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Peperite: a review of magma–sediment mingling

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Abstract

The study of peperite is important for understanding magma–water interaction and explosive hydrovolcanic hazards. This paper reviews the processes and products of peperite genesis. Peperite is common in arc-related and other volcano-sedimentary sequences, where it can be voluminous and dispersed widely from the parent intrusions. It also occurs in phreatomagmatic vent-filling deposits and along contacts between sediment and intrusions, lavas and hot volcaniclastic deposits in many environments. Peperite can often be described on the basis of juvenile clast morphology as blocky or fluidal, but other shapes occur and mixtures of different clast shapes are also found. Magma is dominantly fragmented by quenching, hydromagmatic explosions, magma–sediment density contrasts, and mechanical stress as a consequence of inflation or movement of magma or lava. Magma fragmentation by fluid–fluid shearing and surface tension effects is probably also important in fluidal peperite. Fluidisation of host sediment, hydromagmatic explosions, forceful intrusion of magma and sediment liquefaction and shear liquification are probably the most important mechanisms by which juvenile clasts and host sediment are mingled and dispersed. Factors which could influence fragmentation and mingling processes include magma, host sediment and peperite rheologies, magma injection velocity, volatile content of magma, total volumes of magma and sediment involved, total volume of pore-water heated, presence or absence of shock waves, confining pressure and the nature of local and regional stress fields. Sediment rheology may be affected by dewatering, compaction, cementation, vesiculation, fracturing, fragmentation, fluidisation, liquefaction, shear liquification and melting during magma intrusion and peperite formation. The presence of peperite intraclasts within peperite and single juvenile clasts with both sub-planar and fluidal margins imply that peperite formation can be a multi-stage process that varies both spatially and temporally. Mingling of juvenile clast populations, formed under different thermal and mechanical conditions, complicates the interpretation of magma fragmentation and mingling mechanisms.

Keywords: peperite; review; hydromagmatism; magma–water interaction; magma–sediment mingling

1. Introduction

The term 'peperino' was used by Scrope (1827) to describe clastic rocks from the Limagne d'Auvergne region of central France that comprise mixtures of lacustrine limestone and basalt and

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which resembled ground pepper. This area is now considered the type locality for 'peperite'. Scrope (1858) interpreted the rocks as having originated by a 'violent and intimate union of volcanic fragmentary matter with limestone while yet in a soft state', whereas Michel-Levy (1890) more specifically interpreted them as having formed by intrusion of magma into wet lime mud. The term 'peperite' is now most commonly used to refer to clastic rocks comprising both igneous and sedimentary components, which were generated by intrusive processes, or along the contacts of lava flows or hot volcaniclastic deposits with unconsolidated, typically wet, sediments. The intrusive origin of the majority of the Limagne peperites has been disputed (Kieffer, 1970; Vincent, 1974; De Goër, 2000). Jones (1969) interpreted the rocks as the product of simultaneous deposition of lime mud and reworked volcanic clasts, but most of the Limagne 'peperites' are now interpreted as pyroclastic fall and base surge deposits, which were erupted through lime mud, incorporating some of this sediment, or else were emplaced subaqueously on lime mud (De Goër et al., 1998; De Goër, 2000). Hence, in France the term 'peperite' is commonly used in a different sense, to apply to any rock that comprises juvenile glassy volcanic components in a non-juvenile matrix (De Goër, 2000). This semantic conflict highlights the need for a definition of 'peperite' that is widely acceptable (see below and White et al., 2000).

The study of peperite is important for several reasons. Interaction of magma with wet sediment or sediment-laden water is very common (McBirney, 1963; Klein, 1985; Einsele, 1986; White, 1996), especially in subaqueous volcanic environments. Peperite is important because it provides field evidence for mechanisms of magma–water/sediment interaction, including the mixing mechanisms that precede explosive eruptions analogous to fuel–coolant interaction (FCI) (Zimanowski et al., 1997). The study of peperite is particularly relevant to understanding within-vent processes prior to and accompanying Surtseyan or Taalian explosions (Kokelaar, 1983, 1986). Peperite is also important in palaeoenvironmental reconstruction and relative chronology because its presence demonstrates approximate contemporaneity of magmatism and sedimentation. The occurrence of peperite along upper contacts of concordant igneous bodies also helps distinguish lavas from sills (Macdonald, 1939; Branney and Suthren, 1988; Allen, 1992; Boulter, 1993; McPhie, 1993).

Because peperite is a by-product of intrusion into wet sediment, it may be associated with hydrothermal alteration and/or mineralisation. Transfer of heat from such intrusions can affect the temperature, pressure and density of the pore fluid, and initiate or modify fluid circulation for long periods of time. Hydrological modeling of fluid flow around syn-volcanic intrusions suggests that significant hydrothermal systems may be generated (McPhie and Orth, 1999). In addition, there is the possibility of a direct contribution of magmatic fluids to the pore water reservoir (Delaney, 1982), with significant consequences for its chemistry and mineralising potential. Thus correct identification of peperite is crucial in locating syn-volcanic intrusions that might prove to be economically important.

Accounts of peperite which involve either andesitic, trachytic, dacitic or rhyolitic magmas include Williams (1929), Smedes (1956), Snyder and Fraser (1963), Bromley (1965), Williams and Curtis (1977), Brooks et al. (1982), Hanson and Schweickert (1982), Kokelaar (1982), Lorenz (1984), Kokelaar et al. (1985), Leat (1985), Branney and Suthren (1988), Kano (1989, 1991), Riggs and Busby-Spera (1990), Hanson (1991), Boulter (1993), Hanson and Wilson (1993), McPhie (1993), Goto (1997), Allen and Cas (1998), Busby (1998), Cas et al. (1998), Goto and McPhie (1998), Kano (1998), Moore (1998), Sakamoto (1998), Hanson and Hargrove (1999), Hunns and McPhie (1999), Coira and Pérez (2002, this volume), Donaire et al. (2002, this volume), Gifkins et al. (2002, this volume) and Kano (2002, this volume). Peperite involving mafic intrusions or lava is described by Lacroix and Blondel (1927), Macdonald (1939), Smedes (1956), Wilshire and Hobbs (1962), Snyder and Fraser (1963), Schmincke (1967), Korsch (1984), Walker and Francis (1986), Busby-Spera and White (1987), White and Busby-Spera (1987), Krynauw et al. (1988), Leat and Thompson (1988), Sanders and Johnston (1989), Godchaux et al. (1992), Rawlings (1993), Assorgia and Gimeno (1994), Brooks (1995), Goto and McPhie (1996), Cas et al. (1998), Skilling (1998), Rawlings et al. (1999), Doyle (2000), Mueller et al. (2000), Corsaro and Mazzoleni (2002, this volume), Hooten and Ort (2002, this volume), Jerram and Stollhofen (2002, this volume), Lorenz and Büttner (2002, this volume) and Squire and McPhie (2002, this volume). Papers providing extended discussion of the physical mechanisms of magma mingling with wet sediment include Kokelaar (1982), White (1996), Hanson and Hargrove (1999), Lorenz and Büttner (2002, this volume), Wohletz (2002, this volume) and Zimanowski and Büttner (2002, this volume).

2. Definition

We concur with Brooks et al. (1982), that the term peperite is best used in a genetic sense. White et al. (2000) defined the term as follows:

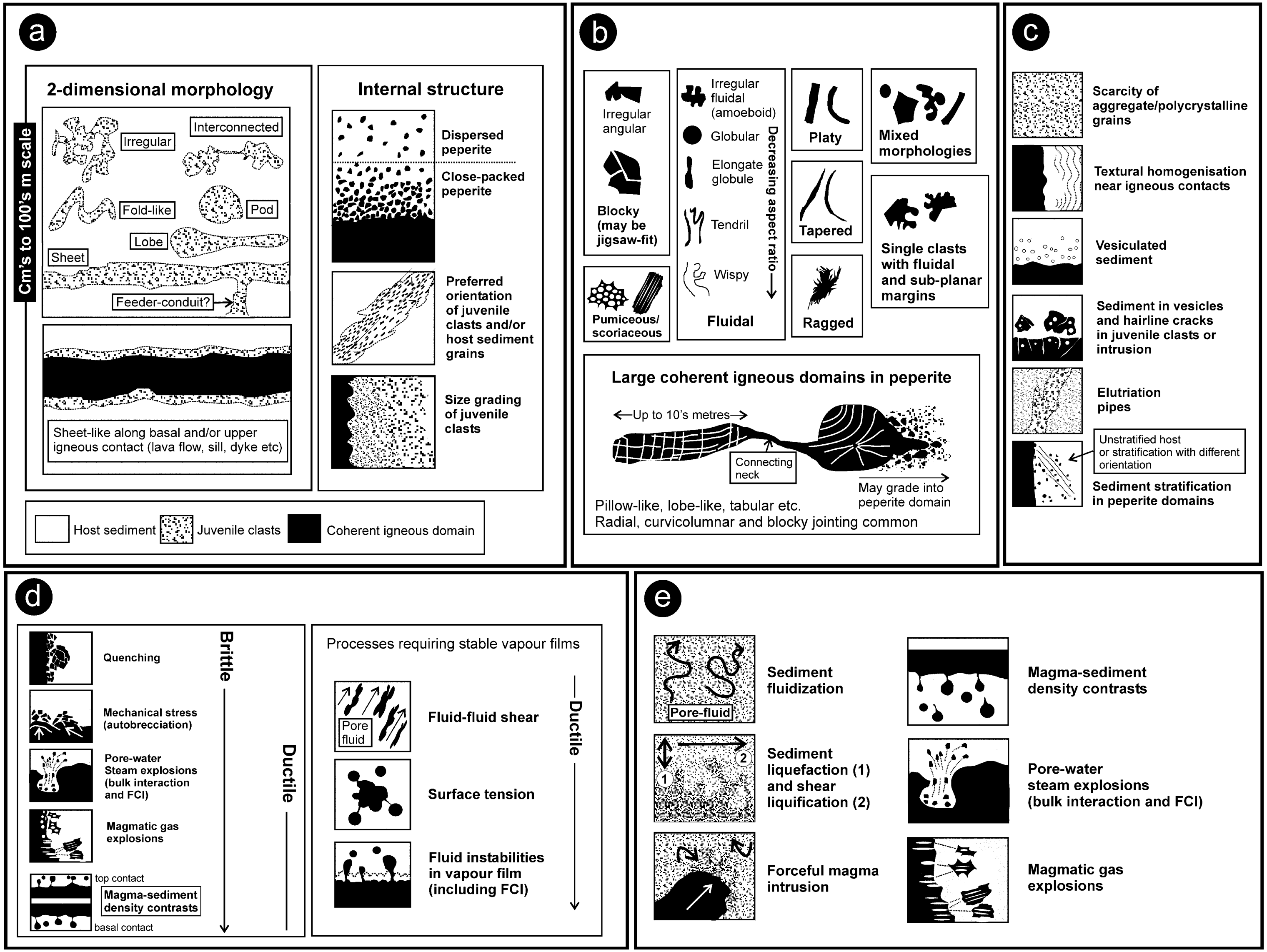
Peperite (n): a genetic term applied to a rock formed essentially in situ by disintegration of magma intruding and mingling with unconsolidated or poorly consolidated, typically wet sediments. The term also refers to similar mixtures generated by the same processes operating at the contacts of lavas and other hot volcaniclastic deposits with such sediments.

3. Successions containing peperite

Peperite develops in a wide variety of successions formed where magmatism and sedimentation are contemporaneous, and where the host sediment is unconsolidated or poorly consolidated, and probably wet. It is very commonly associated with syn-volcanic intrusions in submarine sedimentary sequences (Macdonald, 1939; Snyder and Fraser, 1963; Brooks et al., 1982; Hanson and Schweickert, 1982; Kokelaar, 1982; Lorenz, 1984; Kokelaar et al., 1985; Busby-Spera and White, 1987; White and Busby-Spera, 1987; Kano, 1989, 1991, 1998; Hanson, 1991; Boulter, 1993; Hanson and Wilson, 1993; McPhie, 1993; Rawlings, 1993; Assorgia and Gimeno, 1994; Brooks, 1995; Goto, 1997; Busby, 1998; Goto and McPhie, 1998; Moore, 1998; Hanson and Hargrove, 1999; Hunns and McPhie, 1999; Doyle, 2000, Mueller et al., 2000; Coira and Pérez, 2002, this volume; Dadd and Van Wagoner, 2002, this volume; Donaire et al., 2002, this volume; Gifkins et al., 2002, this volume; Kano, 2002, this volume; Squire and McPhie, 2002, this volume). Peperite has also been described from lacustrine successions (Cas et al., 2001), and subaerial successions, including vent-fills in phreatomagmatic volcanoes (Leat and Thompson, 1988; White, 1991; Vazquez and Riggs, 1998; Hooten and Ort, 2002, this volume; Lorenz and Büttner, 2002, this volume; McClintock and White, 2002, this volume; Zimanowski and Büttner, 2002, this volume), associated with lavas (Schmincke, 1967; White, 1990; Rawlings et al., 1999; Jerram and Stollhofen, 2002, this volume), and at the base of pyroclastic flow deposits (Leat, 1985; Branney, 1986).

4. Gross characteristics of peperite

The volume and geometry of peperite, its spatial relationship to the parent intrusion, lava or volcaniclastic deposit, its internal structure, and spatial variations in texture are the gross characteristics that enable discrimination of peperite from other similar volcaniclastic rocks. Peperite domains range in volume from less than a few m^3 for examples along contacts between sediments and intrusions, lavas and hot volcaniclastic deposits, to several km^3 (Snyder and Fraser, 1963; Hanson and Wilson, 1993). Two-dimensional morphologies of peperite domains are illustrated in Fig. 1a, and range from irregular to lobe or pod-like (Doyle, 2000) to sheet or dyke-like (Snyder and Fraser, 1963; Schmincke, 1967; Brooks et al., 1982; Kano, 1989; Godchaux et al., 1992; Boulter, 1993; Hanson and Wilson, 1993; Hanson and Hargrove, 1999; Doyle, 2000). Peperite domains may appear interconnected within the host sediment (Doyle, 2000). Kano (1989) suggested that dyke-like bodies of peperite were intruded along syn-sedimentary


a
2-dimensional morphology
Cm's to 100's m scale
Irregular
Interconnected
Fold-like
Pod
Lobe
Sheet
Feeder-conduit?
Sheet-like along basal and/or upper igneous contact (lava flow, sill, dyke etc)
Internal structure
Dispersed peperite
Close-packed peperite
Preferred orientation of juvenile clasts and/or host sediment grains
Size grading of juvenile clasts
Host sediment
Juvenile clasts
Coherent igneous domain
b
Irregular angular
Blocky (may be jigsaw-fit)
Pumiceous/ scoriaceous
Irregular fluidal (amoeboid)
Globular
Elongate globule
Tendril
Wispy
Decreasing aspect ratio
Fluidal
Platy
Tapered
Ragged
Mixed morphologies
Single clasts with fluidal and sub-planar margins
Large coherent igneous domains in peperite
Up to 10's metres
Connecting neck
May grade into peperite domain
Pillow-like, lobe-like, tabular etc.
Radial, curvicolumnar and blocky jointing common
c
Scarcity of aggregate/polycrystalline grains
Textural homogenisation near igneous contacts
Vesiculated sediment
Sediment in vesicles and hairline cracks in juvenile clasts or intrusion
Elutriation pipes
Unstratified host or stratification with different orientation
Sediment stratification in peperite domains
d
Quenching
Mechanical stress (autobrecciation)
Pore-water Steam explosions (bulk interaction and FCI)
Magmatic gas explosions
top contact
Magma-sediment density contrasts
basal contact
Brittle
Ductile
Processes requiring stable vapour films
Pore fluid
Fluid-fluid shear
Surface tension
Fluid instabilities in vapour film (including FCI)
Ductile
e
Pore-fluid
Sediment fluidization
①
②
Sediment liquefaction (1) and shear liquification (2)
Forceful magma intrusion
Magma-sediment density contrasts
Pore-water steam explosions (bulk interaction and FCI)
Magmatic gas explosions

faults, which may have developed in poorly consolidated sediment during intrusion of magma. Corsaro and Mazzoleni (2002, this volume) interpret sedimentary material now occupying cores of lava pillows as peperite formed as a result of sediment capture by rising basaltic magma at Etna.

Peperite typically has contacts that are discordant to stratification in the host sediment. Juvenile clasts in peperite commonly occur close to the margins of the parent intrusion, lava or volcaniclastic deposit, but can also be more widely dispersed within the host sediment. Hanson and Wilson (1993) distinguished between close-packed peperite and dispersed peperite, with reference to the relative proportions of juvenile clasts and host sediment (Fig. 1a). Coherent intrusions may grade through close-packed peperite to domains of dispersed peperite (Hanson and Wilson, 1993). The distance between a coherent igneous domain and the limit of dispersed peperite derived from it is difficult to estimate because the specific parent intrusion may not be obvious, but distances of up to a 100 m or more are likely (Hanson and Wilson, 1993; Hanson and Hargrove, 1999). The maximum distance that individual clasts are transported through the host sediment is unknown. Domains of close-packed peperite are typically broadly parallel to the contacts of the parent intrusion, or lie along linear zones oblique to this contact. Domains of dispersed peperite are commonly more irregular in shape.

Peperite is typically not bedded or laminated, but juvenile clasts and/or matrix grains in the host sediment may display a preferred orientation or lamination, which is not present in, or differs from that of the adjacent host sediment (Busby-Spera and White, 1987; Branney and Suthren, 1988; Brooks, 1995; Doyle, 2000). Some authors have also recorded domains of peperite that resemble fold structures, adjacent to undeformed sediments (Lorenz, 1984; Brooks, 1995). Size sorting and grading of clasts within peperite have also been recorded (Brooks et al., 1982; Brooks, 1995). Brooks (1995) and Doyle (2000) noted a transition from peperite with coarse juvenile clasts into one with finer clasts near the contact with the parent intrusion.

5. Characteristics of juvenile clasts

The shape, size and internal characteristics, such as vesicularity and groundmass texture, of juvenile clasts in peperite vary widely. Juvenile clast morphologies are illustrated in Fig. 1b. Busby-Spera and White (1987) recognised two types of peperite, which they called blocky and fluidal, in reference to the dominant shape of the juvenile clasts. Peperite may also consist of a mixture of fluidal and blocky clasts (Brooks et al., 1982; Kokelaar, 1982; McPhie, 1993; Hanson and Hargrove, 1999; Doyle, 2000; Squire and McPhie, 2002, this volume), and single clasts commonly have both sub-planar and fluidal margins (Boulter, 1993; Hanson and Wilson, 1993; Hanson and Hargrove, 1999; Doyle, 2000). Other juvenile clast shapes have been described from peperite (Fig. 1b) and are discussed below.

Blocky clasts are sub-equant, polyhedral to tabular, with curviplanar to planar surfaces. Groups of blocky clasts commonly display jigsaw-fit texture, characteristic of in situ fragmentation. Blocky peperite is described by Lacroix and Blondel (1927), Smedes (1956), Schmincke (1967), Brooks et al. (1982), Hanson and Schweickert (1982), Kokelaar (1982), Busby-Spera and White (1987), Branney and Suthren (1988), Kano (1989), Sanders and Johnston (1989), Hanson (1991), Boulter (1993), Hanson and Wilson (1993), Rawlings (1993), Brooks (1995), Goto and McPhie (1996, 1998), Goto (1997), Rawlings et al. (1999), Doyle (2000), Coira and Pérez (2002, this vol-

Fig. 1. Summary of (a) gross characteristics of peperite domains. Note that peperite domains are commonly developed in association with large coherent igneous domains, and that more than one type of peperite domain may be present. Note also that the morphology of a peperite domain and whether it appears connected to other peperite or coherent igneous domains, depends on the orientation of the section; (b) juvenile clast morphology; (c) evidence for unconsolidated nature of host sediment; (d) juvenile clast generation; and (e) mingling of juvenile clasts and host sediment. Note that juvenile clast generation and mingling with the host sediment often take place simultaneously.

ume), Dadd and Van Wagoner (2002, this volume), Jerram and Stollhofen (2002, this volume) and Squire and McPhie (2002, this volume). Clasts in fluidal peperite have fluidal or globular morphology, often with complex outlines, and range in shape from irregular (amoeboid) to globules and high aspect-ratio lobes (Smedes, 1956; Busby-Spera and White, 1987; McPhie, 1993) to low aspect-ratio laminae, tendrils or wisps (Lorenz, 1984; White and Busby-Spera, 1987; Skilling, 1998). Fluidal clasts may be connected by thin necks (Hanson and Hargrove, 1999; Doyle, 2000), a morphology which mirrors that of larger coherent lobes and tongues, as described below. Fluidal clasts may be deformed around rigid clasts in the host sediment (Brooks et al., 1982). Fluidal peperite is described by Smedes (1956), Snyder and Fraser (1963); Brooks et al. (1982), Kokelaar (1982), Korsch (1984), Lorenz (1984), Walker and Francis (1986), Busby-Spera and White (1987), White and Busby-Spera (1987), Branney and Suthren (1988), Riggs and Busby-Spera (1990), Kano (1991), Boulter (1993), McPhie (1993), Assorgia and Gimeno (1994), Goto and McPhie (1996), Goto (1997), Rawlings et al. (1999), Doyle (2000), Coira and Pérez (2002, this volume), Corsaro and Mazzoleni (2002, this volume), Dadd and Van Wagoner (2002, this volume), Donaire et al. (2002, this volume), Martin and White (2002, this volume) and McClintock and White (2002, this volume).

Other juvenile clast shapes described from peperite include platy, tapered and ragged forms. Platy and tapered clasts are recorded by Boulter (1993), Brooks (1995), Goto and McPhie (1996) and Doyle (2000), and ragged clasts by McPhie (1993) and Boulter (1993). Platy clasts are elongate in section, with planar, subplanar or curviplanar margins, tapered clasts are elongate with thinner ends, and ragged clasts have irregular spinose margins (Fig. 1b). Brooks (1995) recorded platy clasts that were parallel to cooling-contraction fractures in the parent intrusion. Doyle (2000) noted that platy clasts are most abundant in closely packed peperite. In the example described by Goto and McPhie (1996), platy and tapered clasts are associated with concentric spherical fractures at the margins of a dyke. Hanson and Hargrove (1999) recorded similar elongate andesitic clasts, the long axes of which were parallel to aligned long axes of plagioclase phenocrysts. Similarly, Brooks et al. (1982) described elongate juvenile clasts in peperite, which were fractured parallel to magmatic flow laminae.

The vesicularity of juvenile clasts in peperite is highly variable. Depending on the confining pressure, the volatile content of the parent magma before and during mingling may be an important factor determining peperite texture. In the examples described by Doyle (2000), dispersed peperite commonly contained highly vesicular clasts, which were absent in close-packed peperite. He also described local mixing of vesicular and non-vesicular juvenile clasts. Rawlings (1993) recorded highly vesicular clasts that were broken along curved fractures joining areas of maximum vesicle content. He also noted the presence of elongate clasts, which were fractured parallel to elongate vesicles, and poorly vesicular clasts, which were bounded by planar surfaces.

In some cases, juvenile clasts in peperite are pumiceous (Hunns and McPhie, 1999; Gifkins et al., 2002, this volume). These examples were partly or substantially vesicular at the time of mingling. The juvenile clasts are typically ragged and wispy, tube-vesicle or round-vesicle pumice fragments that show no preferred alignment. Development of highly vesicular peperite is favoured by intrusions emplaced beneath thin wet-sediment cover and/or in relatively shallow-water settings in which the confining pressure is sufficiently low to allow significant magma vesiculation.

Large coherent igneous intrusive domains, to tens of metres across, are commonly dispersed within peperite or host sediment (Fig. 1b), and are either apparently detached or appear connected to a parent intrusion by narrower necks (Snyder and Fraser, 1963; Brooks et al., 1982; Kokelaar, 1982; Hanson, 1991; Hanson and Wilson, 1993; Hanson and Hargrove, 1999; Doyle, 2000). Coherent domains are often pillow-like, tabular or tongue-like in two dimensions, may display a preferred orientation (Snyder and Fraser, 1963; Dewit and Stern, 1978; Kano, 1989, 1991; Hanson and Wilson, 1993; Doyle, 2000), and can grade into peperite domains (Hanson and

Wilson, 1993; Doyle, 2000). They are commonly complexly jointed in a blocky, radial, columnar or curvicolumnar fashion, with joints or fractures occupied by host sediment or peperite (Brooks et al., 1982; Hanson and Wilson, 1993; Doyle, 2000). Gently curved, first-order cooling joints are common and may intersect, outlining polyhedrons. Hanson and Wilson (1993) and Hanson and Hargrove (1999) suggested that coherent igneous domains represent major feeder conduits that supplied magma to developing peperite domains.

6. Characteristics of the host sediment

Sediment of a wide range in grain size (clay to pebble size), composition, sorting, cohesiveness, porosity and permeability has been recorded as a host to peperite (Lorenz, 1984; Busby-Spera and White, 1987; Squire and McPhie, 2002, this volume). Processes accompanying peperite formation, discussed below, may modify original sediment characteristics. Evidence that host sediments were unconsolidated or poorly consolidated (Fig. 1c), and most likely wet, at the time of interaction with the magma or lava includes the scarcity of aggregate or polycrystalline host-sediment grains, destruction of sedimentary structures adjacent to igneous contacts (Hanson and Schweickert, 1982; Kokelaar, 1982; Branney and Suthren, 1988; Kano, 1991; McPhie, 1993; Brooks, 1995; Goto and McPhie, 1996; Dadd and Van Wagoner, 2002, this volume), vesiculated sediment (Kokelaar, 1982; Walker and Francis, 1986; Branney and Suthren, 1988; Sanders and Johnston, 1989; Brooks, 1995; Skilling, 1998; Hunns and McPhie, 1999; Squire and McPhie, 2002, this volume), sediment in vesicles or fractures in the intrusion (Kokelaar, 1982; Brooks et al., 1982; Walker and Francis, 1986; Branney and Suthren, 1988; Hanson and Wilson, 1993; Brooks, 1995; Rawlings et al., 1999; Doyle, 2000; Dadd and Van Wagoner, 2002, this volume), along hairline cracks in juvenile clasts (Brooks et al., 1982; Branney and Suthren, 1988; Boulter, 1993), and in vesicles in juvenile clasts near the contact with sediment (Branney and Suthren, 1988; Goto and McPhie, 1996; Dadd and Van Wagoner, 2002, this volume). The presence of fines-depleted, massive, pipe-like structures within peperite domains or host sediment (Kokelaar, 1982; Busby-Spera and White, 1987) also implies that the sediment was unconsolidated. Sediment within peperite domains may display stratification that is discordant with stratification in the adjacent host sediment, or display stratification even though the adjacent sediment is massive (Brooks et al., 1982; Branney and Suthren, 1988; Brooks, 1995; Doyle, 2000). Such stratification may be relict original stratification (Kokelaar, 1982; Hanson and Wilson, 1993; Brooks, 1995), be developed during infiltration of sediment that postdates peperite formation, or be formed during sediment fluidisation. Sediment fluidisation is suggested by stratification which is parallel to the margins of fractures in the parent intrusion or in juvenile clasts (Kokelaar, 1982; Branney and Suthren, 1988; Doyle, 2000).

Although wet sediment is probably essential to form fluidal peperite, it may not be essential for the formation of some types of blocky peperite. Jerram and Stollhofen (2002, this volume) describe breccia comprising blocky basalt clasts in a sandy matrix, and inferred an origin involving dynamic interaction between basaltic lava flows and underlying dry aeolian sand.

7. Peperite-forming processes

Peperite formation involves disintegration or fragmentation of magma to form juvenile clasts and mingling of these clasts with a sediment host. Fragmentation and mingling is probably often simultaneous, but some juvenile clasts, particularly those generated by processes such as quenching and autobrecciation during intrusion, may mingle with the adjacent sediment after initial disruption. Mingling is favoured when the density and viscosity of the magma are similar to that of the wet sediment, at least locally at the time of mingling (Zimanowski and Büttner, 2002, this volume). Several factors may influence the resulting textures, including magma rheology (Brooks et al., 1982; McPhie, 1993; Goto and McPhie, 1996; Dadd and Van Wagoner, 2002, this volume), volatile and vesicle content of the magma (Rawlings, 1993; Hunns and McPhie, 1999; Doyle, 2000; Gifkins et al., 2002, this volume), rheology of the host sediment (Kano, 1989), grain-size, sorting, permeability and structure of the host sediment (Busby-Spera and White, 1987; Hanson and Hargrove, 1999), magma/water mixing ratio (Busby-Spera and White, 1987), total volumes of magma and sediment mingled, rate of magma–sediment mingling (Hanson and Wilson, 1993), magma injection velocity, total volume of pore water heated (Hanson and Wilson, 1993), confining pressure (Kokelaar, 1982; White and Busby-Spera, 1987; Hanson, 1991; Hanson and Wilson, 1993; McPhie, 1993; Coira and Pérez, 2002, this volume) and the nature of local and regional stress fields (Kano, 1989). Most of these factors could vary spatially and temporally during peperite generation. Brooks et al. (1982), Goto and McPhie (1996), Doyle (2000) and Squire and McPhie (2002, this volume) inferred a change from fluidal to blocky peperite generation with time, which they suggested was due to an increase in magma viscosity on cooling.

8. Fragmentation of magma

Fragmentation of magma intruding wet sediment can be due to several processes, including quenching, mechanical stress (autobrecciation), pore-water steam explosions (including FCI-type explosions), explosive juvenile vesiculation, shearing of magma during movement of pore water and fluidised sediment (fluid–fluid shear), surface tension effects, magma–sediment density contrasts and fluid instabilities in vapour films (Fig. 1d). The interpretation of fragmentation and mingling mechanisms is complicated because single juvenile clasts that display both fluidal and sub-planar margins suggest that fragmentation can be multi-stage. Similarly, the fact that peperite can comprise a mixture of blocky and fluidal clasts or vesicular and non-vesicular clasts implies that clast populations that formed under different thermal or mechanical conditions are commonly mingled. Magma vesicularity, magmatic flow banding and crystal size, shape and distribution influence juvenile clast shape in all processes of magma fragmentation, including peperite formation.

8.1. Blocky juvenile clasts

Blocky juvenile clasts imply fragmentation of magma in the brittle regime, giving rise to several morphologies including blocky, platy and tapered clasts (Fig. 1b). Brittle fragmentation may also affect earlier-formed juvenile clasts during and after mingling. Brittle fragmentation will be favoured when magma viscosity is high and/or strain rates are high. Most blocky clasts are probably generated by quenching and mechanical stresses, and by hydromagmatic explosions. Quench fragmentation and hydromagmatic explosions require relatively rapid transfer of magmatic heat to the pore fluid, implying that insulating vapour films were not developed or not sustained. Busby-Spera and White (1987) suggested that coarse grain size, high permeability and poor sorting of the host sediment favour blocky clast development, because vapour films are disrupted by the presence of large clasts which cannot be entrained within the films. The jigsaw-fit texture that is common in blocky peperite, particularly close-packed peperite, is widely inferred to reflect in situ quench fragmentation (Brooks et al., 1982; Kokelaar, 1982; Hanson and Wilson, 1993; Brooks, 1995; Moore, 1998; Doyle, 2000). In cases where large blocky clasts are more widely dispersed within the host sediment (Brooks et al., 1982; Busby-Spera and White, 1987; Hanson and Hargrove, 1999), it is possible that hydromagmatic explosions operated, although foundering of dense igneous clasts within low-strength sediment may also be significant. Hanson and Wilson (1993) suggested that blocky juvenile clasts were formed by quench fragmentation along intrusion margins, and were later dispersed within the host sediment by a non-explosive process.

8.2. Fluidal juvenile clasts

Fluidal juvenile clasts are fragmented in the ductile regime. At present, the only plausible explanation for this process is that vapour films along magma–sediment contacts prevented direct contact with the pore fluid. It is not clear how vapour films remain stable during intricate mingling and complex deformation of magma clasts. Processes inferred to give rise to fluidal clasts include fluid instabilities within vapour films (Wohletz, 1983), magma–sediment density contrasts (Donaire et al., 2002, this volume), host sediment vesiculation (Skilling, 1998) and hydromagmatic explosions (Busby-Spera and White, 1987). Surface tension and fluid–fluid shearing at the interfaces of mingling magma and fluidally behaving sediment must also promote fragmentation (Fig. 1d).

Most examples of fluidal peperite described in the literature involve mafic to intermediate magmas. Examples involving felsic magmas imply much lower viscosities than are typical for these compositions. Lower viscosities could be due to emplacement at high pressures that foster retention of water in the melt (Kokelaar, 1982; Hanson, 1991; McPhie, 1993), but could also arise as a consequence of high concentrations of components that could cause depolymerisation, such as alkalis or halogens. Kokelaar (1982) suggested that fluidal intrusion of magma into wet sediment is accompanied by fluidisation of host sediment in vapour films along magma–sediment contacts. This type of fluidisation, and hence formation of fluidal peperite, is most efficient in fine-grained, well-sorted and loosely packed sediments (Busby-Spera and White, 1987; McPhie, 1993; Hanson and Hargrove, 1999).

8.3. Ragged juvenile clasts

The occurrence of ragged juvenile clasts in pumiceous peperite suggests that their generation may be favoured by actively vesiculating silicic magma (Hunns and McPhie, 1999; Gifkins et al., 2002, this volume). However, clasts with ragged forms have also been interpreted as having formed during non-explosive mixing of poorly vesicular basaltic magma with sediment, following slumping of peperite debris extruded at the surface (Lorenz, 1984; White and Busby-Spera, 1987). A ragged spinose morphology suggests ductile fragmentation under conditions close to the glass transition temperature.

9. Mingling of juvenile clasts and host sediment

Mingling of juvenile clasts and host sediment is promoted by fluidisation of sediment, forceful intrusion of magma, hydromagmatic explosions, magma–sediment density contrasts and sediment liquefaction and liquification (Fig. 1e).

9.1. Sediment fluidisation

In peperite studies, the term ‘fluidisation’ has not been used in the strict sense to refer to particle support by an upward-moving fluid (Davidson et al., 1985), but rather to particle support and transport by a fluid moving in any direction. Fluidisation of host sediment, in this sense, is probably an important process accompanying intrusion of magma into wet sediment, and probably gives rise to mingling of sediment and juvenile components. Kokelaar (1982) suggested that prolonged heating of pore water in the host sediments could result in sustained large-volume fluidisation, whereas pressure release during the opening of fractures would generate short-lived, low-volume fluidisation. Large-volume fluidisation probably requires sustained influx of large volumes of magma. The main evidence cited for sediment fluidisation in peperite formation is the presence of narrow, often localised, zones along igneous-sediment contacts where destruction of original sediment textures has taken place (Kokelaar, 1982; Kano, 1989, 1991; McPhie, 1993; Goto and McPhie, 1996; Hanson and Hargrove, 1999; Dadd and Van Wagoner, 2002, this volume). Kokelaar (1982) also noted large slabs of sediment along these contacts, and inferred that they were transported by fluidised flows.

Evidence for low-volume fluidisation of sediment during peperite generation includes the presence of fines-depleted pipe-like structures in peperite or host sediment (Kokelaar, 1982; Busby-Spera and White, 1987). Such structures range from sub-mm to dm in size and are perhaps best developed in areas close to the intrusive contacts (Busby-Spera and White, 1987). Mobility of host sediment during peperite formation is also demonstrated by the presence of sediment filling fractures or joints in the parent intrusion (Macdonald, 1939; Kokelaar, 1982; Brooks et al., 1982; Walker and Francis, 1986; Branney and Suthren, 1988; Hanson and Wilson, 1993; Brooks, 1995; Doyle, 2000), invading hairline cracks in juvenile clasts (Brooks et al., 1982; Boulter, 1993), filling vesicles in juvenile clasts near the contact with sediment (Goto and McPhie, 1996; Dadd and Van Wagoner, 2002, this volume). Mobilised sediment can also invade syn-sedimentary faults in the host sediment (Kano, 1989). Goto and McPhie (1996) noted that the infilling sediment is often finer than the bulk of the host sediment. Sediment within cracks commonly displays laminae parallel to the crack margins (Branney and Suthren, 1988; Brooks, 1995).

9.2. Hydromagmatic explosions

Sub-surface hydromagmatic explosions have been inferred to occur during peperite formation (Busby-Spera and White, 1987; Branney and Suthren, 1988; Boulter, 1993; Hanson and Hargrove, 1999; Dadd and Van Wagoner, 2002, this volume) to account for domains in which juvenile clasts are widely dispersed in the host sediment. Blocky juvenile clasts in peperite domains enclosed within an intrusion (Branney and Suthren, 1988; Brooks, 1995) may have formed by small steam explosions of the bulk-interaction type (Kokelaar, 1986), but could also arise from quenching and/or mechanical stressing of chilled margins during envelopment of the sediment.

Confining pressure is an important influence on the occurrence of hydromagmatic explosions (Kokelaar, 1986). The limiting confining pressure for explosions is poorly constrained for sediment–fluid mixtures, but must be lower than the critical pressure for sediment-free water. Explosions are probably most common along intrusive contacts, but may also occur during mingling. They are unlikely to give rise to large-volume dispersed peperite, because they are not sustainable, although prolonged mingling might generate multiple explosions that collectively affect substantial volumes. Explosions are more likely to occur during initial intrusion of magma, when the heat transfer and volatile-release rates are highest. Later explosions could give rise to further fragmentation and mingling in areas of pre-existing peperite. The influence of peperite formation on larger-scale phreatomagmatic explosions is discussed later.

9.3. Other mechanisms

Mingling may also be driven by forceful intrusion of magma, magma–sediment density contrasts and soft sediment deformation processes, including sediment liquefaction and shear liquification (discussed below, Fig. 1e), but the relative importance of these processes is not clear. Donaire et al. (2002, this volume) describe fluidal rhyolitic peperite that they suggest was generated by buoyant rising of vesiculating rhyolite globules through the host sediment. The observation that peperite is better developed or restricted to either the upper contacts (McPhie, 1993; Brooks, 1995; Doyle, 2000) or basal contacts (Brooks et al., 1982; Kokelaar, 1982; White and Busby-Spera, 1987) of sills suggests that magma–sediment density contrasts are an important control on mingling, at least in these contact areas. Similarly, Leat (1985) noted that peperite was developed only where a densely welded pyroclastic flow deposit was underlain by a low-density pumiceous fallout deposit, and was absent where underlain by denser deposits.

Fluidisation of sediment requires water or vapour movement sufficient to support the host-sediment grains, and sufficiently good sorting of the host to prevent bubbling or localisation of the flow into elutriation pipes. For poorly sorted or cohesive sediments, fluidisation is difficult to achieve, but these sediments are susceptible to disruption of initial loose packing, and the generation of a fluidally deforming mass in which the grains are not just supported by a fluid that is moving past them, but are entrained or flow as a complex two-phase fluid. This process may be initiated by liquefaction, as a consequence of cyclic shear stress and/or shear liquification, as a result of a unidirectional shear stress (Fig. 1e, and Nichols, 1985). Zimanowski and Büttner (2002, this volume) termed the sediment-bearing fluid that interacts with a melt under experimental conditions a ‘liquefied’ system on this basis. The failure and mixing of magma with clay-rich sediments reported by Lorenz (1984) was probably a liquefaction or shear liquification controlled magma–sediment interaction. Liquefaction and shear liquification could be induced by seismic activity, physical jostling of sediment during magma intrusion and adjacent peperite formation, or by shock waves from explosions. Eruptions during peperite development would also have the potential to liquefy adjacent host sediment.

10. Thermal and mechanical effects on host sediment

Magma intrusion and associated peperite genesis can result in local dewatering, textural homogenisation, vesiculation, fluidisation, liquefaction, shear liquification, compaction, folding, contact metamorphism, cementation, fracturing, fragmentation, alteration and melting of the host sediment. The precise timing of these effects is rarely clear. If they predate or accompany mingling, then they will influence the nature of peperite formed, as they modify the grain size, permeability, porosity and hence rheology of the sediment. Extensive contact metamorphism, cementation and some types of alteration will prevent peperite formation. However, if the effects are localised or affect only certain components within the sediment, then peperite formation may still occur. Hanson and Schweickert (1982) recorded evidence of early local lithification of siliceous sediment prior to peperite formation. Brooks et al. (1982) noted that peperite was developed only locally along the contact between an andesite sill and chert, and suggested that dewatering of the chert locally took place prior to peperite generation. Carbonates, Fe-oxides and silica occurring along the contacts of juvenile clasts and host sediment (Wilshire and Hobbs, 1962; Kokelaar, 1982; Walker and Francis, 1986; Rawlings, 1993; Squire and McPhie, 2002, this volume) may be related to hydrothermal alteration during and after peperite genesis.

Locally consolidated host sediment may also be fractured during peperite genesis, as shown by the fact that angular clasts of host sediment occur in some peperites (Macdonald, 1939; Brooks et al., 1982; Kokelaar, 1982; Kokelaar et al., 1985). McClintock and White (2002, this volume) describe a peperite developed at the contact of basalt with coal in an intra-vent setting. The coal was finely fragmented during intrusion, and a slurry of coal fragments was mingled with basalt to form a peperite. In addition, coal is thermally unstable, and at small scales there is evidence that the coal softened sufficiently in response to heating to allow mm-scale mutual injection of fluidal basalt into coal and vice versa.

Clasts of earlier formed peperite also occur in some peperite (Cas et al., 1998). Hanson and Schweickert (1982) recorded brittle fractures in host sediment which had been locally silicified. Fragile clasts, such as pumice, in the host sediment may be easily fragmented. Leat (1985) describes an airfall pumice lapilli deposit in which the lapilli were finely fragmented during mingling with an overlying pyroclastic flow.

Fusion, partial fusion and moulding of some host sediments prior to and during peperite generation can occur (Schmincke, 1967; Ito et al., 1984; Yamamoto et al., 1991; McPhie and Hunns, 1995; WoldeGabriel et al., 1999; Martin and White, 2002, this volume). A particularly interesting example of sediment fusion is associated both with magma–sediment mingling, forming peperite, and a subaqueous phreatomagmatic eruption (Yamamoto et al., 1991). In this example, a shallow basaltic intrusion was emplaced into pumiceous sediment just below the seafloor. The sediment was annealed, locally remelted to form silicic pumice, and then caught up in a series of phreatomagmatic explosions triggered by withdrawal of magma and consequent inrush of seawater.

Vesiculation of sediment has been described by several authors (see references above). It is important, as it is the only unequivocal evidence for the generation of a gas phase in the sediment during peperite formation. Vesiculation can be restricted to certain areas, such as close to the intrusion (Kokelaar, 1982), parallel to laminae or beds in the host sediment (Brooks, 1995) or within sediment clasts in the igneous component (Walker and Francis, 1986). Vesicles in sediment are uncommon however, or not commonly preserved, even in very fine-grained sediment (Busby-Spera and White, 1987). Several authors record soft-sediment deformation of the host sediment along or close to the contact with peperite and/or the intrusion (Brooks et al., 1982; Hanson and Schweickert, 1982; Kokelaar, 1982; Lorenz, 1984; Duffield et al., 1986; Walker and Francis, 1986; Krynauw et al., 1988; Kano, 1989; Brooks, 1995). Such deformation could be due to many processes, including sediment fluidisation, liquefaction, shear liquification and differential compaction, forceful intrusion (Duffield et al., 1986; Krynauw et al., 1988; Kano, 1989), explosions, and seismic or eruptive activity. Brooks (1995) attributed the origin of folds in host sediments adjacent to peperite to dispersal during peperite genesis of large juvenile lithic blocks near the contact, rather than to forceful intrusion of magma.

11. Peperite and large-scale explosive magma–water interaction

Peperite has implications for large-scale explosive magma–water interaction. Busby-Spera and White (1987) noted that intimately mixed 'microglobular' (mm-scale fluidal juvenile clasts) peperite may represent an arrested FCI.

In addition to mixing ratios of magma with water or sediment-laden water, there are a number of other factors that control whether magma–sediment mingling escalates to produce significant phreatomagmatic explosions of FCI-type. Perhaps the most significant in volcanic environments are the typical inhomogeneity in terms of grain size, water content, temperature and other physical properties of the host, and the partially confined nature of vents with rigid walls. Events that may trigger phreatomagmatic explosions include volcanotectonic earthquakes at depth, local explosion-generated shocks from elsewhere in the vent, and jolts resulting from collapse and impact of spalling wall rock into the upper vent. All of these factors increase the likelihood that mingling of magma with a clastic host within active volcanic vents will result in explosive interactions (White, 1991, 1996; Morrissey et al., 1999; Wohletz, 2002, this volume). Peperite may be preserved only along the margins of closing-stage intrusions that enter the vent after most eruptions have ceased.

12. Erupted and redeposited equivalents of peperite

Some authors have inferred that some mass-flow deposits associated with peperite represent its erupted equivalent, or have been resedimented from its erupted equivalent (Lorenz, 1984; White and Busby-Spera, 1987; Leat and Thompson, 1988; Sanders and Johnston, 1989; Hanson, 1991; Boulter, 1993; Hanson and Wilson, 1993). Lorenz (1984), White and Busby-Spera (1987), Hanson (1991), Boulter (1993) and Hanson and Wilson (1993) interpreted such deposits as gravity-driven mass flows derived from extruded peperite debris that had been extruded or exposed by slumping. Sanders and Johnston (1989) speculated that similar deposits were mass flows which were directly fed from effusive eruptions of mixed sediment and magma. Leat and Thompson (1988) described massive, poorly sorted deposits comprising mixtures of juvenile components and non-juvenile sediment, which were erupted from phreatomagmatic vents. They discussed a number of possible explosive and effusive origins for their deposits, including deposition from pyroclastic flows, Surtseyan-like jets and effusive or poorly inflated slurries. It is clearly possible for subsurface mixtures of juvenile clasts, sediment and water or steam to erupt, but the importance of such deposits in the rock record is not clear, although Boulter (1993) speculated that they form the dominant kind of volcaniclastic facies in the Iberian Pyrite Belt at Rio Tinto, Spain.

Although the existing terminology is inadequate to describe such deposits, we suggest that the term 'peperite' is inappropriate. The extension of 'peperite' to include these facies is misleading and blurs the distinction between peperite and other mixtures of igneous and sedimentary components, such as those produced by many phreatomagmatic eruptions. We suggest naming such deposits by their emplacement process with an indication of a peperite source (White et al., 2000), e.g. 'peperite-fed debris flow deposits'.

13. Identification of peperite

If the term 'peperite' is to be used in the genetic sense defined above, then we must be able to distinguish it from texturally similar rocks produced by other processes. During initial field studies, and if there is any doubt about the interpretation, descriptive terminology is preferable. Unequivocal interpretation usually requires detailed study of areas with good three-dimensional outcrop. Facies which are texturally similar to peperite but which result from other processes may be difficult to distinguish, especially in the case of blocky peperite. Processes such as water-settling of juvenile pyroclasts contemporaneous with deposition of other sediments, resedimentation of volcaniclastic deposits by mass flows, and infiltration of sediment into volcaniclastic deposits can all produce mixtures of igneous clasts and sediment that resemble peperite (Branney and Suthren, 1988). However, in these facies there will be no evidence of partial fluidisation of the sediment, contact metamorphism or sediment vesiculation. Massive facies resulting from other processes such as pyroclastic fallout of juvenile clasts into unconsolidated sediment, mixing of juvenile and non-juvenile clasts in base surges and pyroclastic flows, and syn-eruptive or post-eruptive collapse of lavas or domes emplaced onto unconsolidated sediment may be more difficult to distinguish. Especially challenging are cases where both the host sediment and the juvenile clasts are glassy and of similar composition, grain size and morphology. In ancient rocks, it may also be difficult to distinguish blocky/angular clasts generated by tectonic processes or by fracture-controlled alteration from those generated during blocky peperite formation (Allen, 1992; McPhie et al., 1993).

14. Unresolved questions

Several aspects of peperite and its genesis are poorly understood, including the gross morphology of large peperite domains, the processes that cause wide dispersal of juvenile clasts, maximum dispersal distances, magma and sediment rheology during mingling, the factors that influence juvenile clast size and shape, the relative importance of fragmentation accompanying mingling compared to fragmentation along the contacts of the intrusions or lavas, and how vapour films remain stable during complex deformation of fluidal magma. The duration of mingling is also unclear, but the occurrence of peperite intraclasts within peperite, and the mixing of different juvenile clast populations, imply that peperite formation is commonly not a single simple event.

Other unresolved questions include whether or not sediment pore water is an essential component (Jerram and Stollhofen, 2002, this volume), and the effects on peperite genesis of confining pressure, magma supply rate, volatile and vesicle content of magma, magma/wet-sediment mixing ratio (Hooten and Ort, 2002, this volume), total volumes of magma and sediment mixed, rate of magma–sediment mixing, the nature of local and regional stress fields, and the total volume of pore water heated at any one time. Further detailed field studies, experimental studies relevant to peperite genesis (Wohletz, 2002, this volume; Zimanowski and Büttner, 2002, this volume) and theoretical studies of magma interaction with sediment-bearing coolants (White, 1996) will help answer these questions.

The feasibility of subsurface convection of pore fluid, entraining sediment and juvenile clasts, and giving rise to mingling has not been addressed. It should be considered, particularly in cases involving interaction between sediment and large volumes of magma, with sustained high temperatures, for example during magma passage through wet and initially highly permeable sediment. Peperite also requires study in a broader context. The role of sub-surface magma–sediment mingling in large-scale phreatomagmatic eruptions has received little attention. Fluidal peperite, erupted equivalents of peperite, and the products of many Surtseyan and Taalian explosions, may represent a continuum, the study of which will advance our understanding of explosive hydromagmatic interaction.

15. Summary

The study of peperite has provided important insights into processes accompanying magma–water and magma–sediment interaction. Peperite can occur in any environment where magmatism and sedimentation are contemporaneous or broadly contemporaneous. Peperite domains range in volume from less than a few m^3, for example along contacts between sediment and small intrusions, lavas and hot volcaniclastic deposits, to several km^3 for examples described from thick volcano-sedimentary sequences. Juvenile clasts in peperite can occur close to the margins of their igneous parent, or be more widely dispersed within the host sediment. Peperite associated with intrusions is typically not stratiform and not bedded, typically discordant to bedding in the host, and often gradational to a parent intrusion.

Juvenile clasts can be subdivided into blocky and fluidal morphologies, but mixed populations are common, and tapered or ragged clasts also occur. Juvenile clasts are generated by quenching, hydromagmatic steam explosions, magma–sediment density contrasts, mechanical stress due to movement of magma or lava beneath a chilled crust, fluid–fluid shearing and surface tension effects. Juvenile clasts have igneous textures, are typically glassy or partly glassy and may display jigsaw-fit texture, implying in situ fragmentation. Mechanisms leading to mingling of juvenile clasts and sediment include fluidisation of pore fluid, sediment liquefaction and liquification, hydromagmatic steam explosions, magma–sediment density contrasts and forceful intrusion of magma. The host sediment in peperite commonly displays localized destruction or distortion of original sedimentary structures. This observation and other features, including the occurrence of vesicles in sediment and the presence of host sediment along hairline cracks and in vesicles in the lava or intrusion imply that the sediment was unconsolidated, and probably wet at the time of peperite formation. Processes of fluidisation, liquefaction, shear liquification, dewatering, compaction, vesiculation, alteration, induration and melting can occur during magma–sediment interaction and will influence sediment rheology. Peperite formation can be a complex multi-stage process that varies both spatially and temporally. Several fundamental aspects of peperite generation are not understood and additional field, experimental and theoretical studies are required.

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