume, dilute PDC = ≤10%

of this volcanic system is analogous to a complex of coalesced diatremes, but because we cannot identify individual steep-walled diatremes within the complex, we refer to inferred single active centers as "vents", each produced by the passage of one debris jet and/or irregular dike (Fig. 2). Overall, volcanic rocks at Coombs Hills represent a cluster of such vent structures, so we describe the resulting volcanic landform as a "vent complex" (Fig. 2).

Geology of Coombs Hills

Victoria Group (Beacon Supergroup)

Rising Ferrar magmas at Coombs Hills were intercepted by fluvial, lacustrine and glacial sedimentary deposits of the Late Carboniferous to Jurassic Victoria Group (Fig. 3). Victoria Group rocks are exposed in situ at elevations lower than most Mawson Formation outcrop in the northern and eastern Coombs Hills, and also occur as tilted, deformed and fractured megablocks (the largest ≥500 m long by 200 m thick) within Mawson Formation rocks and Ferrar Dolerite sills (Fig. 3). Thin, metre-scale lenses of freshwater conchostracan fossil-bearing mudstone, limestone and quartzose sandstone and pebble conglomerate similar to Victoria Group are interlayered with Kirkpatrick basalts and Mawson Formation tuff breccia on Mount Brooke (Fig. 3) (Bradshaw 1987). Victoria Group rocks at Coombs Hills comprise fine- to coarse-bedded and cross-bedded sandstones interlayered with minor coal, conglomerate and carbonaceous siltstone. Some silicic tuff deposits form the youngest pre-Mawson strata known in the area (Elliot et al. 2004). Sandstones throughout the Victoria Group are composed of moderately to well-sorted subangular to rounded quartz grains, with subordinate feldspar, mica, garnet and lithic clasts (mostly highly micaceous carbonaceous siltstone).

The sedimentary features of the Victoria Group in the Coombs Hills area indicate fluvial deposition on broad floodplains (Smith et al. 1998) interspersed with marshes (Krull 1999) and peat domes grown in distal overbank settings (Staub and Esterle 1994) or perhaps along the margins of lakes (Retallack and Alonso-Zarza 1998; Smith et al. 1998). Diverse broadleaf plants and noncalcareous paleosols in the youngest Victoria Group rocks (Lashly Formation) suggest a humid, seasonally snowy climate with mean annual precipitation of about 1 metre/yr immediately prior to Ferrar-Karoo LIP volcanic time (Retallack and Alonso-Zarza 1998). The uppermost Victoria Group strata at Coombs Hills are inferred to have been wet and poorly indurated at the initiation of LIP volcanism on the basis of: (1) extensive peperite, swirly dikes and intrusive hyaloclastite along contacts with intrusions; (2) an abundance of quenched glassy basalt along intrusive contacts (quenched margins), and as a juvenile component of peperite and intrusive hyaloclastite; and (3) deformation and/or destruction of bedding in host Victoria Group sediments adjacent to intrusive contacts, suggesting local remobilisation of host sediment particles. In addition to water trapped in

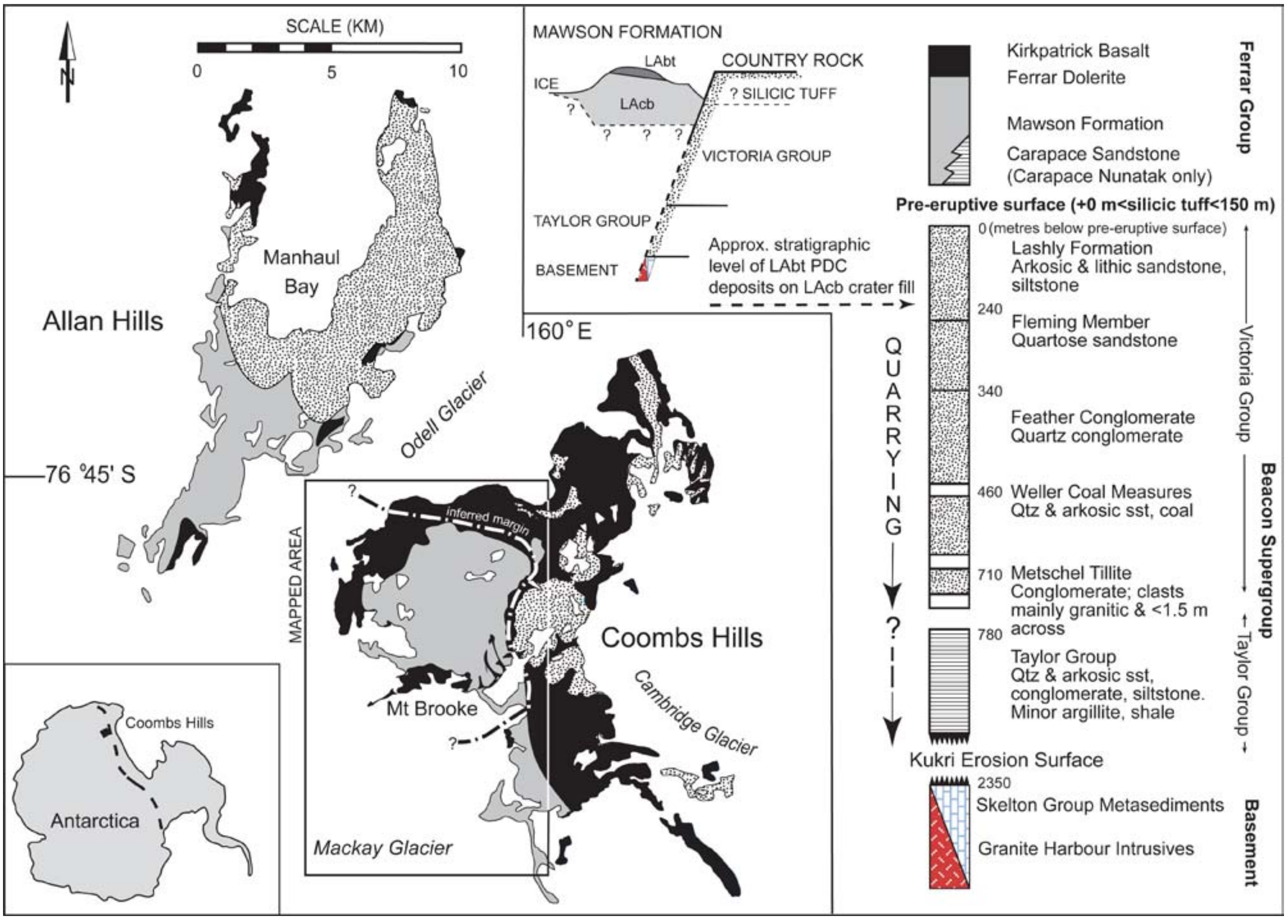


Fig. 3 Location of Coomb Hills, Antarctica. The Transantarctic Mountains are marked by *dashed line* on *inset map*. Simplified geology (*black* = Ferrar Supergroup igneous rocks; *light grey* = Mawson Formation; *stipple* = Beacon Supergroup) after Grapes et al. (1974) and Bradshaw (1987). *Heavy dashed line* = inferred position of the margin of the Coombs Hills vent complex. Regional stratigraphy is summarised at right. Depth of quarrying into underlying rocks during Mawson Formation eruptions is poorly constrained, but most lithic clasts in the Mawson Formation are probably sourced from the Metschel Tillite or overlying rock 700 m below the pre-eruptive surface; ≤0.5% lithics are granite or marble, which may or may not be derived from the sub-Beacon Supergroup basement. The deepest Victoria Group unit exposed at Coombs Hills is the Lashly Formation. = mapped area shown on Fig. 4; *PDC* = pyroclastic density current

porous Victoria Group sediments and sedimentary rocks (porosities 6–21%) (Barrett and Froggatt 1978), surface water was probably present in lakes, streams and swamps (Bradshaw 1987; Retallack and Alonso-Zarza 1998; Smith et al. 1998).

Ferrar dolerite and Kirkpatrick basalt

Ferrar Dolerite forms decimetre to tens of metres thick, feldspar- and pyroxene-phyric dikes and sills, some of which presumably fed surface flows of Kirkpatrick flood basalt (Gunn and Warren 1962). Kirkpatrick flood basalt exposed on Mount Brooke (Fig. 4) shows well-developed columnar jointing, with sub-vertical columns 10–50 cm in diameter, and thinner, irregular platy joints near the summit. On the western end of the Mount Brooke massif, regularly spaced colonnade columns become progressively replaced upsection by more irregular, platy joints defining radiating or curved columns of an entablature zone (Long and Wood 1986; Lyle 2000). The lower colonnade is estimated to be ≥20 m thick, and the entablature ≥30 m thick. Bradshaw (1987) recognised several flow units at Mount Brooke, with the thickest one ca. 70 m thick.

Basalt lavas high on Mount Brooke are interlayered with thin (≤2 m), laterally impersistent lenses of quartzose, Victoria Group-like sediments and Mawson Formation volcaniclastic rocks (TB0u lithofacies; Table 1 and below). The quartzose lenses comprise fine yellow or cream-coloured sandstone and siltstone, and infill cracks in underlying basalt. Most lenses are distorted and indurated. Basalt immediately over- and under-lying these sedimentary rocks shows elevated vesicularity and larger vesicles relative to basalt lower in the section. Kirkpatrick flows displaying pillow-like cross-sections showing thin tachylite rinds enclosing highly vesicular interiors, crop out to the west of the summit, and may correlate with the 10-m-thick layer of pillows reported from the summit by Bradshaw (1987).

Kirkpatrick lavas at Coombs Hills are inferred to have been emplaced as a series of metre to tens of metres-thick

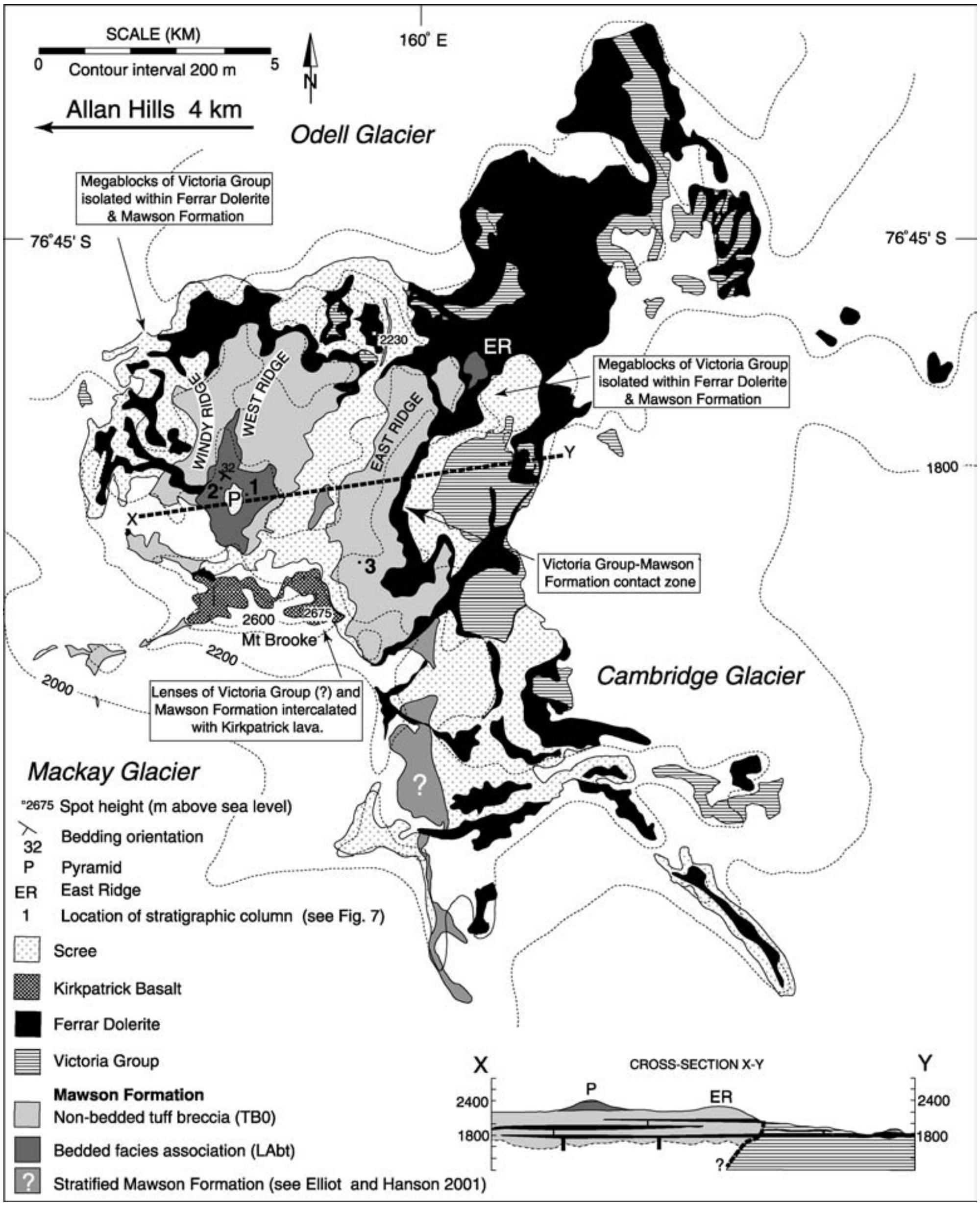


Fig. 4 Geological map of Coombs Hills, showing distribution of structureless tuff breccia relative to bedded volcaniclastic rocks. Outcrops of in situ Victoria Group in the north and east of Coombs Hills delineate the northern and eastern margins of the inferred vent complex; outcrops of Mawson Formation extending beneath the Mackay Glacier leave the extent of the complex to the west and south unconstrained. X-Y= line of section, Pyramid = informal name for hill

subaerial and subaqueous(?) flows into a water-rich, probably low-lying area. Pauses between emplacement of different flows were long enough for deposition of quartzose sediment and of minor Mawson Formation volcaniclastic sediment. Episodes of subaerial phreatomagmatic eruption are suggested by stratified tuff with accretionary lapilli (Bradshaw 1987; P-S Ross, pers. comm. 2004) intercalated with lavas at nearby Carapace Nunatak (Fig. 1).

Mawson formation

Excellent outcrop at Coombs Hills allows detailed observation of lithofacies and unit relationships over most of the >30 km^2 of the Mawson Formation's area (Fig. 4). The formation comprises >350 m of massive tuff breccia and lapilli tuff passing upward into >40 m of flat-lying to gently dipping (<10°) weakly bedded and then well-bedded tuff breccia, lapilli tuff and tuff. These volcaniclastic rocks are associated with once-glassy basalt intrusions with curviplanar to irregular shapes.

Contact relationships between Mawson Formation and Victoria Group rocks

Exposed contacts between in situ Victoria Group and the Mawson Formation are rare at Coombs Hills due to voluminous intervening sills and dikes, which form prominent Ferrar Dolerite cliffs along the inferred contact. The boundary zone between Mawson Formation and Victoria Group outcrops cuts across topography (Fig. 4), and areas in which Mawson Formation and in situ Victoria Group rocks outcrop within a few metres to tens of metres of one another

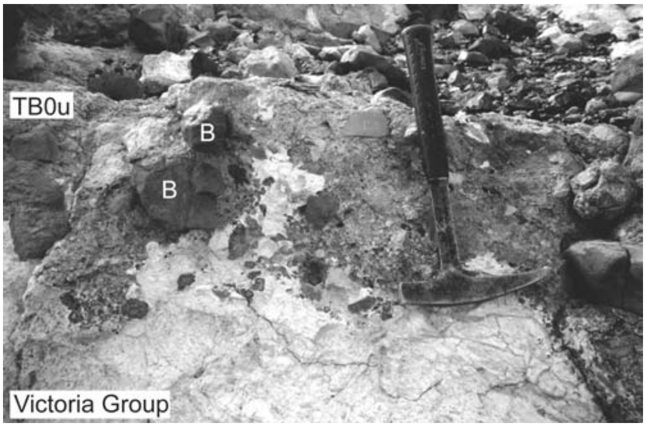


Fig. 5 Detail of contact between Victoria Group sandstone megablock (*white*), intrusive basalt (*B*) and TB0u lithofacies tuff breccia. Round to ragged basalt shreds (perhaps contiguous with an intrusion in the third dimension) isolated within sandstone form a sandstone-basalt peperite. Note granulation of sandstone, represented by sandstone clasts isolated within TB0u tuff breccia along the margin of the sandstone block, and polymict nature of TB0u lithofacies

above, below, and at the same altitude are strongly suggestive of steep, unconformable contacts (see also Elliot and Hanson 2001). Contact zones separating TB0u rocks from in situ Victoria Group delineate the northern and eastern margins of the Mawson Formation at Coombs Hills (Fig. 4), and are characterised by structural complexity, and localised, intensely intruded zones of mingled peperite and tuff breccia (Fig. 5; see below). The contact zone in eastern Coombs Hills (Fig. 4) is marked by a series of thick Ferrar Dolerite intrusions. The Mawson Formation structurally above the sills comprises irregularly shaped basalt dikes intruding a complex zone of peperite, structureless TB0u tuff breccia and many megablocks of Victoria Group country rock. Both TB0u tuff breccia and Victoria Group rocks are silicified and/or indurated adjacent to porphyritic (plagioclase-clinopyroxene-phyric) basalt and dolerite intrusions, but not adjacent to intrusions that show peperite or intrusive hyaloclastite along their contacts (Fig. 5). Later intrusions show poorly developed quench margins against Victoria Group and Mawson Formation rocks.

Componentry of the Mawson Formation

Mawson Formation rocks are made up of: (a) dense to poorly vesicular (mean 10–20% vesicles, rarely >50% vesicles), blocky, rounded, amoeboid, or ribbon-like, formerly sideromelane (now palagonite and clay) juvenile fragments; (b) angular to sub-round lithic fragments of Victoria Group country rock, including siltstone, sandstone, coal, quartz grains and other detrital minerals; (c) lithic clasts of microcrystalline to porphyritic plagioclase-clinopyroxene-phyric basalt; (d) composite clasts comprising fluid-form mingled sediment and basalt, at scales from metres to ≤1 mm; (e) silicic tuff; (f) marble; (g) granitoid rocks; (h) rim-type accretionary lapilli (Schumacher and Schmincke 1991); and (i) rare armoured lapilli (up to 2.5 cm) comprising coarse ash rims around cores of microcrystalline basalt. Accretionary and armoured lapilli are found only in bedded tuff and lapilli tuff. Calcite and zeolite cements are ubiquitous; estimated minus-cement porosity ranges up to 30% (average 5–15%). Calcite and zeolite also fills amygdales in basalt lithic clasts. Grainsize varies from ash to blocks >5 m long; basalt, composite and lithic blocks form a minor component of bedded tuff and lapilli, but are otherwise restricted to structureless tuff breccia.

Lithologies of the Mawson Formation

Bedded tuff breccia, lapilli tuff and tuff lithofacies (TB1, TB2, TB4j L0, L0j, L3, L4, L5, T0, T3–T7) make up lithofacies association LAbt (Table 1). They form a minor component of the Mawson Formation and are described in Table 2. Stratified volcaniclastic rocks with broad similarities to rocks of the LAbt facies association are described from the southeastern Coombs Hills by Elliot and Hanson (2001) but were not looked at in detail as part of this study; these rocks are mapped as a separate group of rocks on Fig. 4 and are not discussed further here.

Polymict, nonbedded tuff breccia and coarse lapilli tuff of TB0u, TB0j and TB0l (Table 1) are described in Table 2. They make up the bulk of the cross-cutting breccia lithofacies association (LAcb; Table 1) and they are the most widespread Mawson Formation deposits, comprising more than 80% of the mapped area across the 400 m+ exposed thickness of volcaniclastic rocks at Coombs Hills (Fig. 4). All TB0-family rocks consist of poorly sorted fine ash to block-sized clasts of sandstone, carbonaceous siltstone, conglomerate, coal, basaltic tuff and lapilli tuff, silicic tuff, limestone, granitoid rocks, and mafic crystalline volcanic rocks, in a matrix of (a) tuff or (b) lapilli tuff of the same components plus juvenile clasts (Fig. 6). An important component of the cross-cutting breccia facies association (LAcb) are basalt dikes and irregular intrusions that cut unbedded volcaniclastic rocks throughout Coombs Hills (Table 2). Concentrations of dikes occur near contacts with in situ Victoria Group, and within steeply dipping zones of tuff breccia that cross-cut unbedded tuff breccia lithofacies. Contacts between these dikes and host rocks are characterised by peperite and intrusive hyaloclastite. Some irregular dikes show a clear transition along their length from coherent basalt to peperite to juvenile-rich tuff breccia. The margins of these dikes become increasingly irregular along strike, with tuff breccia-dominated dike sections merging into host TB0u volcaniclastic rock across increasingly diffuse margins. Juvenile clasts in dike-related tuff breccia comprise the same dense, glassy basalt that dominates the juvenile component of host tuff breccia, and composite clasts broken from peperite zones are common. Dikes can also be traced along strike from Mawson Formation volcaniclastic rock into megablocks of Victoria Group sandstone, where they show similar irregularity of form and development of peperite as dike sections cutting the Mawson Formation. Megablocks of Victoria Group sandstone isolated within unbedded tuff breccia, rafts of

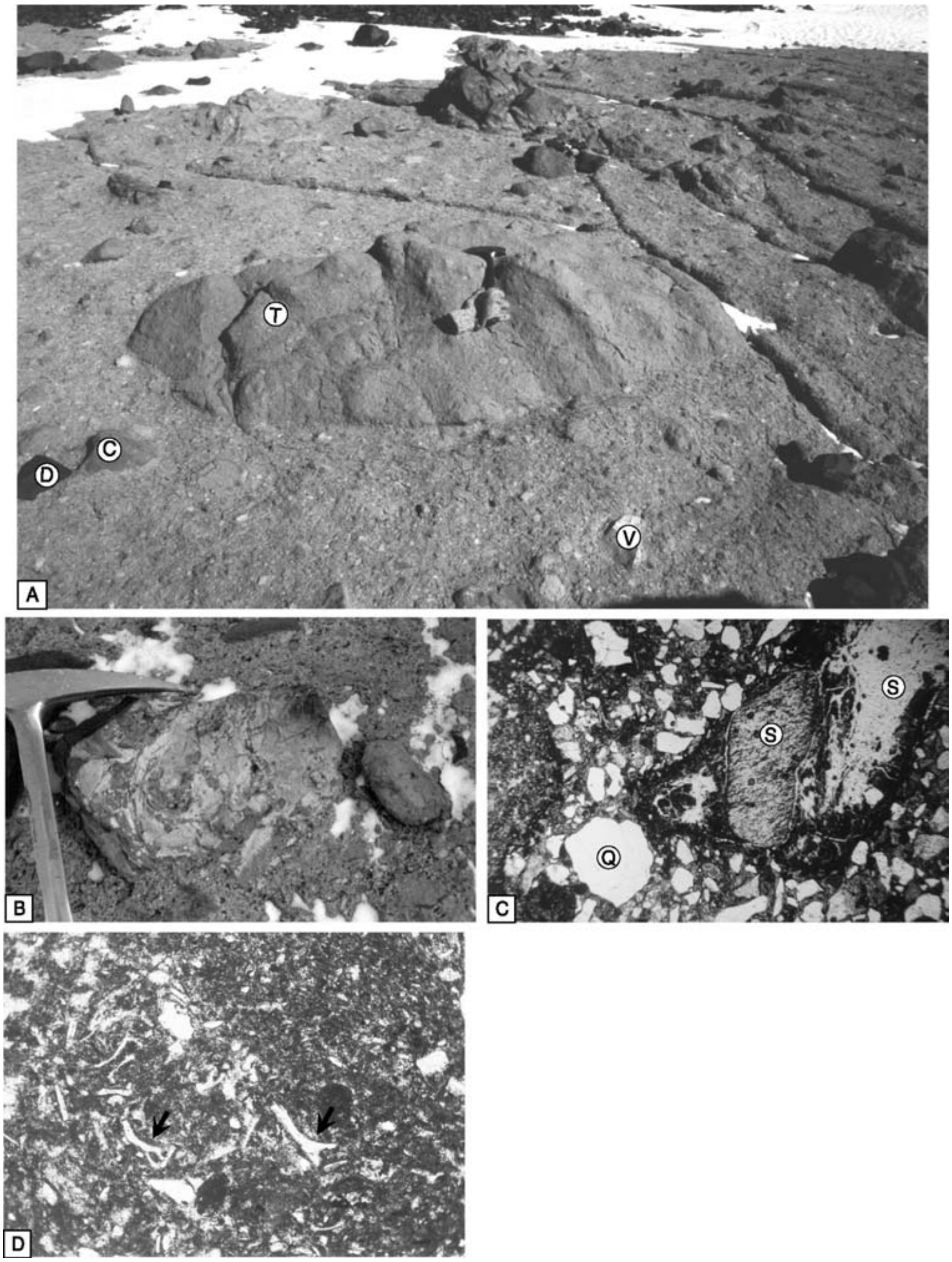


Fig. 6 TB0u lithofacies. **A** Block of fine lapilli tuff to coarse tuff (*I*) within unbedded tuff breccia (TB0u lithofacies). Other lithics include Ferrar Dolerite (*D*), composite, fragmented-peperite clasts (*C*), and Victoria Group sandstone (*V*). **B** Composite block in TB0u tuff breccia, comprising altered glassy basalt (*dark grey*) fluidally mingled with light coloured fine quartzose sand. **C** Photomicrograph of matrix of TB0u lithofacies. Note clast of partially altered sideromelane (*S*) and abundance of quartz grains (*Q*). Width of field of view 4 mm. **D** Photomicrograph of silicic tuff clast within TB0u lithofacies. Note cuspate and Y-shaped shards (*arrows*). Width of field of view 4 mm

volcaniclastic rock and clastic dikes are also included in the cross-cutting breccia facies association (LAcb; Table 2) on the basis of close spatial association and inferred genetic relationships.

Lithofacies interpretations

First-order interpretations of lithofacies are given here before addressing post-Mawson dolerite intrusions, physical and genetic associations of lithofacies. The interpretations are ordered differently from the descriptions provided above; we begin with interpretation of the simpler lithofacies because elements of their interpretation are significant in interpretation of the more complex tuff to tuff breccia lithofacies.

Interpretation of Mawson-linked basalt dikes

The generally glassy basalt comprising dikes that interacted with the Mawson Formation indicates rapid cooling. Peperite, intrusive hyaloclastite and swirly dike forms suggest that this quenching resulted from interaction with water-saturated clastic debris (White 1991; Batiza and White 2000). Dikes with peperite contacts within Victoria Group megablocks contrast with parallel-sided, coherent dikes intruding in situ Victoria Group country rock, and suggest that the megablocks had been weakened and partly unconsolidated as a consequence of being isolated in TB0u lithofacies. Along-strike dike transitions from coherent basalt into peperite that grades imperceptibly into tuff breccia shows the close kinship of processes that formed the tuff breccia and peperite (see below).

Interpretation of intrusive hyaloclastite & adjoining blocky peperite

Jigsaw-fit of rimmed glassy clasts with curviplanar outlines indicates that at least some hyaloclastites at Coombs Hills record in situ quench fragmentation of basalt (Batiza and White 2000; Skilling et al. 2002). An absence of jigsaw-fit in other hyaloclastite may reflect resedimentation, or, in the case of hyaloclastite gradational into lapilli tuff, localised disturbance of hyaloclastite fabric by other processes (see below). Most hyaloclastite preserved at Coombs Hills probably formed when late-stage intrusions of basalt invaded water-saturated sediment, leading to passive quenching of basalt and spalling of basalt fragments into surrounding sediment (White et al. 2000).

Interpretation of fluidal peperite

Features of the glassy basalt ribbons in fluidal peperite, such as merged contacts with adjacent ribbons and coherent dikes, aligned ash and lapilli domains within ribbons, boundaries defined by trains of lithic clasts, and ribbons of coherent basalt enclosing irregularly distributed lithic clasts together suggest injection of liquid basalt into wet tephra and fragmented country rock. Merged contacts along the length of individual ribbons indicate that basalt was fluid for the duration of the interaction. Fractures in Victoria Group clasts filled by lapilli tuff and tuff breccia suggest that the wet tephra was highly mobile during mingling.

Millimetre to centimetre-sized ragged or amoeboid glassy juvenile fragments mixed with lithic clasts in dispersed-clast outer zones of peperite indicate thorough disruption of fluid melt (Skilling et al. 2002). Outward gradations from basalt-dominant peperite over decimetres or metres into dispersed-clast peperite in cryptic contact with host tuff breccia results from melt fragmentation and thorough mixing of basalt fragments with host material. Where early formed Mawson tuff breccia is the host, the outer peperite zones effectively form “new” domains within the already polymict TB0u lithofacies volcaniclastic rock. In other words, a sample from an outer peperite zone would not be distinguishable, if field relationships were not known, from some TB0u (or TB0j) lithofacies rocks that are not in apparent gradational contact with coherent intrusions (a defining characteristic of peperite; White et al. 2000).

Interpretation of Victoria Group megablocks

Victoria Group megablocks were derived from the walls of the volcanic complex. Increased levels of disruption and brecciation of Victoria Group megablocks at greater distances from in situ Victoria Group point to progressive fragmentation as residence time in the vent complex increased. The distance of each block from in situ source strata is a function of block movement and/or vent-wall retreat.

Interpretation of volcaniclastic rafts and clastic dikes

Previous workers have not distinguished volcaniclastic rafts within the Mawson Formation, but identified large steeply dipping tabular bodies of ash interpreted as clastic dikes (Ballance and Watters 1971; Grapes et al. 1974; Bradshaw 1987). This interpretation is attractive for the larger dikes that are internally structureless except for marginal laminations and crosscut all other Mawson lithofacies, and it seems probable that these late-stage dikes formed during subsequent intrusion of large-volume Ferrar Dolerite bodies (Grapes et al. 1974; Ross and White 2005).

We do not favor this explanation for the smaller, well-bedded rafts of volcaniclastic rock at Coombs Hills, however, for two reasons. (1) Componentry, including accretionary lapilli, as well as bed forms and bedding contacts are similar, and in some cases identical, to bedded tuff and lapilli tuff sequences elsewhere within the Mawson Formation, which are interpreted (below) to record pyroclastic density current and fall deposition. We infer that the loss of along-strike stratal continuity for these rafts is a secondary feature. (2) Little or no direct evidence of intrusive emplacement, such as incorporation of wall-rock material along contacts, exists for these bodies.

Analogous blocks of deformed and tilted vent-marginal pyroclastic beds and country rock in vent fill deposits are reported from diatremes (Clement and Reid 1989; White 1991). Both field (Hawthorne 1975) and experimental observations (McCallum et al. 1976) indicate that collapsed blocks of pyroclastic and country rock are commonly concentrated around diatreme margins. The sheared margins shown by some of these volcaniclastic rafts at Coombs Hills are interpreted to record drag along their margins as they sank from high structural levels (e.g., Hearn 1968) through a granular vent fill that at least occasionally behaved as a granular fluid (Iverson 1997; Goldhirsch 2003). It is suggested that the more coherent volcaniclastic rafts subsided into vent fill later than those in which bedding has been mostly wholly destroyed by liquefaction or fluidization; the latter were longer-exposed to volcanic agitation within the vent fill.

Interpretation of unbedded volcaniclastic lithofacies (TB0u, TB0l, TB0j)

The Mawson Formation at Coombs Hills differs markedly from most volcaniclastic deposits described to date in that the fingerprints of transport and deposition processes within the rocks, such as bedforms, deposit structure or texture, are absent or poorly developed across large volumes of

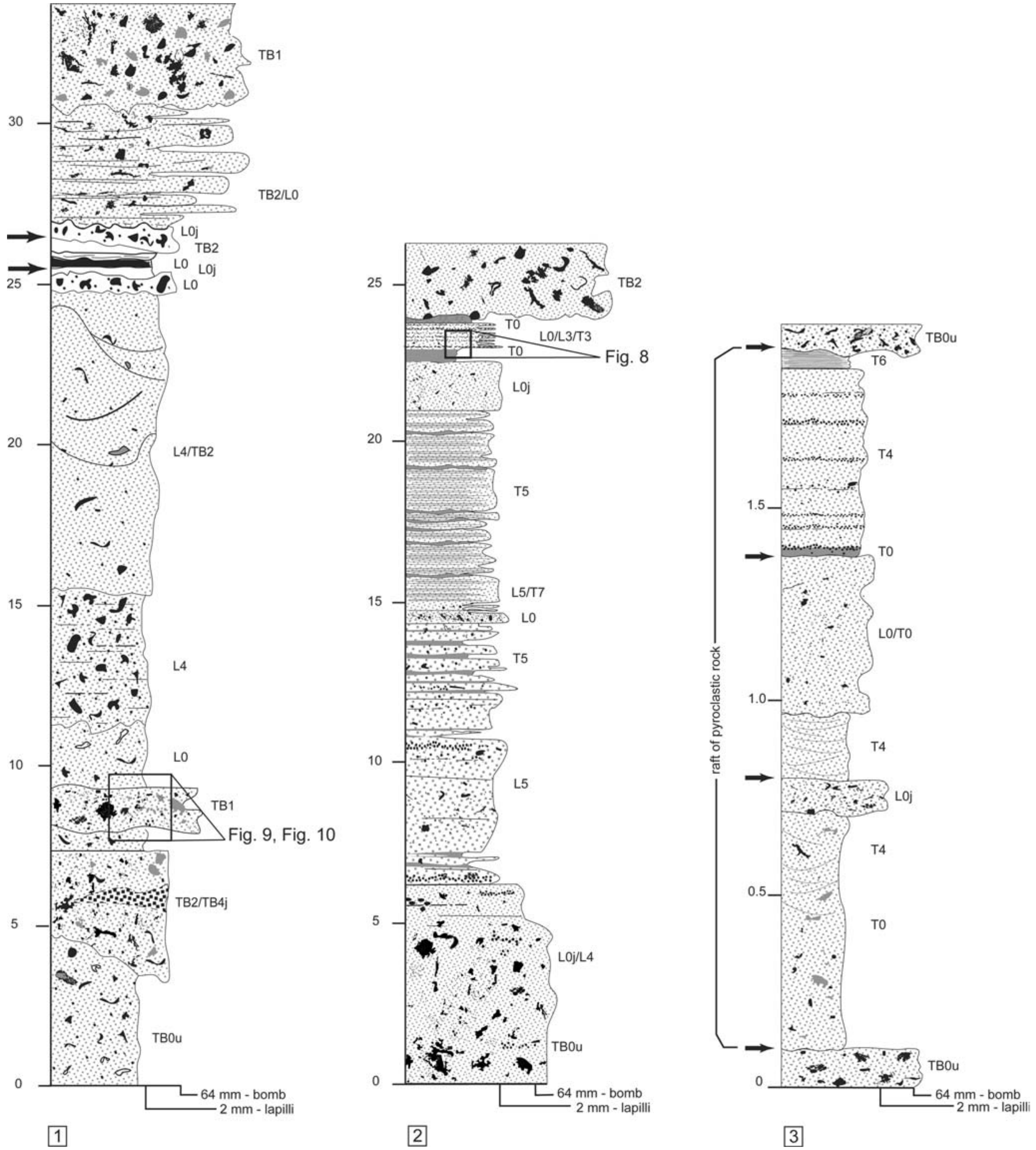


Fig. 7 Stratigraphic columns through bedded volcaniclastic rocks in the uppermost ~50 m of the Mawson Formation at Coombs Hills, and through a megablock of volcaniclastic rock isolated within TB0u lithofacies (see Fig. 4 for column locations). 1 Stratigraphy of the Mawson Formation, east slopes of the Pyramid; 2 Composite stratigraphy for the Mawson Formation, west slopes of the Pyramid; 3 Stratigraphy of a 2-m-thick volcaniclastic rafted block isolated within massive TB0u tuff breccia. Note the similarity of bedforms and componentry within the volcaniclastic raft relative to tuff and lapilli tuff within in situ beds on the Pyramid (1, 2). Lithofacies codes as for Table 1; see Table 2 for descriptions. Scale in metres. *Black* = juvenile and crystalline basalt clasts, *grey* = lithic clasts; *arrows* indicate scoured beds. Bomb/lapilli scale at base of column gives an indication of the average grainsize of beds

rock; instead, volumetrically dominant TB0u lithofacies is poorly sorted to unsorted, coarse grained and is notable for an almost complete absence of layering over >300 vertical metres.

Variable but relatively low juvenile vesicularity (5–50% vesicles) within TB0-family lithofacies rocks indicates that magma was quenched and disrupted at many different points in its degassing history (Houghton and Wilson 1989). Ubiquitous sideromelane points to rapid quenching, most likely by a water phase. Irregular, amoeboid juvenile clast shapes, including some with vesicles and microlites aligned with clast margins, indicate fragmentation of fluid magma. An abundance of lithic clasts in Mawson Formation rocks indicates fragmentation processes sufficiently powerful to shatter consolidated rock. Lithic blocks of basalt could be derived from partially degassed and crystallised magma ponded at high levels in the vent-conduit system, from a disrupted sill in adjacent country rock or vent fill, or from surface lava flows. Lithic clasts enclosed within glassy basalt (cored bombs) imply that fragments of country rock were engulfed by fluid melt during magma uprise or clast fallback, and then ejected or re-ejected. Composite clasts composed of basalt mingled with volcaniclastic rock point to intrusion of basalt into unconsolidated debris to form peperite, which was subsequently fragmented and the fragments deposited with additional lithic debris to form polymict volcaniclastic rock (Lorenz et al. 2002). The presence of silicic tuff clasts tens or hundreds of metres below their original stratigraphic position indicates subsidence of material from high in the pre-volcanic stratigraphy downward into vent fill. In combination, these features suggest fragmentation and dispersal of fluid melt and country rock by phreatomagmatic to magmatic explosions. This interpretation is supported by glassiness and variable but generally low vesicularity of clasts, and by mixtures of ribbon bombs and amoeboid lapilli with significant proportions of country rock and crystalline basalt lithic fragments. Variation in the relative importance of "drier", more magmatic versus "wetter", more phreatomagmatic fragmentation is recorded by variations in abundance of juvenile versus lithic clasts, and variations in clast shape and vesicularity between and within lithofacies. The emplacement processes for different TB0-family lithofacies at Coombs Hills is best inferred from the architecture of these deposits, and is addressed below in the context of a lithofacies association.

Interpretation of bedded volcaniclastic lithofacies (TB1-TB2, TB4j, L0, L0j, L3-L5, T0, T3-T7)

The many lithofacies present in beds at the Pyramid (Fig. 7) and in volcaniclastic rafts are readily interpretable in terms of typical subaerial volcaniclastic transport and deposition processes; Table 2 summarises interpretation of each lithofacies' emplacement. Together these lithofacies comprise lithofacies association LAbt, and particular features of some lithofacies are drawn together in interpretation of the lithofacies association as a whole, below.

Lithofacies associations

Lithofacies association bedded tephra (LAbt); lithofacies TB1-TB2, TB4j, L0, L0j, L3-L5, T0, T3-T7

At the Pyramid, in situ bedded tuff, lapilli tuff, and tuff breccia lithofacies are exposed at the highest levels of the Mawson Formation at Coombs Hills (Figs. 4, 7–10), and are designated as lithofacies association LAbt (Table 2). Thick beds of weakly stratified TB2 tuff breccia, outcropping at the highest levels of the Mawson Formation, have diffuse and/or gradational contacts with overlying structureless and weakly bedded lapilli tuff of TB0u, TB4j and L4 lithofacies (Fig. 7). Processes which result in structureless to weakly stratified depositional units are rainout from dense, inertia-driven tephra jets (Sohn 1996), deposition from high concentration debris flows (lahars), or rapid deposition from overcapacity pyroclastic flows. These beds show no bedding plane sags suggestive of ballistic emplacement, nor inverse grading or imbrication suggesting transport within debris flows; deposition from high concentration pyroclastic density currents (Schumacher and Schmincke 1990; White 1991; Belousov and Belousova 2001) is favoured here.

Block-rich TB1 horizons on the Pyramid (Figs. 7, 9) resulted from episodic block ejection. Persistent horizon thickness implies that the TB1 deposits once covered a broad area, and blocks up to 3 m diameter indicate energetic dispersal. Houghton and Nairn (1991) suggest that repeated block-apron-forming eruptions of White Island were triggered when collapses of the sub-volcanic conduit suddenly brought magma into contact with a water-saturated slurry in the vent and initiated phreatomagmatic explosions, and analogous vent-wall collapse may have triggered discrete, violent eruption bursts at Coombs Hills. Incorporation of material from high in the adjacent stratigraphy is indicated by local occurrence of silicic tuff clasts and dispersed silicic ash shards in TB0u and TB1 lithofacies (Fig. 10).

The thick to thin bedded lithofacies (TB2, TB4j, L0-L5, T0-T7) on the Pyramid and the East Ridge (Fig. 4) are as a group inferred to record deposition from damp, dense to dilute pyroclastic density currents, with minor deposition from fall and 'dry' surges (Table 2). This interpretation is made on the basis of: (1) Widespread soft-sediment deformation structures (e.g., bedding-plane sags, flame structures, flattened, folded or thinned beds and/or accretionary lapilli within bedded lapilli tuff and tuff (Fig. 8), and complete penetration of underlying beds by settled lapilli) suggesting that the beds were cohesive (plastic) on deposition, implying eruption, transport and deposition in a water- or steam-rich environment (Schmincke et al. 1973). (2) Non-mantling beds show lateral changes in thickness, with unidirectional cross-stratification, pinch and swell bedding and scoured contacts (e.g., Waters and Fisher 1971; Schmincke et al. 1973). The occurrence of cross-bedding, including laminated low-angle cross-beds and slightly wavy dune forms associated with planar beds is characteristic of dilute pyroclastic density currents such as pyroclastic (or base)

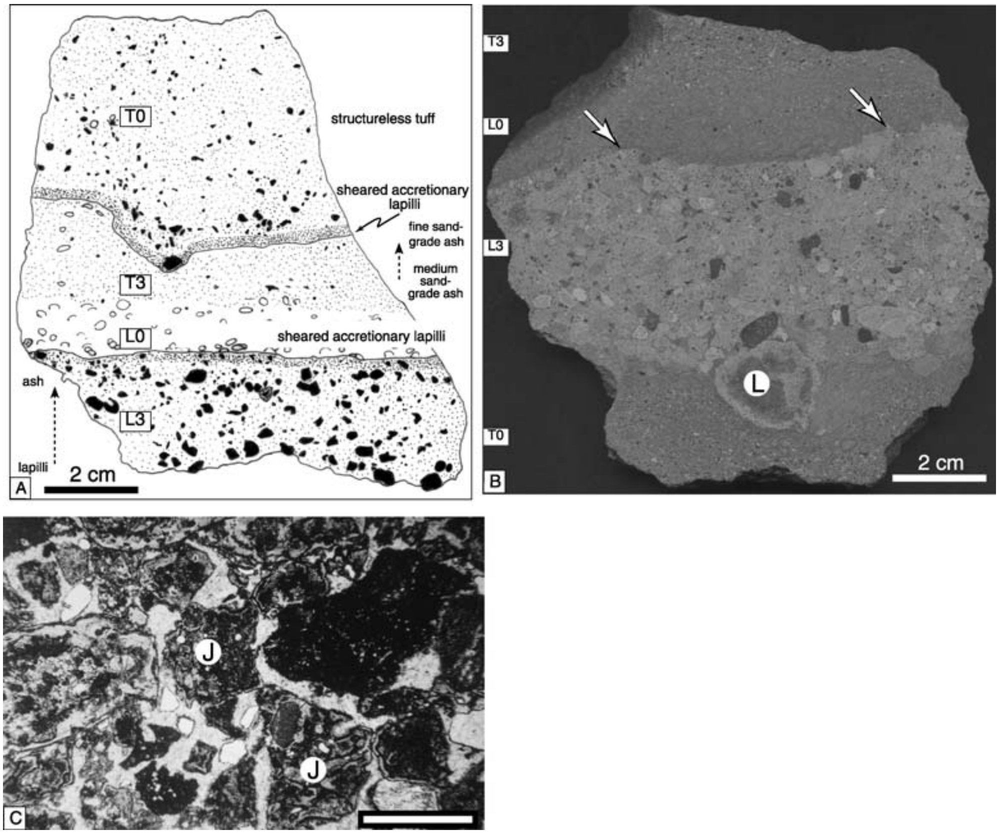
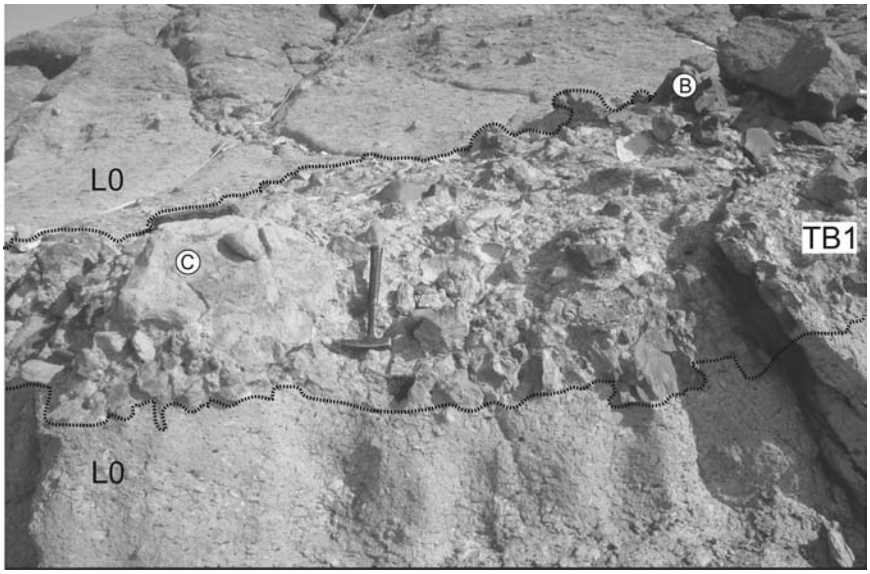


Fig. 8 **A**. Sketch of cut slab showing succession from normally graded lapilli tuff (L3) through structureless tuff composed mainly of sheared accretionary lapilli (*L0*) and normally graded tuff (*T3*) to structureless tuff (*T0*). Sheared accretionary lapilli indicate emplacement in a laterally flowing pyroclastic density current. **B**. Slab showing L3-T3 beds laterally continuous with those shown in sketch (*A*). 2 cm diameter armored lapillus (*L*) (microcrystalline basalt coated with fine ash) occupying sag deforms underlying deposit of accretionary lapilli. Highly irregular L3 upper contact with minor flame-like structures (*arrows*), implies L3 lithofacies was wet and cohesive during L0 emplacement. **C**. Photomicrograph of matrix of L3 lithofacies lapilli tuff. Note dense blocky light-coloured juvenile clasts (*J*). *Scale bar* 1 mm

Fig. 9 Typical TB1 lithofacies tuff breccia, showing block-rich, partly clast-supported character. Note large composite block (*C*), representing a fragment of fluidal peperite, and abundant blocks of basalt (*B*)



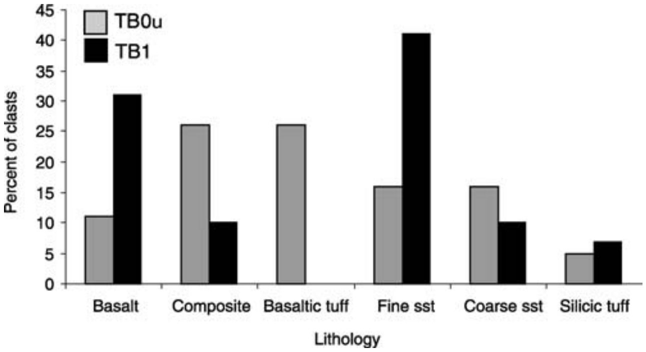


Fig. 10 Lithology and abundance of clasts ≥5 cm diameter in adjacent TB0u and TB1 lithofacies distilled from field clast count, stratigraphic column 1, Pyramid (Fig. 7). Clasts counted ≤15 cm either side of a 3.5-m tape; coarse and fine sandstone (*sst*) (includes siltstone) mostly quartzose. *Composite* = clasts of fragmented peperite, *basaltic tuff* = clasts of early formed Mawson Formation basaltic tuff (T0 facies). Silicic tuff can be hard to identify in the field, and the numbers given here may not be representative

surges (e.g., Valentine and Fisher 2000). (3) Asymmetric bedding sags and deformation of accretionary lapilli and of ribbons of basalt within beds are suggestive of transport and deposition within a system in which individual clasts had a horizontal component of motion (Fig. 8).

It is unclear what proportion of the bedded tuff sequence comprises fall deposits; the majority of the tuffs and lapilli tuffs include structures characteristic of deposits from dilute pyroclastic density currents, or mixed density currents and fall, but interpretation of some beds remains equivocal. Fall deposits tend to lack the unidirectional sedimentary structures characteristic of pyroclastic density currents, but near-surface winds and coeval plume-fed density currents occasionally create bedding and pinch and swell structures in fall deposits (Wilson and Hildreth 1998; Houghton et al. 2000).

Interpretation of LAbt

Overall, LAbt lithofacies association tuff and lapilli tuff (Table 1) are inferred to record pyroclastic surges and flows like those that form tuff rings. Effectively *en masse* deposition from tephra jets can result in deposits that resemble base surge beds but involve little lateral transport (Kokelaar 1986). Sohn (1996) similarly emphasises that tephra jetting mainly results in fall deposition, but further argues that the process forms tuff cones having slopes ≥25°. At Coombs Hills the remnant of an edifice represented by LAbt on the Pyramid (Fig. 4) has low bedding dips and most beds show evidence for deposition from currents; we infer that the original edifice here was a tuff ring. The scattered remnants of bedded pyroclastic rocks now preserved as volcaniclastic rafts within LAcb are similarly inferred to represent the remnants of tuff ring rim beds, now isolated in vent filling deposits.

Lithofacies association crosscutting breccia (LAcb); lithofacies TB0u, TB0j, TB0l, peperite, intrusive hyaloclastite, dikes, megablocks, volcaniclastic rafts, clastic dikes

Characteristic of the bulk of Mawson deposits at Coombs Hills are steeply dipping contacts between different lithofacies of the TB0 family, and between different TB0-family lithofacies and other lithofacies (Fig. 11). Rocks within these steeply dipping tuff breccia zones comprise individual occurrences of subfacies TB0j and TB0l, and many include peperite and localised intrusive hyaloclastite tangled with nonbedded TB0u tuff breccia. Megablocks and volcaniclastic rocks also lie among these lithofacies, and together this assemblage is assigned here to lithofacies association LAcb. TB0-family lithofacies comprise the bulk of LAcb zones, and adjoin one another along steeply dipping to vertical contacts defined by variation in componentry, proportion of block-size clasts, average clast size, and/or colour relative to adjacent tuff breccia. These steep contacts define semi-circular to irregular, amoeboid pipe-like structures 1–100 m (most ≤10 m) in diameter that cover 1–750 m^2 within the LAcb zones.

Lithic-rich TB0l zones within LAcb are generally smaller (≤20 m diameter) than juvenile-rich TB0j ones. Average clast size is sometimes coarser in TB0l zones than in adjacent TB0u or TB0j lithofacies. TB0l zones show few contacts with coherent basalt intrusions, but most include

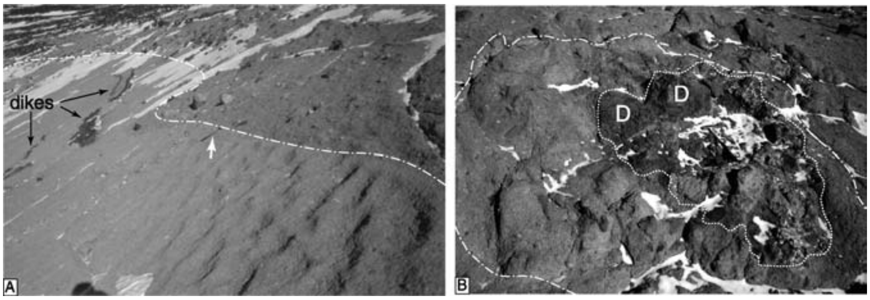


Fig. 11 **A** Steeply dipping contact (*dashed line*) between lithic-rich TB0l tuff breccia within LAcb zone (*bottom left*) and host TB0u lithofacies tuff breccia (*top right*). Note absence of large blocks in LAcb zone relative to host TB0u lithofacies, and irregular, dark coloured basalt dikes cutting LAcb zone but not host TB0u; hammer for scale (*arrow*). **B** Juvenile-rich LAcb zone showing characteristic concentric zoning around central dike (*D*) and irregular, sharp to diffuse contacts between central dike and LAcb tuff breccia (*dotted line*) and between LAcb zone and host TB0u tuff breccia (*dashed line*). Hammer for scale (*centre*)

minor (>10%) juvenile clasts or composite (fragmented peperite) blocks.

TB0j zones in LAcb often show transitions outward from a central plug or dike of coherent basalt through peperite to tuff breccia, with the peperite to tuff breccia contact being very difficult to establish. This is because the clasts being formed in the peperite and dispersed within the tuff-breccia host are of the same sizes, shapes, and composition as clasts that are ubiquitous at varying concentrations throughout TB0u lithofacies host rock.

Figure 15 shows a typical steeply dipping, laterally persistent (~40 m) contact between TB0l and TB0u lithofacies within LAcb, defined by the lighter-coloured weathering surface and comparative paucity of block-sized clasts in the juvenile-rich LAcb tuff breccia relative to host TB0u lithofacies. The contact between the two unbedded units is abrupt on a metre-scale but diffuse in detail, and is irregular on a decimetre scale.

A similar steeply dipping domain, in this case of TB0j tuff breccia, cuts TB0u tuff breccia within LAcb further west. Here, the TB0j tuff breccia is a non-stratified, poorly sorted polymict mixture of sub-angular to sub-spherical lithic, composite and juvenile lithic lapilli and blocks in a matrix of the same components; clasts of crystalline basalt are rare in the matrix size fraction, but are common as block-sized clasts. Moderately vesicular (10–40% vesicles) juvenile fragments are amoeboid with subsidiary blocky clasts. This tuff breccia occupies a zone ca. 2 m across at its widest point, but narrows to ≤0.5 m wide 10 metres along strike, with irregular intrusions of porphyritic basalt mingling with and cutting through the extensions of the tuff breccia zone. Contacts between TB0j rocks and host TB0u tuff breccia are abrupt, but show centimetre-scale, finger-like domains extending into the TB0u host rock.

Interpretation of LAcb

Gradational contacts within LAcb zones of coherent basalt intrusions (as dikes or peperite) that commonly have aligned vesicles, with structureless, unsorted tuff breccia, suggest a close relationship between intrusion of vesiculating magma and formation of juvenile-rich TB0j rocks of the LAcb.

Two types of contact exist between TB0u lithofacies and other breccias within the LAcb association: (1) gradational contacts, defined by variation in composition and colour, indicate mixing of tuff breccias; and (2) sharper, more complex, highly irregular contacts that imply mingling along an unstable, yet well-defined, interface between tuff breccias. The gradational nature of the first type of gradational contact is inferred to result from one of two mechanisms. One is diffusion along a contact between two granular materials (granular fluids), and can result from vibration ~in situ (or during non-differential motion), which causes the granular materials to mingle and diffuse in the same ways, and with similar controls, as two weakly miscible liquids (e.g., Fig. 11) (e.g., Shinbrot et al. 1999). This mechanism can produce diffuse contacts between any two clastic materials, and explains, for instance, the gradational contacts between some megablocks and enclosing TB0-family lithofacies. The second origin of such gradational contacts is formation of fluidal peperite with dispersion of fluidal clasts in the outer peperite zone. This mechanism is specific to TB0j lithofacies in clear contact with TB0u or other lithofacies in the LAcb assemblage. These two mechanisms can both affect, simultaneously or at different times, once or repeatedly, any given domain within LAcb.

In contrast to the many gradational contacts within LAcb, complex, sharp contacts are characteristic where TB0l zones cut TB0u or other lithofacies within LAcb. We infer that these sharp contacts preserve contacts between tuff breccias formed by differential shear and acceleration of one [granular] fluid through the other (Kokelaar 1983).

Discussion

Eruptive processes at Coombs Hills

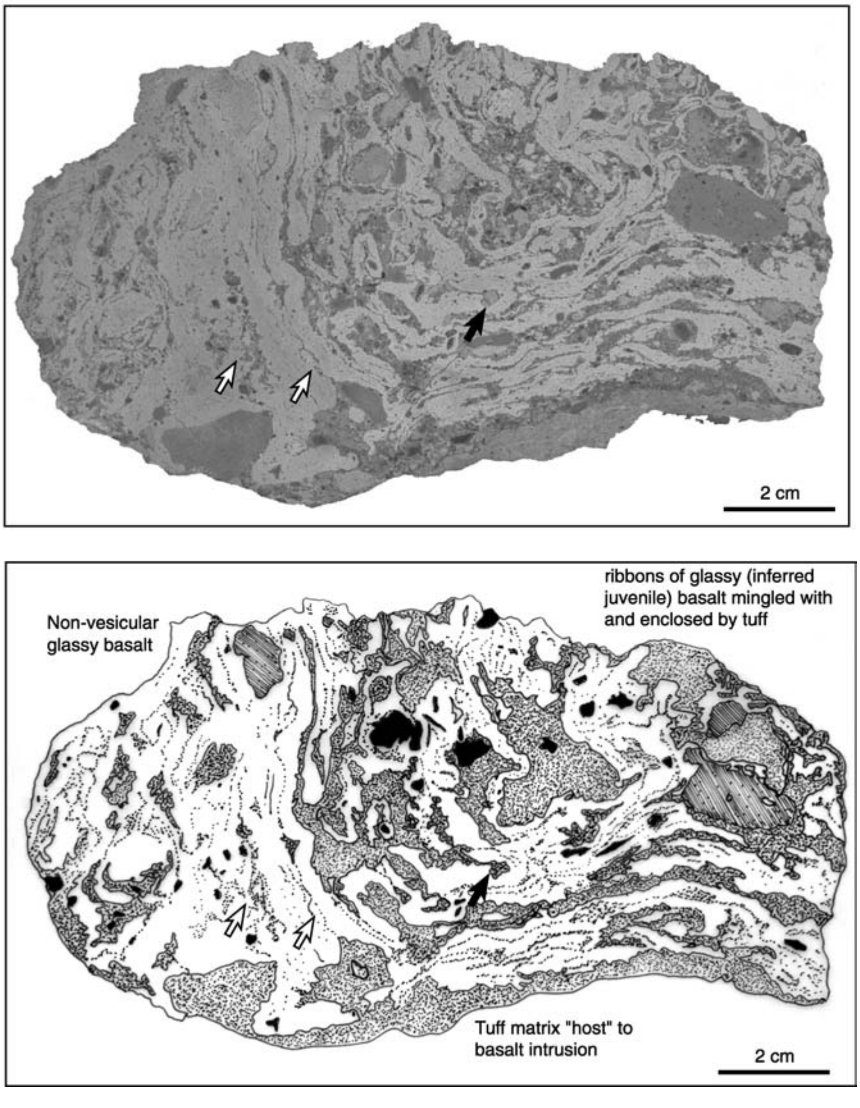
We interpret the thick, nonbedded, heterogeneous volcaniclastic deposits of LAcb that underlie the in situ bedded deposits of LAbt as the remnants of originally subsurface or incised parts of many individual, overlapping eruptive centres (Fig. 2). LAbt was emplaced onto a paleosurface atop massive LAcb vent-filling deposits (Fig. 4), and represents the subaerial deposits of some of the last active centres. It was not derived from the immediately underlying LAcb vent(s), but from nearby ones within the overall Coombs Hills vent complex.

Jets of debris as a transport phenomenon in phreatomagmatic vents

Development of the crosscutting breccia assemblage (LAcb) at Coombs Hills is inferred to have involved subsurface to subaerial passage of jets of debris, magmatic gases, and water vapor ± liquid water. Juvenile clasts in LAcb have clast textures that suggest magmatic degassing was important during generation of many jets of debris, and the abundance of sideromelane, lithic fragments, and absence of heat effects support ubiquitous involvement of water. Subsurface to subaerial jets of debris result when discrete, short-lived explosions entrain material. Whether or not sub-surface jets of debris breach the surface to deposit tephra subaerially must depend largely on the magnitude of the initial explosion, the degree to which vent fill is mobilised, and the thickness of the volcanic pile into which the jet is injected (Kokelaar 1983; White 1991). Deposition in this context takes place at the earth's surface from jets that are sufficiently energetic to punch through the debris overlying the explosion site where the jet originated. Weaker jets, or those originating deeper within the debris-filled vent, will "deposit" their clastic load when upward jet movement ceases within the enclosing debris. In this sense, deposition occurs as the driving gas (magmatic or vaporised

Fig. 12 Irregular ragged juvenile clasts in TB0j lithofacies. Note sub-horizontal alignment of elongate clasts and folding of altered glassy fringes on ragged clasts (*arrows*)

Fig. 13 Photograph and interpretive sketch of slabbed peperite block. Tuff host = *stippled*; dense to weakly vesicular, aphyric to microcrystalline basalt lithics = *black or hachured*; non-vesicular, glassy (inferred juvenile) basalt = *no ornament*. Note large, weakly vesicular (~10% vesicles) clast of microcrystalline basalt centre right. *Open arrows* indicate narrow host domains enclosed by glassy basalt, and *filled arrow* points to a glassy basalt clast, now part of the tuff host, almost isolated within glassy basalt in an intrusive ribbon



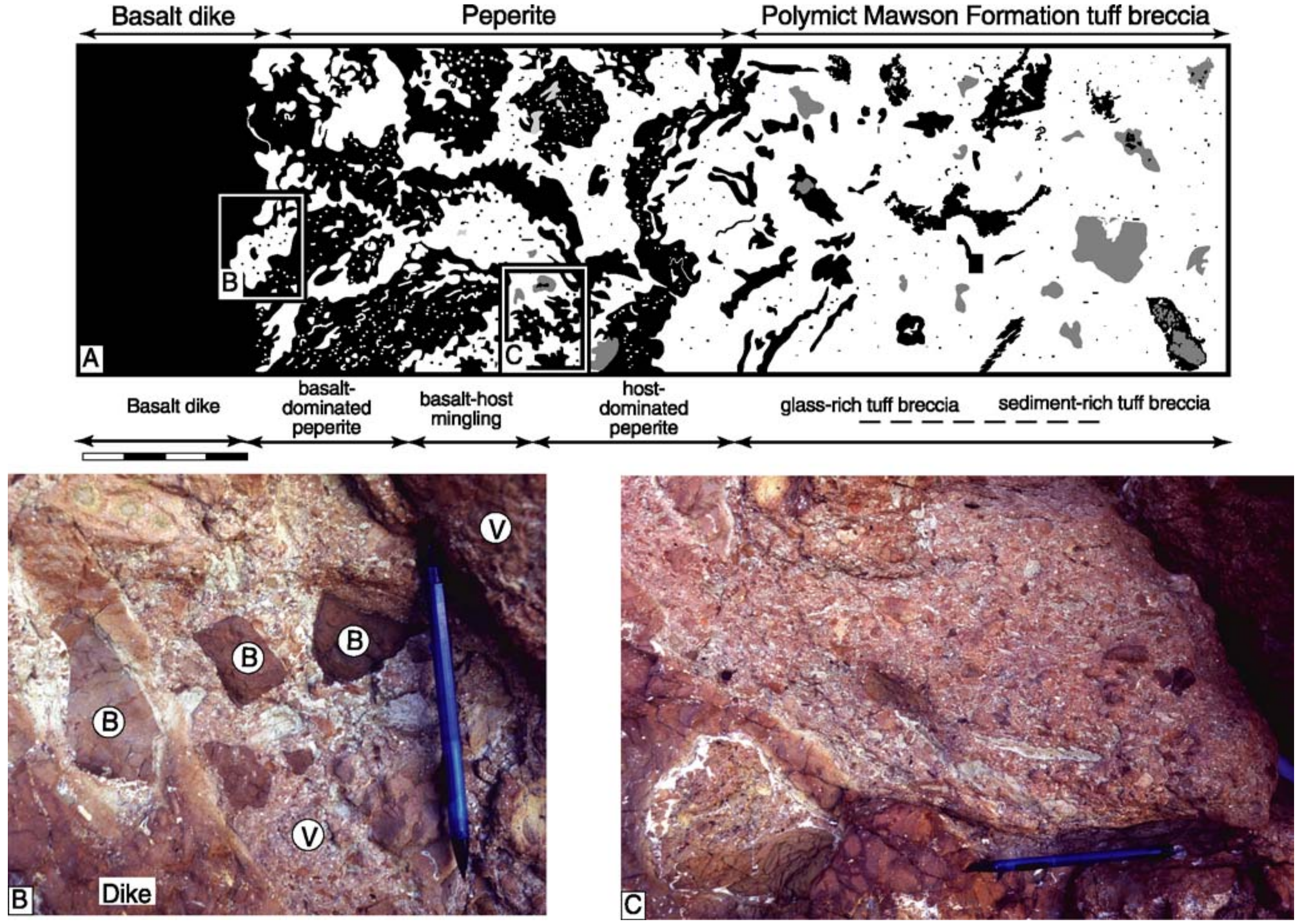


Fig. 14 **A** Schematic representation of transition from a 2.5-m-wide, coherent basalt dike cutting the Mawson Formation through peperite into polymict Mawson Formation tuff breccia. *Black* = basalt, *white* = Mawson Formation host, *grey* = lithic clasts; scale bar 0.5 m. *Inset boxes* = relative location of Figs. 13b and c within dike-volcaniclastic rock transition zone. **B** Basalt-dominated peperite in transition zone, showing cm-scale mingling of basalt with host volcaniclastic rock (*V*), and basalt blocks (*B*), one enclosed by the margin of the adjacent basalt dike. **C** Fluidal peperite within basalt-host mingling zone

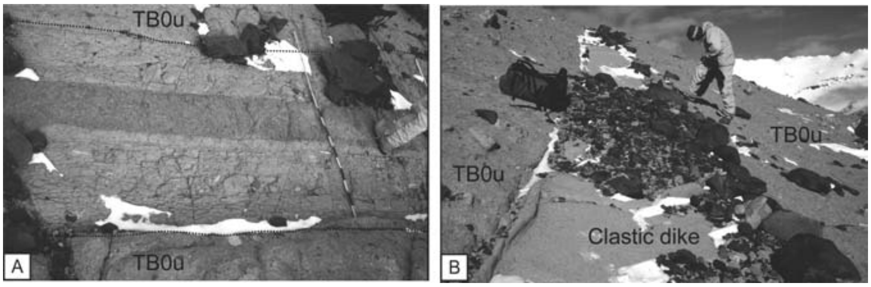


Fig. 15 **A** Bedded tuff and lapilli tuff within volcaniclastic megablock (see Fig. 7 stratigraphic section 3). *Dotted lines* indicate contacts between megablock and host TB0u lithofacies tuff breccia; scale divisions on ruler 10 cm. **B** Clastic dike of coarse tuff bounded by sub-vertical contacts with TB0u lithofacies tuff breccia, Pyramid. Note absence of bedding and blocks within the clastic dike

water) escapes or condenses and the opening made during passage through vent-filling debris stops propagating and closes up. Closure is inferred to take place by gravitational collapse, and specifically by granular flow of the debris into the passageway as soon as jet overpressures are terminated. Because of the depth of debris fill in vents of the Coombs Hills complex, many sub-surface jets of debris probably died out in vent fill before breaching the surface, leading to mixing, and recycling, of clasts that never escaped the vent.

Crosscutting zones in LAcb are distributed within and along the margins of Mawson Formation outcrop at different elevations, and hence structural levels, suggesting initiation of sub-surface jets of debris at many levels in the Coombs Hills vent complex. The range in size of crosscutting zones within LAcb may reflect the longevity of a jet, the power of an explosion driving debris transport through vent fill, variable resistance of different parts of the vent fill to passage of a jet through it, and level of present erosion surface relative to the depth of jet initiation or ground surface. The varied proportions of juvenile and lithic clasts in different LAcb lithofacies probably reflect (1) the population of clasts initially accelerated upward by the magma-water explosions driving the jet; (2) distance of jet travel through vent-filling debris, with potential for incorporation of debris from conduit walls as streams of tephra rush up through the overlying unconsolidated Mawson Formation pile; and (3) collapse of vent-filling debris into conduits created by passage of jets through vent fill between multiple jetting episodes sourced from the same site. Incorporation of wall rock at the fragmentation site is sensitive to the degree and level of hydrovolcanic interaction; entrainment of large-volumes of wall rock only occurs if phreatomagmatic explosions are seated at shallow levels (Valentine and Groves 1996), and then only if explosive energy is directed into wall rock. If most explosive energy is directed upward, or explosions are relatively weak, as suggested by limited mixing and coarse grainsize in TB0l zones within LAcb, little conduit-wall material will be incorporated into the initial jets of tephra. If multiple discrete jets are generated from one site, collapse of debris into more-or-less open conduits will result in subsequent jets incorporating a mixture of clasts fragmented during explosions, and clasts in conduit-filling debris. Peperite and/or hyaloclastite are mainly inferred to reflect late-stage uprise of magma into occluded jet passageways.

Coombs Hills volcanic complex morphology

There is no evidence that the Coombs Hills volcano was ever high standing. The present level of exposure is inferred to be at least 100 m below the syn-eruptive ground surface at the onset of volcanism, based on the presence of debris from both uppermost Lashly Formation rocks and silicic ash deposits that were the last pre-Kirkpatrick deposits formed in the area (Elliot et al. 2004). Bedded deposits of LAbt exposed with a basal contact onto LAcb Mawson Formation at an elevation of 2,200 m indicate that this was at the time of LAbt deposition the floor of that part of the vent-complex. Capping lava flows at Mount Brooke are intercalated with lacustrine deposits at elevations up to 2,650 m, indicating accumulation of water at the post-Mawson ground surface and hence implying a lack of positive relief even after emplacement of the Mawson Formation and at a significantly higher relative elevation.

When the eruptions that formed the Mawson Formation at Coombs Hills were complete, the rocks now cropping out would have been buried below a ground surface of tuff rings and tuff ring remnants with their associated craters. There would be exposed remnants of tuff rings that were partly subsided into craters (cf., White 1991), though not necessarily within the crater from which the ring's material was erupted. Megablocks of Victoria Group would have stuck out from the debris, particularly near the edge of the complex. The complex floor in general would have resembled a larger version of the Rotomahana area following the 1886 eruption that excavated its present topography (Smith 1886; Thomas 1888; Keam 1988), and as at Rotomahana, lower areas would have been favoured sites for accumulation of isolated or conjoined lakes. Small basaltic edifices probably formed at the vent-complex floor where late Mawson Formation dikes reached the surface. This surface may itself have been surrounded in part by cliffs or partly ash-mantled rubble slopes tens of metres high, depending on what thickness of Mawson debris originally lay above the height of the Pyramid.

Evolution of the eruption and volcanic complex

The volcanic complex grew via coalescence of smaller volcanic centres. Collapse at individual centres in the complex led to cannibalization of early tuff ring-like ejecta aprons, some of which are preserved as volcaniclastic rafts in LAcb, and others as in situ remnants formed following cessation of other explosive activity at their site. The Coombs Hills complex may have begun as a cluster of discrete vents, but developed into a larger vent complex most similar to a nest of diatremes, which White and McClintock (2001) called a “phreatocauldron”. Documented examples of similar, smaller complexes comprising a few or many coalesced vents include centres in the Bakony-Balaton Highland volcanic field, Hungary (Nemeth and Martin 1999), Rotomahana, New Zealand (Smith 1886; Thomas 1888; Keam 1988), and Xalapaxco, Mexico (Abrams and Siebe 1994).

The proportionally shallow level of excavation at Coombs Hills is mainly a function of the large size of the complex. The total depth of quarrying below eruption surface is approximately a kilometre (from uppermost silicic ash to a Metschel Tillite granitic boulder source) (Fig. 3), which is not unusual among diatremes (Cloos 1941; Hearn 1968; Lorenz 1986; White 1991; Nemeth and Martin 1999). Deeper quarrying of country rock was probably inhibited by repeated burial and occlusion of the ephemeral vents by inward collapse of vent walls saturated with the water required to sustain phreatomagmatic eruptions. Water for phreatomagmatic explosions also seems to have remained available at shallow levels throughout the eruption (Aranda-Gomez and Luhr 1996; Sohn 1996). During the eruption access of water to vent sites increased following disruption of aquitard beds in the Beacon Supergroup succession (e.g., coal, shale) and fracturing of low permeability sedimentary rock to form breccias and releasing previously locked-up interstital water to the volcanic system (White 1991; Aranda-Gomez and Luhr 1996). Given regional homogeneity of the pre-eruption Victoria Group, the large area of the complex presumably reflects the area over which magma rising toward the surface; the impression given is one of a leaky onset to the Kirkpatrick flood-basalt eruptions, with many closely spaced supply points rather than a small number of large dikes or conduits.

So where was the material erupted from the complex dispersed, and what were the means of dispersal? More than a cubic kilometre of juvenile basaltic material is present in the Mawson Formation at Coombs Hills, and rubble produced from Beacon country rock would also have occupied a greater volume than the original rocks; these considerations require that substantial volumes of material were transported away in order for the final edifice to be a feature of negative relief capable of impounding water. In nearby areas such as Allan Hills, previous workers have reported stratified Mawson Formation and inferred it to have been deposited by lahars (e.g., Ballance and Watters 1971). Regardless of depositional process, the stratified Mawson Formation deposits in adjoining areas are potentially deposits of material transported away from Coombs Hills or a similar source.

Conclusions

Mawson Formation rocks at Coombs Hills were (re-) deposited, (re-) intruded, (re-) fragmented and recycled within a kilometres-scale, high width-to-depth ratio vent complex which increased in size via lateral quarrying of country rock and vent coalescence. Features of volumetrically dominant LAcb deposits suggest repeated injections of debris from depth into pre-existing deposits, churning driven by sub-surface explosions, and syn-eruptive collapse of wall rock into vents. Country rock incorporated into the vent suffered structural disruption by a variety of processes to become digested en masse or grain-by-grain into tephra. Important lessons from the Coombs Hills vent complex include the following: (1) Volcanic structure and process in phreatomagmatic volcanoes is largely independent of scale. Coombs Hills, although several orders of magnitude larger than typical basaltic phreatomagmatic volcanoes, records similar processes of magma-water interaction and phreatomagmatic to magmatic evolution to those found in much smaller systems. (2) Recycling of water is probably as ubiquitous in large phreatomagmatic vent complexes as recycling of pyroclasts, with the result that growth of phreatomagmatic systems is limited not only by local availability of water (restrictions imposed by porosity, permeability, surface flow) but also by proportion of recycled water. (3) Sub-surface jets of debris probably represent an important transport system in diatreme-like vents. (4) Peperite should not be assumed without further investigation to record intrusion of magma into unconsolidated sediment, as some peperites form via mingling of magma with sediment formed from crumbling of consolidated rock as a consequence of intrusion or of churning, shocks, or liquifaction within volcanic vents. This implies that peperite, at least where associated with explosive vent complexes, is not necessarily an indicator of contemporaneous intrusion and sedimentation.

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