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Journal of Volcanology and Geothermal Research 114 (2002) 205–217

Journal of volcanology
and geothermal research

www.elsevier.com/locate/jvolgeores

Granulation of weak rock as a precursor to peperite formation: coal peperite, Coombs Hills, Antarctica

M.K. McClintock *, J.D.L. White

Geology Department, University of Otago, P.O. Box 56, Dunedin, New Zealand

Accepted 20 June 2001

Abstract

Peperite formed by mingling of magma with coal, and with fragmented coal plus other country rock, is exposed at Coombs Hills, Antarctica, in rocks of the Mawson Formation, where Ferrar Supergroup basalt encountered the Beacon Supergroup continental sedimentary succession. An internally laminated, 0.5-m-thick coal bed passes gradationally through a coal-fragment-dominated peperite into a glass-rich, basalt-dominated coal fragment–matrix peperite, and then into coherent basalt. Initial interaction of magma with water-saturated coal and host sediments locally brecciated the coal. Subsequent mingling of basalt with a slurry of coal fragments and water, driven by viscosity and density contrasts between the basalt and the slurry and by flow inhomogeneities in intruding magma, led to increasingly complex mingling of the two fluids via bifurcation of fingering viscous flows. This mingling was complicated by the participation of phases with time- and space-dependent thermal properties and viscosity (coal fragments, coal–water slurry, and basaltic magma), and the generation of multiple (?) gas phases through devolatilisation of heated coal. The initial elastic response of the coal fragments to stress resulted in: (a) fluidal mingling of coal and basalt facilitated by softening of coal during heating associated with intrusion; and (b) localised formation of blocky coal clasts during high stress events associated with passage of a liquid, and/or a gas phase(s), through the coal. The presence of fluidal- and blocky-shaped coal fragments in the coal peperite, with both curved and planar surfaces bounding single coal clasts, suggests that clast morphology in the magma–sediment dispersion was controlled at very small scales by the time-, temperature-, and stress-dependent qualities of the coal. Fluidal and blocky clast shapes in the coal peperite, coupled with vesicles in the coal clasts, suggest that transient properties of either the host or intrusion during non-explosive magma–sediment interaction may exert a strong control on clast morphology and mingling characteristics.

Keywords: peperite; coal; basalt; magma–water interaction; Ferrar Supergroup; Antarctica

1. Introduction

Peperite results from the dynamic mingling of magma with unconsolidated, generally wet, sediment (White et al., 2000), and is the product of a range of complex subsurface magma–sediment interactions, some of which may occur during the initial stages of explosive hydrovolcanism (Koke-

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* Corresponding author. Present address: Dept. Geology and Geophysics, School of Ocean and Earth Sciences and Technology, University of Hawaii at Manoa, 1680 East West Road, Honolulu, Hawaii 96822, USA. Fax: +64-3-479-7519.

E-mail addresses: murraym@soest.hawaii.edu (M.K. McClintock), james.white@otago.ac.nz (J.D.L. White).

PII: S0377-0273(01)00292-X

laar, 1983, 1986; Wohletz, 1986). Recognition of peperite in the rock record can help to establish contemporaneity of sedimentation and volcanism (Busby-Spera and White, 1987; Riggs and Busby-Spera, 1990; Brooks, 1995), and certain types of peperite are regarded as examples of 'frozen' fuel–coolant interactions (FCI) that might precede phreatomagmatic explosions (Kokelaar, 1986; White, 1991, 1996; Hanson and Hargrove, 1999). Peperite has been described from diverse geological settings, with published examples reflecting mingling of a range of sediment types with magmas of mafic to silicic composition (Brooks et al., 1982; Hanson and Schweickert, 1982; Kokelaar, 1982; Busby-Spera and White, 1987; Leat and Thompson, 1988; White, 1991; McPhie et al., 1993; Rawlings, 1993).

The peperite described here formed by interaction of basaltic magma with coal (lignite to sub-bituminous rank), a deposit type which has physical characteristics distinct from those of host sediments for the bulk of peperite described to date. The coal is of interest because it appears to respond to applied stress as either a viscous fluid or brittle solid as a function of strain rate and temperature, rather than solely as a granular fluid as do most other host sediments. The differing material behaviour is inferred to result from at least three factors: (1) the extremely low strength of the single, variably degraded, partially intertwined plant fragments that forms coal; (2) the low bulk strength of partly lithified coal (lignite or sub-bituminous coal); and (3) the ability of the organic material comprising coal to oxidise (burn) at temperatures less than that of magma. These properties are reflected in features now preserved in clasts of coal within the peperite. Larger scale mingling to produce the peperite occurred primarily between magma and a water-saturated slurry of coal fragments.

1.1. Geological setting

Widespread Jurassic–Early Cretaceous magmatism associated with Gondwana break-up involved enormous outpourings of flood basalt, forming the Jurassic Karoo lavas in southern Africa, the Cretaceous Paraná-Etendeka volcanic rocks in South America and Namibia, and the Deccan basalt in India (Hanson and Elliot, 1996). In Antarctica, the major phase of tholeiitic magmatism related to supercontinent fragmentation is represented principally by the Middle Jurassic Ferrar Supergroup, comprising the Kirkpatrick Basalt, associated pyroclastic rocks, including the Mawson Formation, and co-magmatic Ferrar Dolerite sills in the Transantarctic Mountains (Hanson and Elliot, 1996). Petrological, structural and volcanological data suggest that the Jurassic pyroclastic rocks and overlying flood basalt were erupted into a volcano-tectonic rift system associated with lithospheric extension and decompression melting (Elliot, 1992).

The pyroclastic precursor to Ferrar Supergroup flood-basalt volcanism in the central Transantarctic Mountains is the Mawson Formation (ca. 184 Ma (K–Ar); Hall et al., 1982). The Mawson Formation at Coombs Hills, Victoria Land (Fig. 1), and correlative Exposure Hill and Prebble Formations elsewhere in the Transantarctic Mountains, comprise crater-fill and laharic tuff breccia, lapilli tuff and tuff with associated peperite, hyaloclastite, base surge deposits, and dikes and sills (Ballance and Watters, 1971; Grapes et al., 1974; Korsch, 1984; Bradshaw, 1987; Elliot and Larsen, 1993; Hanson and Elliot, 1996). An abundance of recycled and composite (peperite-cored) clasts, and debris derived from underlying Beacon Supergroup sediments and sedimentary rocks (Fig. 2) within these deposits, suggest that explosive phreatomagmatic activity was driven by the interaction of rising basaltic magma with wet sediment and groundwater (Hanson and Elliot, 1996).

1.2. Coal peperite

The most widespread Mawson Formation facies is unbedded calcite- or zeolite-cemented tuff breccia, comprising 5 cm to > 1 m diameter clasts of tuff and lapilli tuff, carbonaceous siltstone, fine-grained sandstone, coal, marble, granite, and a variety of mafic volcanic rocks, in a matrix of the same but finer components. The juvenile component of the tuff breccia comprises fluidal, blocky or amoeboid glassy basaltic clasts (now

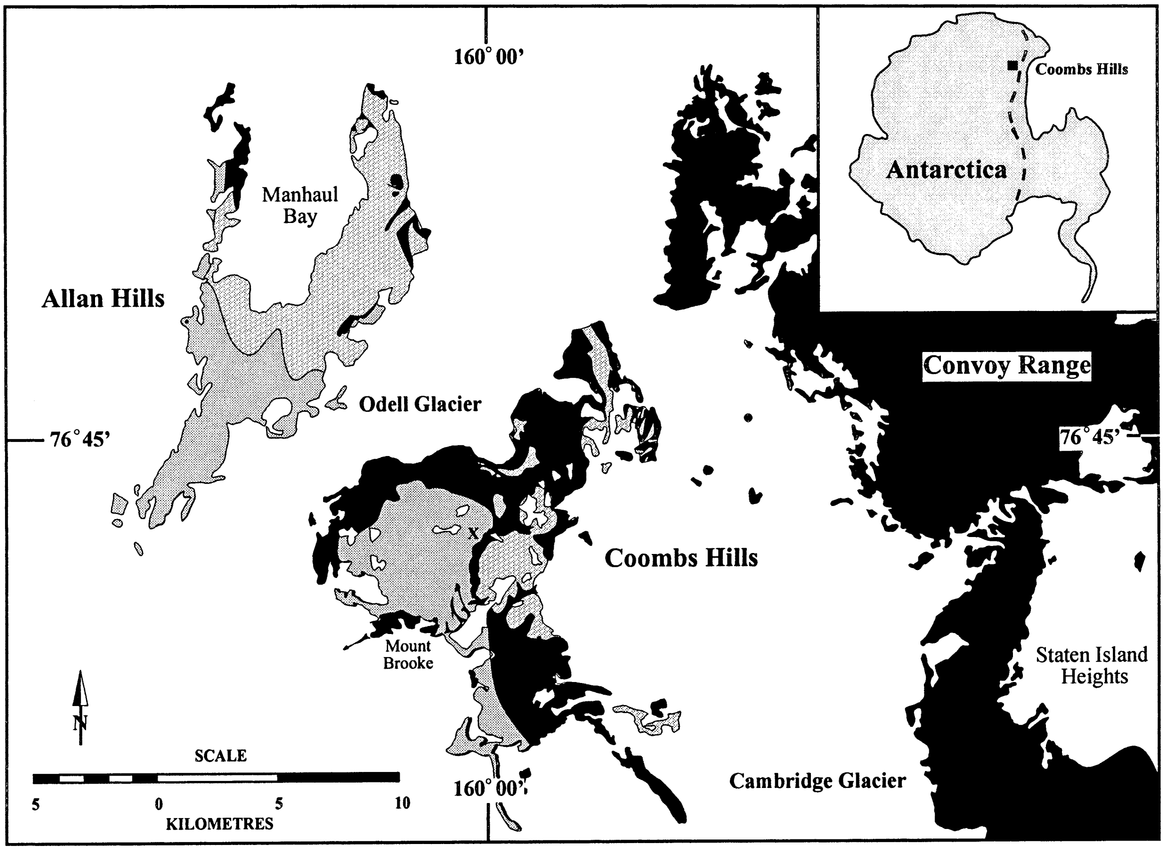

Fig. 1. Location of Coombs Hills, Victoria Land, Antarctica. The Transantarctic Mountains are marked by dashed line on inset map. The coal peperite outcrop is marked by the black X. Simplified geology (black, Ferrar Supergroup igneous rocks; grey, Mawson Formation; stippled, Beacon Supergroup; unpatterned, ice) after Grapes et al. (1974) and Bradshaw (1987).

altered). Minor bedded tuff and lapilli tuff are also present. The tuff breccia includes megablocks of Victoria Group (Beacon Supergroup) sedimentary rocks and tuffaceous sandstone (ca. 50 m in length and width and up to 20 m thick), inferred to represent blocks of mainly poorly consolidated wall rock that collapsed into vents during undermining of vent margins (McClintock and White, 2000). Peperite occurs at the margins of the megablocks where they are in contact with Ferrar basalt. Peperite is gradational into the tuff breccia that characterises the bulk of the Mawson Formation; the complete transition from Victoria Group sedimentary rock through peperite into Mawson Formation tuff breccia is commonly preserved, with the fragmented basaltic component of the peperite preserved as amoeboid or ribbon-like glassy particles or as discrete clasts of finely crystalline basalt in the tuff breccia.

Coal is widespread at Coombs Hills as thin, largely continuous beds and lenses within the Victoria Group and as isolated fragments (up to 10 cm long) within Mawson Formation tuff and tuff breccia. The coal peperite considered here is a small body (ca. 60 cm across) on the margin of a sandstone megablock (ca. 150 m^2) isolated within dolerite of the Ferrar Supergroup along the contact between the Mawson Formation and the Victoria Group (Fig. 3). The megablock is one of a series of sandstone bodies within the Ferrar dolerite along the Mawson Formation–Victoria Group contact, with sandstone–basalt peperite and earlier formed tuff, lapilli tuff and tuff breccia of the Mawson Formation locally in contact with

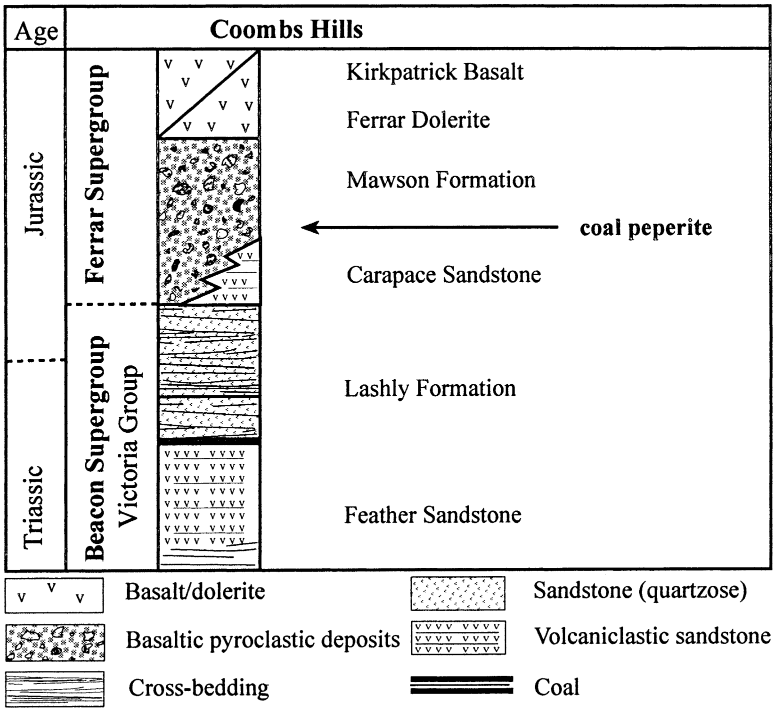

Fig. 2. Simplified stratigraphic column for the Beacon and Ferrar Supergroups at Coombs Hills after Ballance (1977), Collinson et al. (1983) and Elliot (1992).

the megablock. The megablock margins vary from straight to highly irregular at scales of centimetres to metres, with tongue-like and cuspate forms being common. Bedding in the sandstone megablocks has been distorted and tilted by the Ferrar intrusions, with bedding in adjacent megablocks dipping in random directions (Fig. 3). Sandstone in the megablock comprises sub-angular to rounded, medium sand- to pebble-sized quartz, and is interbedded with thin (<30 cm), streaky or thinly laminated coal seams. The sandstone exhibits well-developed trough and planar cross-bedding. The coal beds include leaf fossils along bedding planes, and show partly preserved microcellular structures. The coal rank in the sandstone megablock is bituminous to semi-anthracite; rank in the coal peperite is anthracite to meta-anthracite.

At one site, the megablock margin passes outward from an internally laminated, 0.5-m-thick coal bed, through a coal fragment-dominated peperite into a glass-rich, basalt-dominated coal fragment–matrix peperite, and then into coherent basalt, which intrudes the megablock as narrow (<1 m) irregular dikes (Fig. 4). The transition from coal fragment-dominated ($>50\%$ coal fragments) to basalt-dominated ($>50\%$ basalt) peperite is gradational. Coal fragment-dominated peperite domains are more common than basalt-dominated peperite domains. Elsewhere, along the margins of the sandstone megablocks, the basalt is mingled with fine quartzose sandstone instead of coal fragments.

At almost all scales, peperite described here includes coal fragments, basalt, and quartz grains. The coal fragments and quartz were probably derived from sandstone and coal present in the adjacent megablock. In hand specimen, the coal peperite comprises angular to round or amoeboid fragments of coal (ca. 5 cm diameter) containing subordinate fine sandy lenses, intimately mingled with light brown, glassy basalt fragments (ca.

Fig. 3. Victoria Group sandstone megablocks (B) 'floating' within Ferrar Dolerite (F), Coombs Hills. Bedding in megablock at left is shallowly dipping, whereas bedding in megablock at centre is steeply dipping. White areas are snow; scree obscures the contact between the two rafts. Fig. 4 illustrates contact relationships between an extension of one of the megablocks, basalt and tuff breccia of the Mawson Formation.

2 cm). Highly irregular, frayed or 'raggy' contacts between coal fragments and basalt are observed at outcrop and hand-specimen scale, and are also evident on a microscale (Fig. 5). Elongate to round, fluidal, 'tongue-like' trains and globules of coal trail from the margins of single large clasts (ca. 2 cm) of coal mingled with basalt, isolated within a matrix of millimetre-sized coal and basalt clasts, into surrounding domains in which coherent basalt encloses coal clasts. The glassy basalt has decomposed to brown cryptocrystalline alteration products and feldspar microlites. Coal clasts also contain discontinuous trains of closely packed, round to elongate glass particles, and of ovoid vesicles. The trains of glassy basalt within the coal clasts are commonly interconnected, although in some cases no feeder tubes for the glass are evident. Apparently isolated particles of glass also occur, but may be connected in three dimensions. Within the coal clasts and along coal-clast margins, clusters of quartz grains are present in a matrix of glass. Some of this quartz has irregular, corroded margins.

The coal host to basalt intrusion in peperite at Coombs Hills comprises centimetre- to millimetre-sized clasts of coal, each of which are intruded by coherent basalt, or mixed with basalt fragments. The coal clasts occur as either: (a) dominantly fluidal clasts enclosed in basalt, with blocky clast shapes predominating away from larger coal-clast margins; or (b) mixtures of coal fragments and quartz grains with glassy basalt in narrow, dike-like domains intrusive into larger (>1 cm) coherent coal clasts.

Fluidal coal clasts predominate in the coal peperite, with blocky coal clasts present only locally along the margins of larger fluidal coal clasts enclosed by basalt. These domains of basalt laden

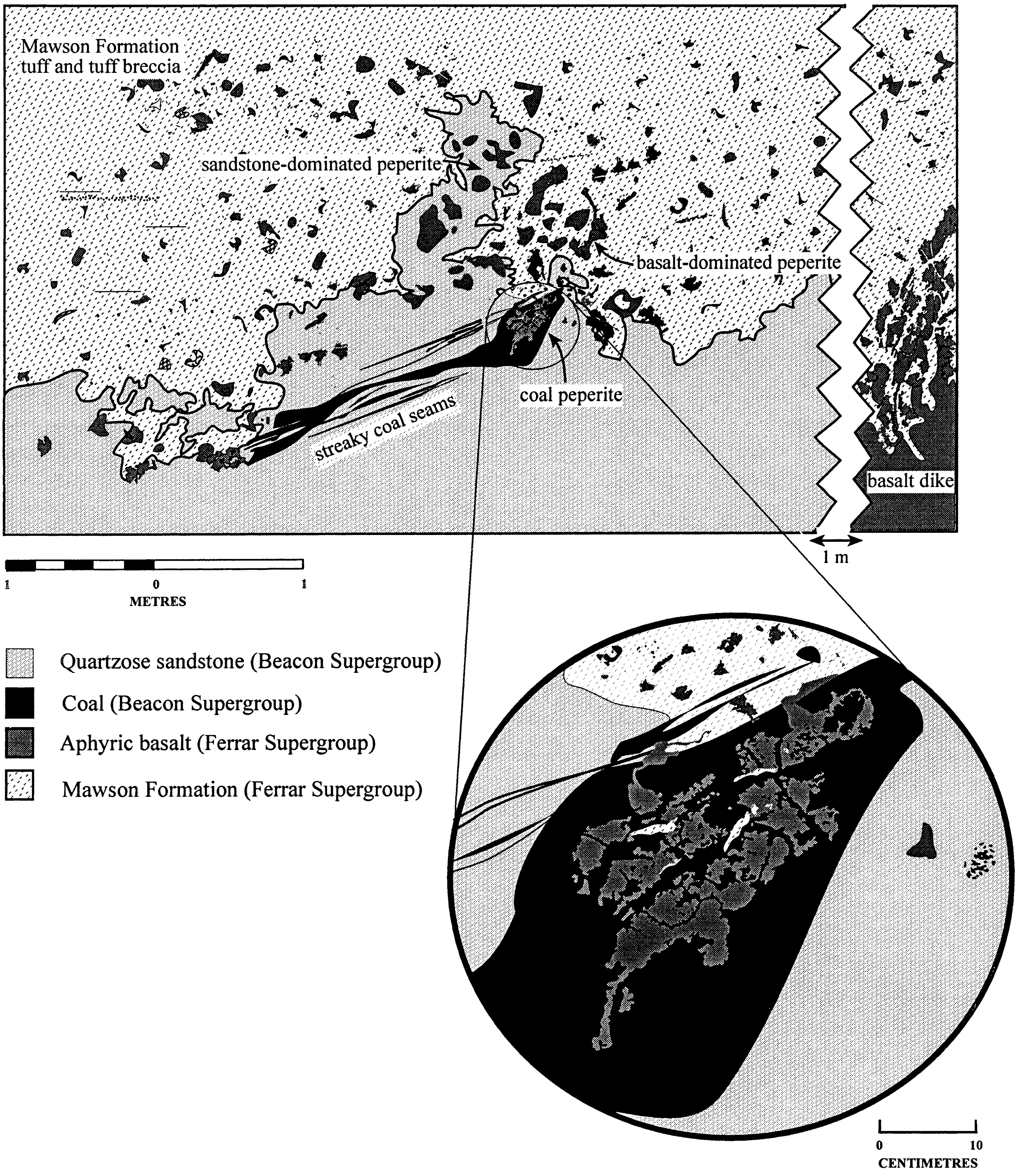

Fig. 4. Sketch of Victoria Group–Mawson Formation contact relationships, showing quartz sandstone, coal peperite and Mawson Formation tuff and tuff breccia along the margin of a quartz sandstone megablock, Coombs Hills. The nearest exposed intrusion is a basalt dike ca. 1 m away from the coal seam; no contact between the dike and the peperite is exposed, but the eroded remnant of the dike extends along the foot of the outcrop, and the basalt-dominant peperite is inferred to have been gradational over a few tens of centimetres with coherent basalt. Enlargement shows coal peperite comprising black coal (in streaky, largely discontinuous seams) mingled with aphyric, glassy basalt (grey). Note minor lenses of sandstone. Fluidal morphologies predominate, with isolated coal fragments (mainly blocky) in basalt-dominated domains.

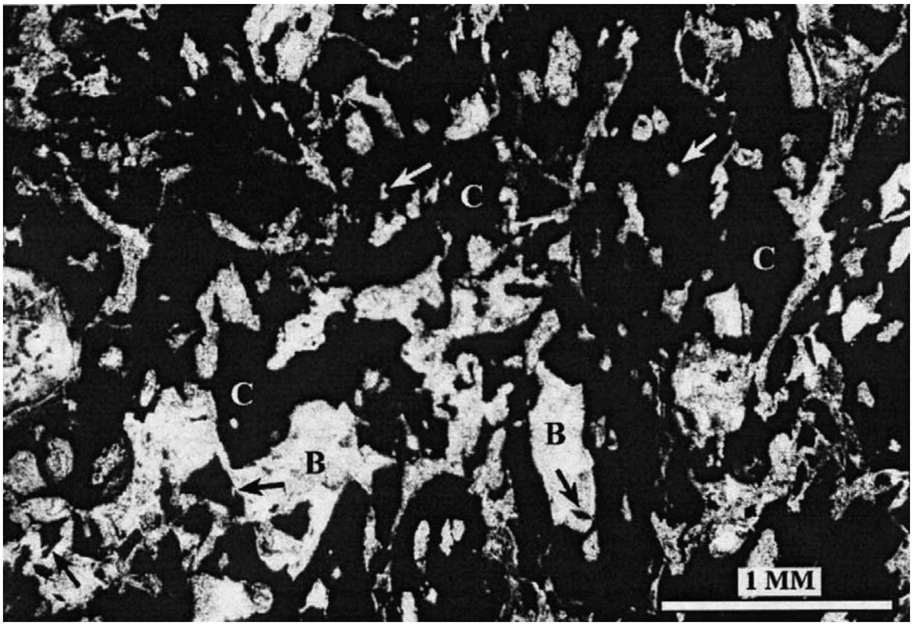

Fig. 5. Photomicrograph of coal peperite, showing a mixture of fluidal and blocky coal (C) and basalt (B) clasts, representing mingling of coal and basalt on a sub-millimetre scale. Black arrows indicate typical blocky coal clasts, with arcuate edges truncating embayments in clast margins. White arrows indicate rounded to irregular vesicles within coal.

with blocky coal fragments, some exhibiting 'jig-saw-fit', are gradational into mixtures containing fluidal coal and basalt clasts, and then into in situ coal. Blocky coal fragments are also locally present without accompanying basalt adjacent to in situ coal, forming a clast-supported, calcite-cemented coal breccia.

2. Discussion

2.1. Environment of peperite formation

The Victoria Group strata are considered to have been wet and poorly consolidated at the time of intrusion by basalt on the basis of: (1) extensive development of peperite, swirly dikes and intrusive hyaloclastite along contacts between intrusions and host sediments; (2) an abundance of glassy basalt along intrusive contacts, and as a juvenile component of the peperite and intrusive hyaloclastite; and (3) destruction and/or deformation of bedding in host sediments adjacent to intrusive contacts. We infer that the coherency of these Victoria Group strata was reduced, prior to peperite formation, during the time they were incorporated in the Mawson Formation vent-filling tuff breccia (White and McClintock, 2001).

2.2. Properties of coal

Coalification (the transformation of vegetation through peat into coal; Thomas, 1992) is primarily controlled by temperature (Galloway and Hobday, 1996). Formation of peat is achieved by surficial biochemical diagenesis, which extends to depths of about 10 m where purely chemical processes become dominant, with lignite (brown coal) developed at depths of 200–400 m as a result of compaction and dewatering (Galloway and Hobday, 1996). High temperature promotes geochemical (as distinct from biochemical) coalification (Stach et al., 1975). Devolatilisation and dewatering of coal following rapid heating during basalt intrusion is inferred to have contributed to thermal metamorphism and rank elevation of the coal in the peperite relative to coal elsewhere in the megablock.

When any carbon-rich sediment is heated to temperatures in excess of 300°C in anoxic conditions, a proportion is converted to volatiles (Stach et al., 1975). These volatiles can be either liquid or gaseous, and comprise methane, carbon dioxide, carbon monoxide, nitrogen and ethane (Thomas, 1992). The viscosity of carbon-rich sediments is dependent on the volatile content and the amount and rate of heating. High-volatile coal will soften upon heating (e.g. Lumsden, 1967), but the viscosity of the plastic coal remains high, with minimum values of 10^4–10^5 Pa s (Nomura et al., 1999). A decrease in volatile content will result in a decrease in viscosity. Higher rates of heating lead to lower viscosity for a sediment of given volatile content (Stach et al., 1975). Viscosity of the coal, therefore, is time-dependent during intrusion and devolatilisation, with resistance to flow decreasing with volatile-loss and/or heating rate. The permeability of coal is highly stress-dependent, decreasing as the level of stress is increased (Thomas, 1992). Coal subjected to high stresses exhibits lower permeability, which retards the movement of fluids (liquids or gases) through the coal, effectively increases viscosity and leads to brittle failure.

In order for local non-brittle mingling of coherent coal and magma to occur, the coal must have been able to behave as a viscous fluid under certain conditions at the time of intrusion. Beacon Supergroup coal elsewhere in South Victoria Land is inferred to have been of no more than sub-bituminous rank prior to Ferrar Supergroup magmatism, with subsequent rank elevation to bituminous and greater rank via heating associated with Ferrar Supergroup intrusions (Schapiro and Grey, 1966; Kyle, 1977; Rose and McElroy, 1987; Retallack and Alonso-Zarza, 1998). During basalt intrusion, heating of low-rank coal is likely to have resulted in rapid, highly localised changes of initially wet, lignitic to sub-bituminous coal to anthracite, potentially during single mingling events.

2.3. Properties of basalt

As a crystallising, cooling, highly non-Newtonian fluid, basaltic magma has an inherently time-dependent viscosity (Spera, 2000). Processes that modify the behaviour of flowing magma and therefore affect magma–sediment interface geometries in peperite are constriction of pipes and conduits, and viscosity increases with cooling, crystallisation, and the presence of a bubble-forming vapour phase within the magma (Manga and Loewenberg, 2001). The glassy, aphyric and vesicle-poor basalt involved in peperite formation at Coombs Hills is assumed to have been largely free of the viscosity complications introduced by crystallisation and bubbles, but constriction of conduits and a dramatic increase in viscosity due to rapid cooling are both likely to have occurred. In the case of the coal peperite, the local ‘conduits’ are the highly irregular pipes and dikes of basalt that intruded the coal in the Victoria Group sandstone megablock. The basalt conduits had transient geometries during peperite formation because of the varying elastic and thermal properties of the surrounding coal with varying rates of heating and applied stress.

2.4. Formation of the coal peperite

Formation of coal peperite at Coombs Hills attests to two modes of local mingling of basalt and coal (Fig. 6). The bulk of the peperite appears to record mingling of basalt with a clastic coal host generated via (probably explosive) brittle fragmentation of coherent coal seams (Fig. 6, 1a–c). The coal in the peperite comprises discrete, angular clasts, which contrast with the continuous, coherent coal seams interleaved with adjacent Victoria Group sandstone. The intimate mixture of coal fragments and basalt within the peperite is characterised by fluidal clasts of basalt and coal adjacent to margins of larger coal clasts, and blocky clasts of basalt and coal further away from large coal-clast margins (Fig. 5). This suggests initial fine-scale mingling coal and basalt, now preserved only as single clasts comprising mingled basalt and coal. These fragments of coherent basalt+coherent coal peperite were mixed with blocky basalt clasts and sand grains during ongoing fragmentation and mingling in the bulk of the peperite. Alternatively (Fig. 6, 2a,b), intimate mingling of coherent basalt with small do-

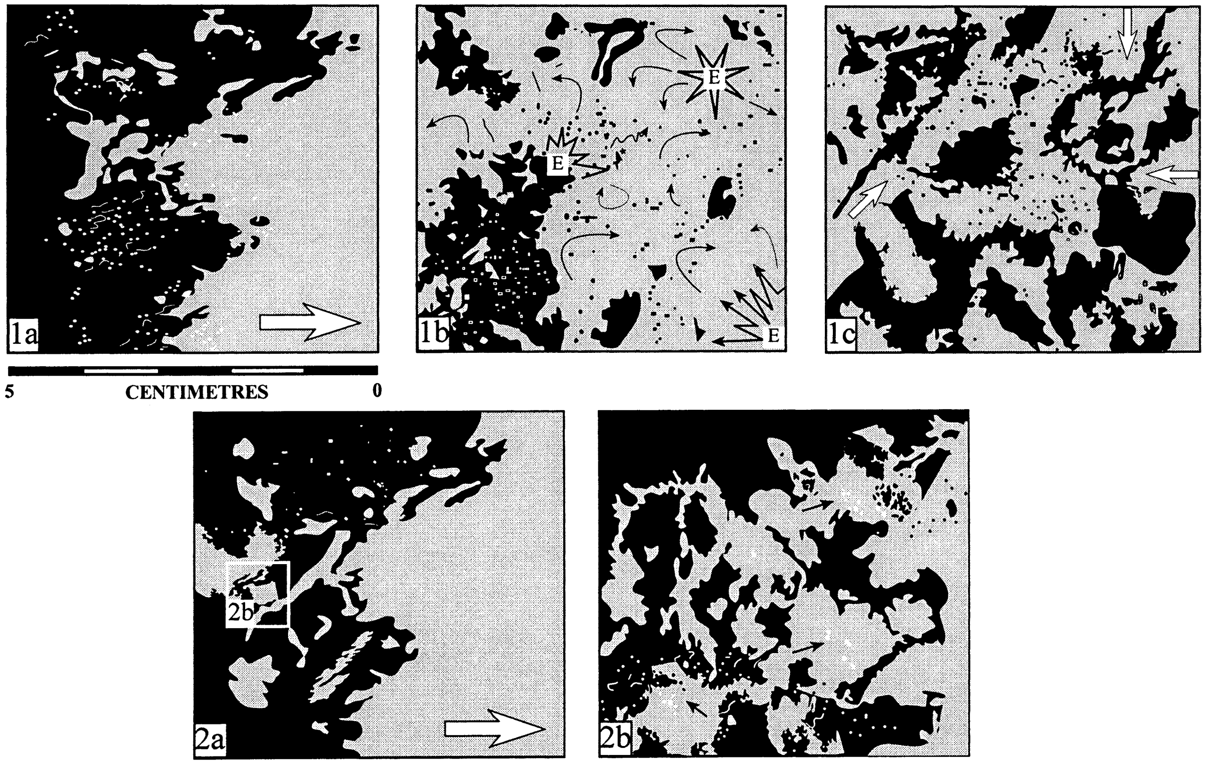

Fig. 6. Diagrammatic sketch of two possible mechanisms of coal peperite formation. (1a) Mingling of coherent coal and minor quartz sand (grey) and basalt (black: intruding in direction indicated by arrow). (1b) Fragmentation of coal and basalt by localised thermohydraulic explosions (E) rooted in coal and involving a water coolant in the immediate vicinity or beyond the mingling zone. (1c) Basalt intrudes the newly created clastic coal-fragment host (arrows) to form peperite. An alternative process (2a) invokes essentially passive mingling of intruding basalt and coherent coal, with mechanical fragmentation of coal clasts during basalt intrusion to form a clastic host to further intrusion. Subsequent mingling of basalt within single clasts (2b), some softened by heating, results in complex millimetre-scale fluidal textures; vesicles generated during devolatilisation (white) indicated by arrows. Scale is the same for all panels except 2b.

mains of coherent coal comprising coal fragments could have taken place after mechanical fragmentation of coal during intrusion of basalt, with enhanced softening induced by heating during the mingling of basalt with the coal-fragment slurry.

The transition from intact coal, and host Victoria Group sediments with undisturbed sedimentary structure, into Mawson Formation pyroclastic rock comprising fragments of ribbon-like and amoeboid basalt thoroughly mixed with finely comminuted sedimentary rock at Coombs Hills suggests fragmentation of Victoria Group and fluid magma by phreatomagmatic explosions (White and McClintock, 2001). These explosions are interpreted to result from self-driven FCI (e.g. Wohletz, 1986; White, 1996) rooted in water-saturated Victoria Group sediment and sedimentary rock singly or in combination with magmatic explosivity (McClintock, 2001). Textures in the coal-fragment peperite appear to record an initial, coarse mixing stage of FCI. Mingling via fluid–fluid contact instabilities (Wohletz, 1986) to form peperite containing fluidal basalt and coal clasts (Fig. 5) is inferred to have been facilitated by thermal insulation of the magma (fuel) from the coherent coal and surrounding water-saturated sediment (coolant) by stable vapour films (Zimanowski et al., 1991). Inferred initial fragmentation of the coherent coal seams could reflect rapid pressure fluctuations during explosions (Büttner and Zimanowski, 1998) rooted in adjacent sediment, leading to brittle failure of the coal (e.g. Fournier, 1999). Alternatively, the coal could have been mechanically fractured and broken up during processes such as wall rock collapse or shearing during magma flow. Disruption and subsequent dispersion over metres to decimetres of clasts from the coal peperite, intermixed with additional wall-rock and earlier formed debris, is inferred to be recorded by surrounding Mawson Formation tuff and tuff breccia. The current outcrop preserves products of a situation in which fragmentation within and of the developing peperite ceased because of a change in magma supply rate, water availability or some other control on disruption and dispersal.

The close association of fluidal basalt clasts and ovoid vesicles enclosed by coal clasts suggests vesicle generation by a vapour phase related to intruding basalt. The globular morphology, both of basalt clasts and of the vesicles within coal fragments, is interpreted to reflect surface tension effects. Surface tension acted on molten basalt within softened coal to produce the globular basalt clasts, and at the interface with vesicles that formed as a result of devolatilisation of the heated coal (see above). Similarly, ‘gas vacuoles’ reported from Beacon Supergroup coals by Schapiro and Grey (1966) are interpreted to record devolatilisation associated with Ferrar Supergroup intrusion. An alternative explanation is that the gas phase was superheated steam generated at the wet sediment–magma interface. Locally, movement of the gases through the coal clasts could have resulted in formation of clast-supported blocky coal-fragment breccia without direct intrusion of basalt (e.g. Kent et al., 1992).

2.5. Time- and space-dependent behaviour of coal during basalt intrusion

Fundamentally, peperite described to date represents the mechanical mingling of two immiscible fluids, magma and a granular fluid resulting from disruption of the host-sediment framework, in a three-dimensional open system, in which the component interfaces interact with the flow in the fluids and modify them (e.g. Ottino, 1989). The mingling of fluidal and blocky coal fragments with basalt in the coal peperite, with both curved and planar bounding surfaces on single coal clasts, suggests that coal clast morphology in the magma–sediment dispersion was controlled at very small scales by the time-, temperature-, and stress-dependent qualities of the coal. Fluidal shapes of coal fragments may have formed as a result of rapid and/or prolonged heating, with accompanying devolatilisation, under relatively low stress in either coherent coal or discrete coal fragments, increasing the plasticity of the coal, and allowing the coal to behave as a fluid of high to moderate viscosity and mingle with the intruding basalt. This plastic bahaviour led to formation of (1) mingled fluidal coal–basalt clasts; and (2) clasts of coal enclosing ovoid vesicles. It is also possible that some fragments of coal were softened and reshaped during mingling of basalt with the coal fragment–water slurry.

Under high stress conditions, for example during explosive expansion of vapour (steam, exsolving magmatic volatiles, or coal-sourced gases), the permeability of both coal beds and coal fragments would have dropped, resulting in elevated resistance to the passage of fluids (magma or gases). If the timescale for stress relief was less than that required for lowered viscosity through heating, the viscosity of the coal would remain high, leading to brittle fragmentation of the coal.

In material the viscosity of which is very temperature-dependent (magma), flow from a chamber through a cooled conduit can develop a fingering instability or time-dependent behaviour, depending on the elastic properties of the source, the viscosity–temperature relationship, and the geometry of the conduit (Whitehead and Helfrich, 1991). The dynamic instability that develops in these magma flows as a result of the time- and space-dependent properties, coupled in this case with instabilities introduced by time- and space-dependent behaviour of the host coal, is characterised by the development of branching, highly irregular fingers of magma. This unstable process is driven by the displacement of a fluid of one viscosity and density (coal: viscosity, η 10^4–10^5 Pa s; Nomura et al. (1999), density, $\rho \sim 1190$ kg/m^3; Thomas (1992)) by a second fluid of lower viscosity and higher density (basalt: $\eta \sim 100$ Pa s at liquidus temperatures and low pressure, $\rho \sim 2600$ kg/m^3 (Spera, 2000)) (e.g. Saffman and Taylor, 1958), the velocity of one phase relative to the other (Homsey, 1987), and vapour film oscillations along magma–sediment interfaces (Wohletz, 1986; Busby-Spera and White, 1987). Amplification of such instabilities during progressive mingling of magma and coal fragments could account for the increasingly complex interface geometries between the coal clasts and basalt (Fig. 5). At some point in the mingling process, the intruding fingers did not remain connected and broke into smaller fragments. Local magma velocities may have been such that injected blebs of magma were completely encapsulated within the coal prior to solidification as glass to form 'blobs' of basalt isolated within coal. The stretching and break-up of large 'blobs' was probably dominated by inertial and viscous forces; however, if the length scales of the 'blobs' increased, surface tension forces would be dominant and prevent further stretching and break-up (Ottino, 1989).

Coal is a thermally unstable, relatively cohesive sediment and is an unusual host to intrusions, but many of the behaviours illustrated by the coal peperite may apply to other clastic sediments involved in magma–sediment interaction. The most relevant of these behaviours are: (1) changes in density and viscosity of sediment through addition or subtraction of water during interaction with magma; (2) participation of phases with time- and space-dependent behaviours very different from those of the original host (e.g. steam, fluidised sediment); and (3) variation in response to applied stress with changing rates and magnitudes of stress.

3. Conclusion

Coal peperite at Coombs Hills resulted from at least two closely coupled phases of magma–sediment mingling. Viscous mingling of softened coal with basalt took place at very small scales (< 10 mm), controlled by the changing rheological properties of coal during heating as a result of basalt intrusion. Brittle fragmentation of coal to form a coal fragment–water slurry allowed mingling of basalt with what was effectively a coal-clast sand to form the bulk of the described peperite. This early fragmentation of a coherent but brittle host was triggered by phreatomagmatic explosions rooted in coal or adjacent strata and/or by mechanical fracturing and break-up of sediment during magma intrusion, forming a slurry that could mingle fluidally with intruding basalt. In some cases, particularly for small-volume peperite, a weakly to moderately lithified host can undergo local disaggregation during intrusion to allow subsequent mingling with magma.

Acknowledgements

We thank Antarctica New Zealand and the University of Otago for logistical and financial support, Rachel Brown and Tim Barry for expert assistance in the field, and Brent Pooley and Steven Read for technical assistance. Thorough, insightful reviews by Jocelyn McPhie and reviewers Brian Jones and David Rawlings are greatly appreciated.

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