Bull Volcanol (1999) 60:610–626

ORIGINAL PAPER

R. E. Hanson · U. S. Hargrove

Processes of magma/wet sediment interaction in a large-scale Jurassic andesitic peperite complex, northern Sierra Nevada, California

Received: 8 June 1998 / Accepted: 4 December 1998

Abstract The Middle Jurassic Tuttle Lake Formation in the northern Sierra Nevada, California, comprises a thick volcaniclastic sequence deposited in a submarine island-arc setting and penetrated by numerous related hypabyssal intrusions. A composite andesite-diorite intrusive complex ≥4.5 km long and ≥1.5 km thick was emplaced while the host Tuttle Lake sediments were still wet and unconsolidated. Large parts of the intrusive complex consist of peperite formed where andesitic magma intruded and intermixed with tuff, lapilli-tuff and tuff-breccia. The southern half of the complex consists of augite-phyric andesite containing peperite in numerous small, isolated pockets and in more extensive, laterally continuous zones. The peperites comprise three main types recognized previously in other peperite studies. *Fluidal peperite* consists of small (≤30 cm), closely spaced, at least partly interconnected, globular to amoeboid andesite bodies enclosed by tuff. This peperite type developed during intrusion of magma into fine-grained wet sediment along unstable interfaces, and fluidization of the sediment facilitated development of complex intrusive geometries. *Blocky peperite* and *mixed blocky and fluidal peperite* formed where magma intruded coarser sediment and underwent variable degrees of brittle fragmentation by quenching and dynamic stressing of rigid margins, possibly aided by small steam explosions. The northern half of the intrusive complex consists predominantly of a different type of peperite, in which decimetre-scale plagioclase-phyric andesite clasts with ellipsoidal, elongate, or angular, polyhedral shapes are closely packed to widely dispersed within disrupted host sediment. Textural features suggest the andesite clasts were derived from conduits through which magma was flowing, and preserved remnants of the conduits are represented by elongate, sinuous bodies up to 30 m or more in length. Disruption and dispersal of the andesite clasts are inferred to have occurred at least partly by steam explosions that ripped apart a network of interconnected feeder conduits penetrating the host sediments. Closely packed peperite is present adjacent to mappable intrusions of coherent andesite, and along the margin of a large mass of coarse-grained diorite. These coherent intrusions are considered to be major feeders for this part of the complex. Examples of magma/wet sediment interaction similar in scale to the extensive peperites described here occur elsewhere in ancient island-arc strata in the northern Sierra Nevada. Based on these and other published examples, large-scale peperites probably are more common than generally realized and are likely to be important in settings where thick sediment sequences accumulate during active volcanism. Careful mapping in well-exposed terrains may be required to recognize large-scale peperite complexes of this type.

Key words Peperite · Magma/sediment interaction · Jurassic island-arc deposits · Northern Sierra Nevada

Introduction

Peperites result from interaction between magma and wet sediment and exhibit a range of complex textures that record different stages in disruption of the magma-sediment system. Prior to the 1980s there were few detailed descriptions of these rocks in the literature, some exceptions being the papers by Macdonald (1939), Snyder and Fraser (1963), Smedes (1966), and Schmincke (1967). More recent work makes it clear that peperites are common in a variety of geological settings where magma comes in contact with wet sediment (Brooks et al. 1982; Hanson and Schweickert 1982; Kokelaar 1982; Korsch 1984; Lorenz 1984; Kokelaar et al. 1985; Busby-Spera and White 1987; Walker and Francis 1987; White and Busby-Spera 1987; Bran-

Editorial responsibility: J. McPhie

Richard E. Hanson (✉) · Ulysses S. Hargrove
Department of Geology, Texas Christian University,
P.O. Box 298830, Fort Worth, Texas 76129, USA
Fax: 817–257–7789, e-mail: hanson@gamma.is.tcu.edu

ney and Suthren 1988; Kano 1989; Riggs and Busby-Spera 1990; Boulter 1993; McPhie 1993; Rawlings 1993; Brooks 1995; Goto and McPhie 1996). Many described peperites are local, centimetre- to metre-scale mixtures of igneous material and sediment along the margins of shallow-level intrusions. A different scale of interaction is represented by large-volume peperites, where several cubic kilometres or more of magma have intermixed with sediment to form extensive intrusive masses characterized by complicated internal relations between host sediment and quenched igneous material (e.g. Snyder and Fraser 1963; Hanson and Wilson 1993). Disruption and intermixing of magma and sediment are thought to result from dominantly non-explosive processes (e.g. quench fragmentation) and/or from phreatomagmatic activity involving steam explosions produced by rapid heating of pore water in the sediment host. In this regard, peperites are of interest because they provide insight into the manner in which phreatomagmatic volcanic eruptions are initiated (Kokelaar 1986; Hanson and Elliot 1996; White 1996).

Documented examples of large-volume peperites are sparse. Here we present the results of detailed mapping of extensive peperites within Middle Jurassic submarine island-arc strata of the northern Sierra Nevada, California. Glaciated exposures provide the opportunity to examine the results of magma/wet sediment interaction that occurred on a large scale within the Jurassic island arc.

Geological setting

Jurassic arc rocks in the study area form part of the Northern Sierra terrane, one of a series of terranes intruded by the Mesozoic Sierra Nevada batholith and located outboard of the Paleozoic North American continental margin (Harwood 1992). The terrane contains an impressive succession of Devonian to Jurassic island-arc deposits resting unconformably on the early to mid-Paleozoic Shoo Fly accretionary complex (Fig. 1). This succession records the development of superimposed mid-Paleozoic, Permian, and Jurassic arcs, and consists dominantly of submarine volcanic and volcaniclastic deposits cut by penecontemporaneous hypabyssal intrusions (Hannah and Moores 1986; Hanson and Schweickert 1986; Harwood 1992; Hanson et al. 1996). After deposition of Middle Jurassic strata, the entire arc succession and its basement underwent bulk rotation to the east, presumably during extensional faulting. This was followed by contractional deformation and regional metamorphism, generally to greenschist facies, and by intrusion of Jurassic and Cretaceous plutons (Hanson et al. 1996; Kulow 1996). Parts of the arc succession, however, show little structural disturbance other than regional tilting and domainal development of cleavage.

Peperites are important in various parts of the arc succession (Hanson et al. 1996) and have been described in detail from glaciated exposures in mid-Paleozoic strata near the base of the succession (Brooks et al. 1982; Hanson and Schweickert 1982; Brooks 1992, 1995). Brooks et al. (1982) noted the occurrence of chaotic mid-Paleozoic peperite masses up to 20,000 m^2 in extent that formed where andesitic magma was quenched and intermixed with unconsolidated, hemipelagic siliceous ooze. At roughly the same stratigraphic

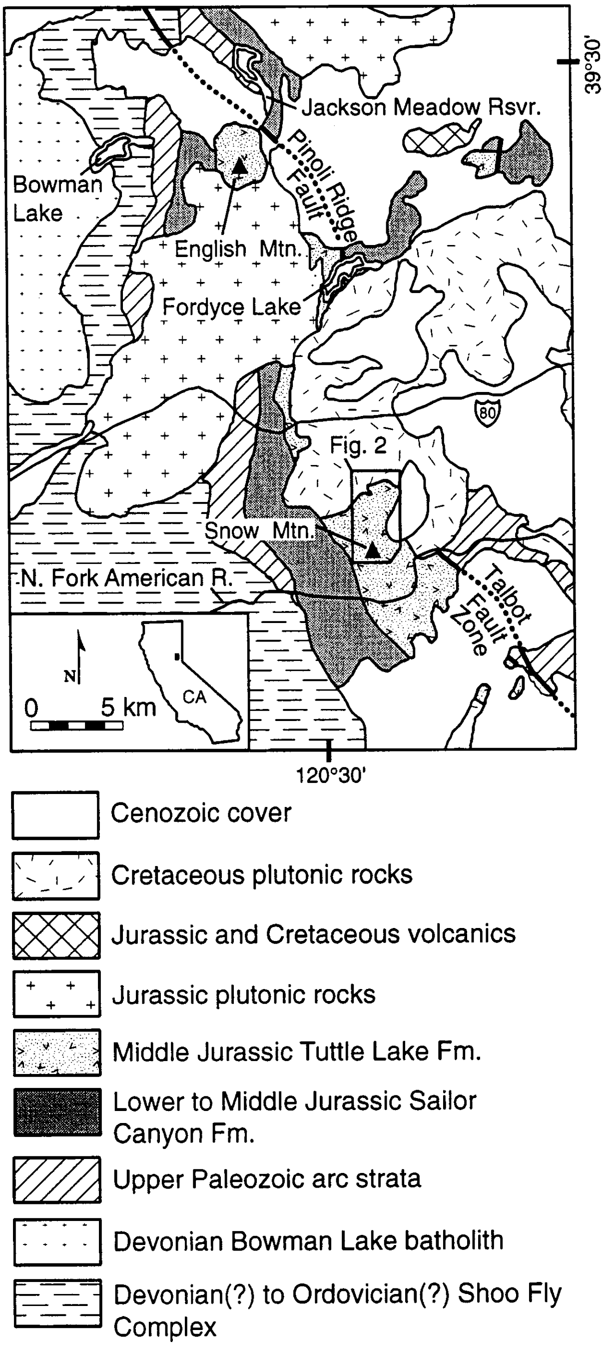

Fig. 1 Regional geological setting of the study area in the northern Sierra Nevada, California. Location of Fig. 2 (area of Huntley Mill Lake intrusive complex) is indicated. Modified from Harwood (1992) and Hanson et al. (1996)

level, Hanson (1991) mapped a large, andesite to rhyolite hypabyssal intrusive complex up to 800 m thick that contains voluminous intrusive hydroclastic breccias and related peperites formed by non-explosive interaction between magma and wet sediment.

The peperites described in this paper occur within the Tuttle Lake Formation, which comprises the youngest Jurassic arc strata in the area of Fig. 1 (Harwood 1992). The formation consists dominantly of massive, thickly bedded, heterolithological andesitic debris-flow deposits containing abundant lithic clasts ≤2 m long supported in a crystal-rich tuffaceous matrix. Bedding is defined primarily by interbeds up to a few metres thick of planar-bedded and laminated andesitic tuffaceous rocks that locally contain marine pelecypod fossils (Templeton 1991; Harwood 1992; Mielke 1996). Sedimentary structures in the tuffaceous rocks generally indicate deposition below storm wave base from subaqueous ash falls and turbidity currents. However, medium-scale trough cross-bedding unrelated to Bouma sequences occurs in some tuffaceous interbeds and is taken to indicate accumulation of parts of the volcaniclastic pile in relatively shallow water where intermittent tractional reworking of turbidites and suspension deposits was possible (Templeton 1991; Hanson et al. 1996).

The Tuttle Lake Formation is ≥4 km thick and can be traced discontinuously for ~50 km along strike south of the area shown in Fig. 1 (Fisher 1992). It overlies the Lower to Middle Jurassic Sailor Canyon Formation, which consists dominantly of fine-grained andesitic volcaniclastic turbidites, subaqueous ash-fall tuffs, and mudstone deposited in a marine basin of regional extent (Hanson et al. 1996; Schweickert 1996). Onset of deposition of the Tuttle Lake Formation is inferred to record progradation of subaqueous volcaniclastic aprons into the Sailor Canyon basin, reflecting a shift in the locus of volcanism in the Jurassic arc (Templeton 1991). The time span of Tuttle Lake volcanism is constrained by Middle Jurassic (Bajocian to Bathonian) fossils in the underlying Sailor Canyon Formation and by U–Pb zircon isotopic ages of 168±2 to 163±4 Ma for Jurassic plutonic rocks that cut the Tuttle Lake Formation (Hanson et al. 1996). Gradstein et al. (1994) place the top of the Bathonian at 164.4±3.8 Ma, implying that the Tuttle Lake Formation accumulated in a relatively short time interval in the Middle Jurassic.

Abundant hypabyssal intrusions in the Tuttle Lake Formation were emplaced into wet, unconsolidated host sediments during or shortly after deposition (Templeton 1991; Templeton and Hanson 1991; Fisher 1992; Mielke et al. 1995; Mielke 1996). They were first described in detail by Templeton (1991) from extensive glaciated exposures in the English Mountain area (Fig. 1) and have also been documented by Mielke (1996) in outcrops east and south of English Mountain. In both areas, mappable hypabyssal andesite/microdiorite intrusions are associated with smaller elongate, tubular or tongue-like intrusions up to 18 m long that cut parts of the host debris-flow sequence. Peperite occurs along intrusion margins and as isolated pockets up to 20 m^2 in areal extent. Templeton (1991) inferred that the elongate bodies represent feeder conduits that carried magma from larger intrusions to localized zones of fine-scale magma-sediment intermixing.

We describe particularly extensive, well-exposed peperites in the Tuttle Lake Formation south along strike from the above areas (Fig. 1). The peperites make up major parts of a large, composite andesite-diorite hypabyssal intrusion termed the Huntley Mill Lake intrusive complex. They contrast with other examples in the Tuttle Lake Formation in the scale of peperite formation and the apparent involvement of explosive processes in magma disruption and dispersal.

Huntley Mill Lake intrusive complex

The Huntley Mill Lake intrusive complex is exposed in glaciated outcrops near and on Snow Mountain, Placer County, California (Figs. 2, 3a), and is named after a small lake near the eastern edge of the complex. The northern part of the complex is cut by Cretaceous plutonic rocks (Kulow 1996), which also intrude the eastern margin of the complex along a contact covered by Cenozoic deposits.

In this region the arc succession has an average dip of ~50° to the northeast, so that Fig. 2 essentially represents a cross section of the intrusive complex. The lower (western) contact is broadly concordant with bedding in the host Tuttle Lake strata, but the original geometry of the upper (eastern) contact is unknown. The southern margin of the complex is poorly constrained, because it runs into cliffs in the gorge of the North Fork American River. The contact is at least locally discordant in that region (Fig. 2) but may bend again to the south before the intrusive complex terminates in cliffs on the north side of the river gorge. The complex is absent south of the river, where the Tuttle Lake Formation consists primarily of thickly bedded tuff-breccia debris-flow deposits typical of the unit as a whole (D. Harwood, pers. commun.).

The intrusive complex is a minimum of 1.5 km thick and 4.5 km long, and its generally concordant lower contact suggests that the complex originally had the form of a thick sill or laccolith. Despite the uncertainties regarding its original geometry, the complex contains a complicated series of intrusive phases that provide insight into the nature of interactions between andesitic magma and wet volcaniclastic sediment at shallow levels beneath the sea floor.

Most of the Tuttle Lake Formation in the area of Fig. 2 lacks a foliation and exhibits a static greenschist-facies metamorphic overprint. Primary textures are generally well preserved on outcrop and hand-sample scales. However, within a dynamothermal aureole a few hundred metres wide along the margins of the Cretaceous plutons to the north and east, a penetrative folia-

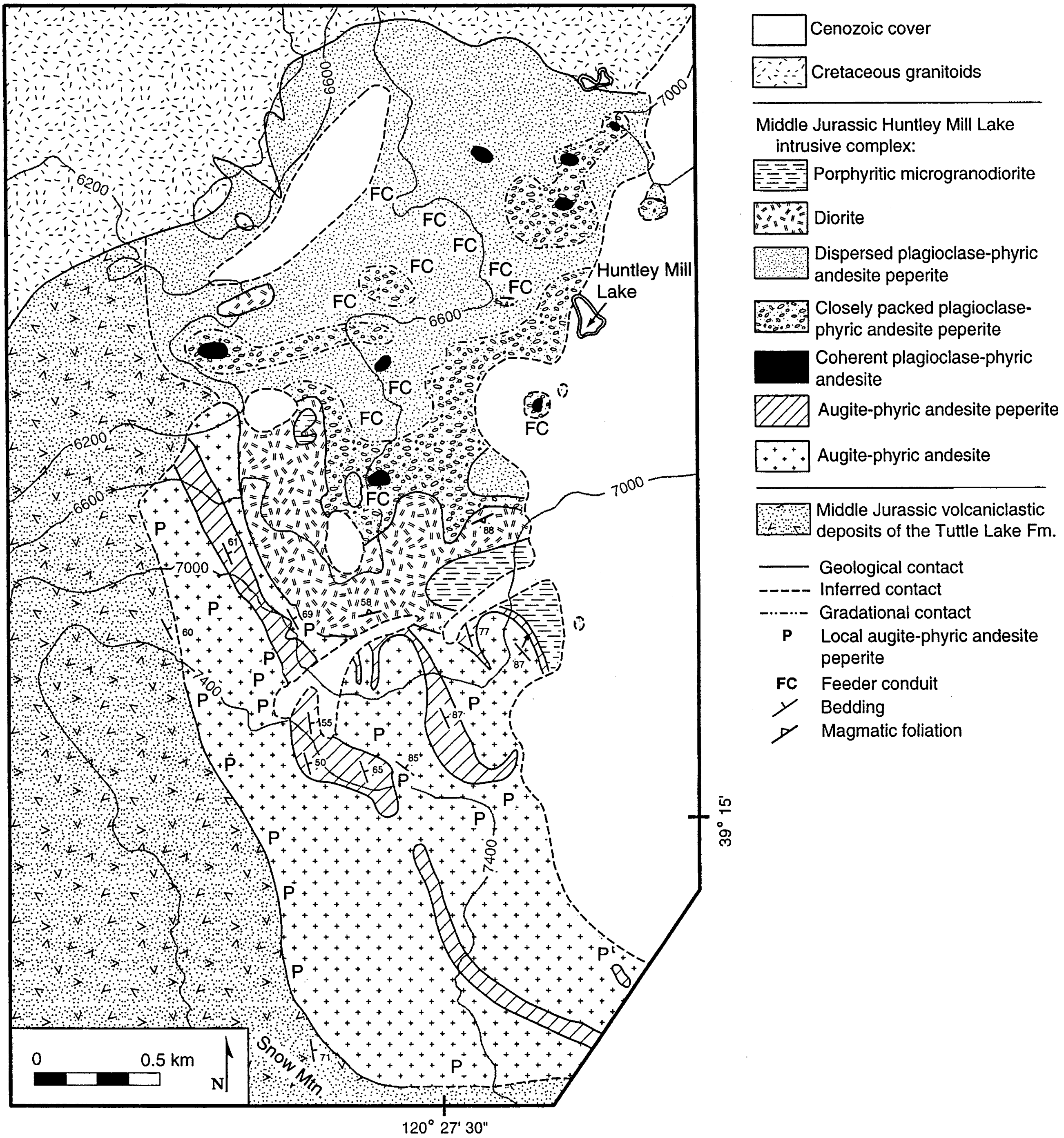

Fig. 2 Geological map of the Huntley Mill Lake intrusive complex and environs. Top of Snow Mountain is indicated near bottom of figure. Topographic contours are shown at 400-ft (120-m) intervals

tion is present in the Tuttle Lake Formation, and metamorphic grade increases to the amphibolite facies.

Internal make-up of the intrusive complex

The Huntley Mill Lake intrusive complex contains several distinct phases (Fig. 2), including two major types of andesite showing different styles of peperite formation as described herein. Lithological features of the phases are summarized in Table 1, and representative chemical analyses are given in Table 2. Additional descriptions are given by Hargrove (1995).

Augite-phyric andesite forms a large, composite mass in the southern half of the intrusive complex. Much of it is unbrecciated, but peperite is common and locally extensively developed. The northern half of the intrusive complex consists mostly of plagioclase-phyric andesite peperite. Both andesite types comprise several subphases characterized by variations in sizes and pro-

Table 1 Lithological descriptions of major phases in the Huntley Mill Lake intrusive complex

Augite-phyric andesite	Up to 35% euhedral augite phenocrysts, ≤3 mm. Plagioclase occurs as andesite phenocrysts (≤2 mm) and lath-shaped microlites enclosed by altered mesostasis. Phenocrysts and microlites are typically randomly oriented, but flow banding defined by groundmass colour changes is locally present
Plagioclase-phyric andesite	Thirty to 60%, euhedral, randomly oriented to flow-aligned plagioclase phenocrysts, 1–3 cm (rarely to 5 cm). These show oscillatory zonation, expressed in hand sample as a thin white rim surrounding a darker core. Augite phenocrysts typically are ≤0.5–1 cm and less abundant (ca. 10%). Phenocrysts are set in an aphanitic, highly altered groundmass
Diorite	Interlocking, subhedral to euhedral plagioclase crystals identical in size, habit and internal zonation to plagioclase phenocrysts in plagioclase-phyric andesite. Augite is typically finer grained (≤1 cm) and forms interstitial crystals between plagioclase, together with minor amounts of fine, granophyric feldspar and quartz. Augite generally ranges in abundance from 7 to 20%, but increases locally to form patches and zones up to 10 m across of augite-rich gabbro and clinopyroxenite. Plagioclase is locally aligned parallel to the margins of the diorite; local augite-rich schlieren also parallel this magmatic foliation
Porphyritic microgranodiorite	Fifteen percent, euhedral, randomly oriented to flow-aligned plagioclase crystals identical to those in diorite and plagioclase-phyric andesite. Together with ca. 10% augite phenocrysts (≤1 cm), these are set in a very fine-grained, phaneritic groundmass of intergrown quartz, plagioclase and K-feldspar

All phases are affected by generally static, low-grade metamorphism. Plagioclase is partly replaced by fine amphibole, biotite, sericite and epidote. Augite is generally completely replaced by fine intergrowths of amphibole and biotite, although unaltered cores are locally present. Groundmass textures in thin section are partly to completely obliterated by metamorphic recrystallization

Table 2 Representative chemical analyses of different phases in the Huntley Mill Lake intrusive complex

	plagioclase-phyric andesite			augite-phyric andesite	diorite	porphyritic microgranodiorite
	TH-1	TH-47	TH-162	TH-94	TH-53	TH-100
SiO_2 (wt.%)	55.40	56.34	54.91	57.46	54.07	65.35
TiO_2	0.76	0.71	0.81	0.57	0.67	0.70
Al_2O_3	18.94	19.08	17.47	14.44	22.35	15.09
FeO^*	7.29	7.49	8.21	8.07	5.28	5.40
MnO	0.11	0.12	0.14	0.16	0.08	0.09
MgO	3.38	2.53	4.02	6.56	1.73	1.77
CaO	7.47	10.05	9.82	9.22	9.76	4.28
Na_2O	3.91	2.39	3.77	2.41	3.70	3.03
K_2O	2.22	0.53	0.60	1.12	1.98	3.76
P_2O_5	0.23	0.23	0.23	0.16	0.19	0.27
Total	99.72	99.47	99.97	100.17	99.82	99.74

* Total Fe expressed as FeO. Analysed at the GeoAnalytical Laboratory, Washington State University, by XRF on fused glass beads with a lithium tetraborate flux

portions of phenocrysts. These have not been distinguished during mapping but are interpreted to record injection of slightly different magma batches during progressive intrusion. Small, coherent intrusions of augite-phyric andesite of the same type that is present to the south occur in the area occupied by plagioclase-phyric andesite peperite. Augite-phyric andesite peperite is locally developed along the margins of these intrusions, only one of which is large enough to show on the scale of Fig. 2.

All of the andesite is weakly to non-vesicular. Quartz-filled amygdules up to 2 cm in diameter are more abundant (up to ~10%) in the uppermost exposed parts of the intrusive complex, implying that lower confining pressure favoured limited volatile exsolution at those levels. The low vesicularity suggests that magmatic volatile-driven explosivity was not an important factor in development of the peperites in the complex.

Diorite (Table 1) forms an irregular mass in the central part of the intrusive complex that is surprisingly coarse grained, given the high level of emplacement. A separate, smaller diorite body intrudes plagioclase-phyric andesite peperite to the north (Fig. 2). In two separate areas the main diorite grades into porphyritic microgranodiorite over a distance of several metres. Inclusions of diorite occur within the microgranodiorite. The two phases have markedly different compositions (Tables 1, 2), suggesting that the microgranodiorite represents a different magma batch that was intruded prior to solidification of the diorite and developed gradational contacts with it.

The southern contact of the main diorite against augite-phyric andesite is sharp. Xenoliths and cross-cutting dikes generally indicate that the diorite is intrusive into the augite-phyric andesite. However, the opposite relations also occur locally, implying that intrusion of the two phases partly overlapped. As discussed more fully later, field and petrographic evidence indicates that the diorite is directly related to the plagioclase-phyric andesite to the north.

Augite-phyric andesite peperite

Peperite forms several mappable zones in the augite-phyric andesite in the southern part of the intrusive complex (Fig. 2). Two large zones are elongate subparallel to bedding in the host Tuttle Lake sequence and are presumably tabular in three dimensions. Two other zones farther east, at structurally higher levels, are more irregular in shape. Bedding within the peperite zones has commonly been disrupted, but intervals of undisturbed, planar-laminated tuff up to ~7 m thick and ≤300 m long are locally present. Generally, the preserved bedding is subparallel to bedding in the Tuttle Lake Formation elsewhere in the study area. An exception occurs in the easternmost peperite zone, where the bedding defines a synform (Fig. 2).

Smaller pockets of peperite ≤30 m wide are present in many places in otherwise coherent augite-phyric andesite away from the larger peperite zones. They also occur in numerous places along the base of the intrusion (Fig. 2).

The peperite consists of generally closely packed clasts and globular bodies of andesite in a matrix of tuff, lapilli-tuff, or tuff-breccia. The intrusive andesite is easily distinguished where the host is tuff. Where the host is lapilli-tuff and tuff-breccia, intrusive andesite bodies and clasts are recognized by lithological similarity and close association with adjacent coherent augite-phyric andesite, by their generally coarser size relative to transported clasts in the host sediments, by fluidal shapes, and by the presence of jigsaw-fit fragmental textures (described below).

The peperites are divided into two end-member types, which correspond to *blocky* and *fluidal (globular)* as defined by Busby-Spera and White (1987). *Fluidal (globular) peperite* contains centimetre- to decimetre-scale, irregular to globular bodies surrounded by host sediment, and is inferred to reflect fluidal interaction between magma and sediment. *Blocky peperite* contains angular clasts of intrusive igneous rock set within host sediment, and is inferred to result from magma disruption by quench fragmentation, dynamic stressing of chilled margins (Kokelaar 1986), and steam explosivity. This terminology is followed herein, although it should be noted that a significant proportion of the clasts in the blocky peperite have highly irregular forms and are not simple, polyhedral blocks. In many cases the intrusive igneous rock develops both blocky and fluidal forms intermixed together in various proportions, as also noted by Busby-Spera and White (1987). We term such cases *mixed blocky and fluidal peperite*.

Fluidal peperite

Fluidal peperite is the least common peperite type in augite-phyric andesite and occurs only where the host is tuff. It is present over areas up to tens of metres across and is characterized by complex geometrical relations between intrusive andesite and tuff. Most commonly the andesite appears on two-dimensional outcrop surfaces as closely spaced, roughly ovoid to amoeboid bodies separated by several centimetres of tuff (Fig. 3b, c). The bodies are typically ≤30 cm long but in places are associated with larger, ellipsoidal or tongue-like andesite masses up to 1 m or more long (Fig. 3b). The margins of the bodies are either smooth or highly irregular and crenulate on a fine scale. Locally, small pieces detached from the margins occur a short distance into the adjacent tuff. In other cases, bodies have broken into several pieces separated by thin veinlets of host tuff. The margins of the bodies are texturally similar to interiors but have a darker colour in some cases. Similar colour changes occur in coarse clasts in contact with tuff in other parts of the Tuttle Lake Formation and are inferred to reflect limited chemical exchange between clasts and matrix during metamorphism.

Based on observations of many outcrop surfaces intersecting at different angles, the bodies are inferred to have either globular or complex, amoeboid forms in three dimensions. The ovoid outlines (e.g. Fig. 3b, c) do not represent cross sections through elongate tubes of the type formed in pillow lava, because similar aspect ratios are apparent on outcrop surfaces oriented at high angles to those shown in the figures. Narrow necks between adjacent, bulbous bodies are seen in places, and many of the bodies are probably connected by similar necks in three dimensions. Accordingly, the term “clast” is inappropriate for these small, intrusive andesite bodies. In local pockets within fluidal peperite, discrete, globular bodies are absent, and instead the andesite forms a complex series of centimetre-scale, highly irregular, branching tongues and crenulate lobes in the host tuff (Fig. 3d).

Blocky peperite

Blocky peperite in the augite-phyric andesite occupies areas up to hundreds of square metres in extent. The host sediment in almost all cases is tuff-breccia and lapilli-tuff; Fig. 4a and b shows an exceptional case where the host is tuff. Bedding in the host sediments is typically obliterated. In places, tongues of coherent andesite up to several metres long are present and have jagged, brecciated margins (Fig. 4a). Fragments of intrusive andesite are typically ≤30 cm long (Figs. 3a, 4a, b). Many are blocky and polyhedral, with sharp corners, but others have partly rounded margins or concave indentations resulting from breakage along smooth, curved fractures (cf. “pseudo-pillows” of Yamagishi 1991; McPhie et al. 1993). A third fragment type has complexly indented, jagged margins that reflect disaggregation along a series of irregular, interconnecting fractures (Fig. 4b). Angular and polyhedral to highly irregular, millimetre- to decimetre-sized clasts of intrusive

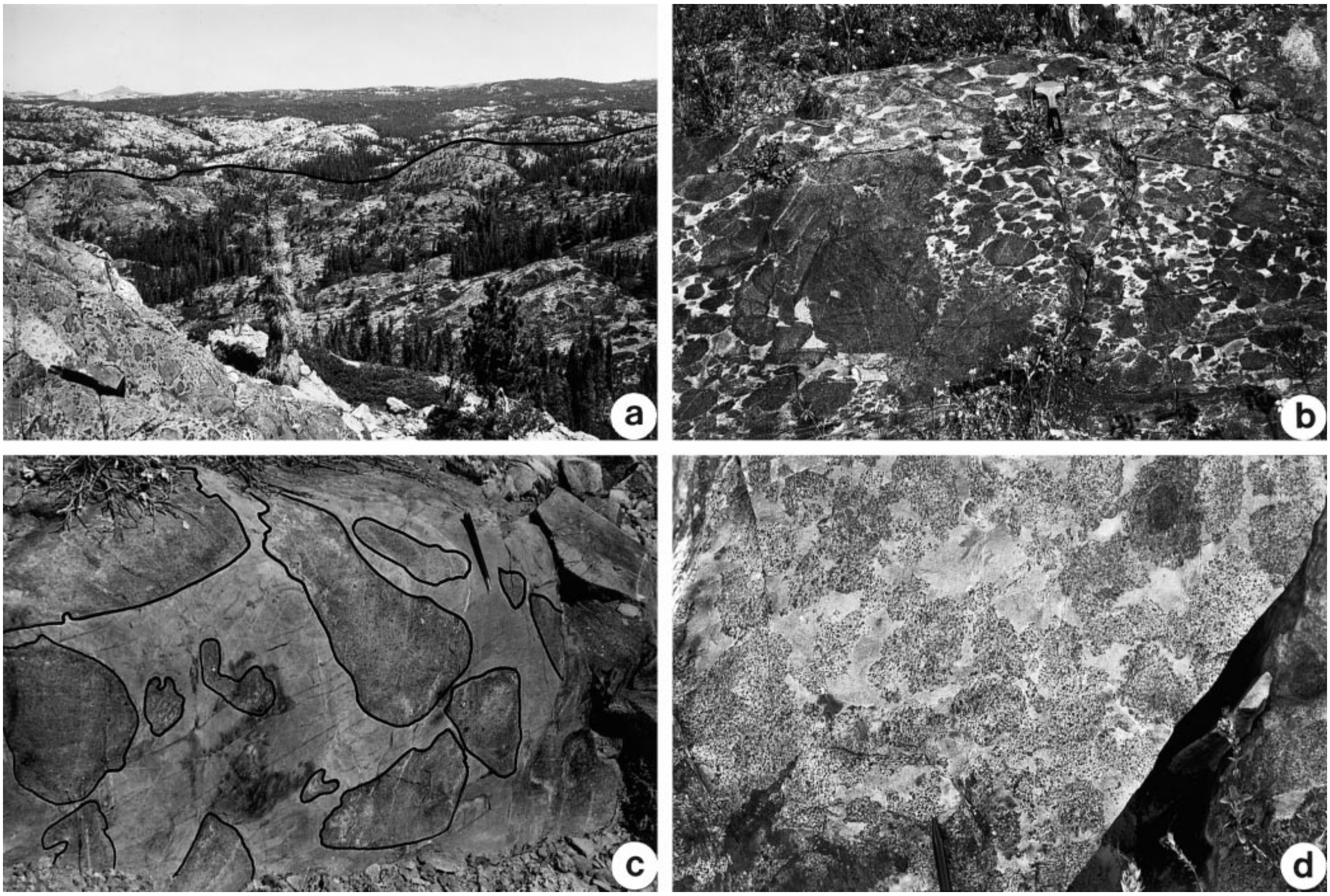

Fig. 3 **a** View of part of Huntley Mill Lake intrusive complex, looking north from flank of Snow Mountain. Blocky augite-phyric andesite peperite in foreground. Dead tree behind outcrop is ~10 m tall. Intrusive contact of light-coloured Cretaceous granitoids against dark-coloured plagioclase-phyric andesite peperite of Huntley Mill Lake complex is outlined. High peak in distance is English Mountain, where other extensive exposures of the Tuttle Lake Formation are present (Fig. 1). **b** Typical fluidal augite-phyric andesite peperite. Dark-coloured andesite bodies are contained in a matrix of light-coloured andesitic tuff. *Hammer* for scale. **c** Closer view of augite-phyric andesite bodies (*outlined*) within lighter coloured tuff in fluidal peperite. *Diagonal lines* in tuff are joints; *irregular dark spots* that cross contacts between andesite and tuff in lower centre are alteration. *Pencil* for scale. **d** Complex contact relations between fluidal augite-phyric andesite and light-coloured host tuff. *Small, dark spots* in andesite are augite phenocrysts. *Dark core* in andesite body at *upper right* is due to alteration. *Pencil* for scale

andesite are intermixed with the disrupted host sediment between the larger fragments. Commonly, the blocky peperite is chaotic (Fig. 4a), but jigsaw-fit textures are preserved in places and record in situ fragmentation (Fig. 4b).

Mixed blocky and fluidal peperite

Mixed blocky and fluidal peperite is the most abundant peperite type in the augite-phyric andesite and is widespread in the mappable peperite zones shown in Fig. 2. It is most commonly hosted by tuff-breccia and lapilli-tuff but also occurs in tuff. Variable proportions of fluidal andesite bodies similar to those described previously are intermixed with angular to irregular andesite fragments, many of which have partly preserved fluidal shapes (Figs. 4c, d, 5). Connections or necks between preserved fluidal bodies are visible on some outcrop surfaces (Fig. 5). Relatively large, tongue-like or irregularly shaped andesite masses ≥1 m long show jigsaw-fit fracture patterns along their margins, forming angular, decimetre-scale clasts separated by sediment (Fig. 4c, d). Small, closely packed fragments in pockets between the larger andesite bodies preserve jigsaw-fit texture to various degrees.

Detailed relations between intrusive andesite and host sediment

Delicate planar lamination in tuff is preserved to various degrees in many places between intrusive andesite bodies in fluidal and mixed blocky and fluidal peperite (Fig. 5). The lamination is commonly truncated at the margins of intrusive andesite bodies, which in some cases are rimmed by narrow zones of structureless, homogeneous tuff where the lamination has been destroyed (Fig. 5). As discussed herein, such relations

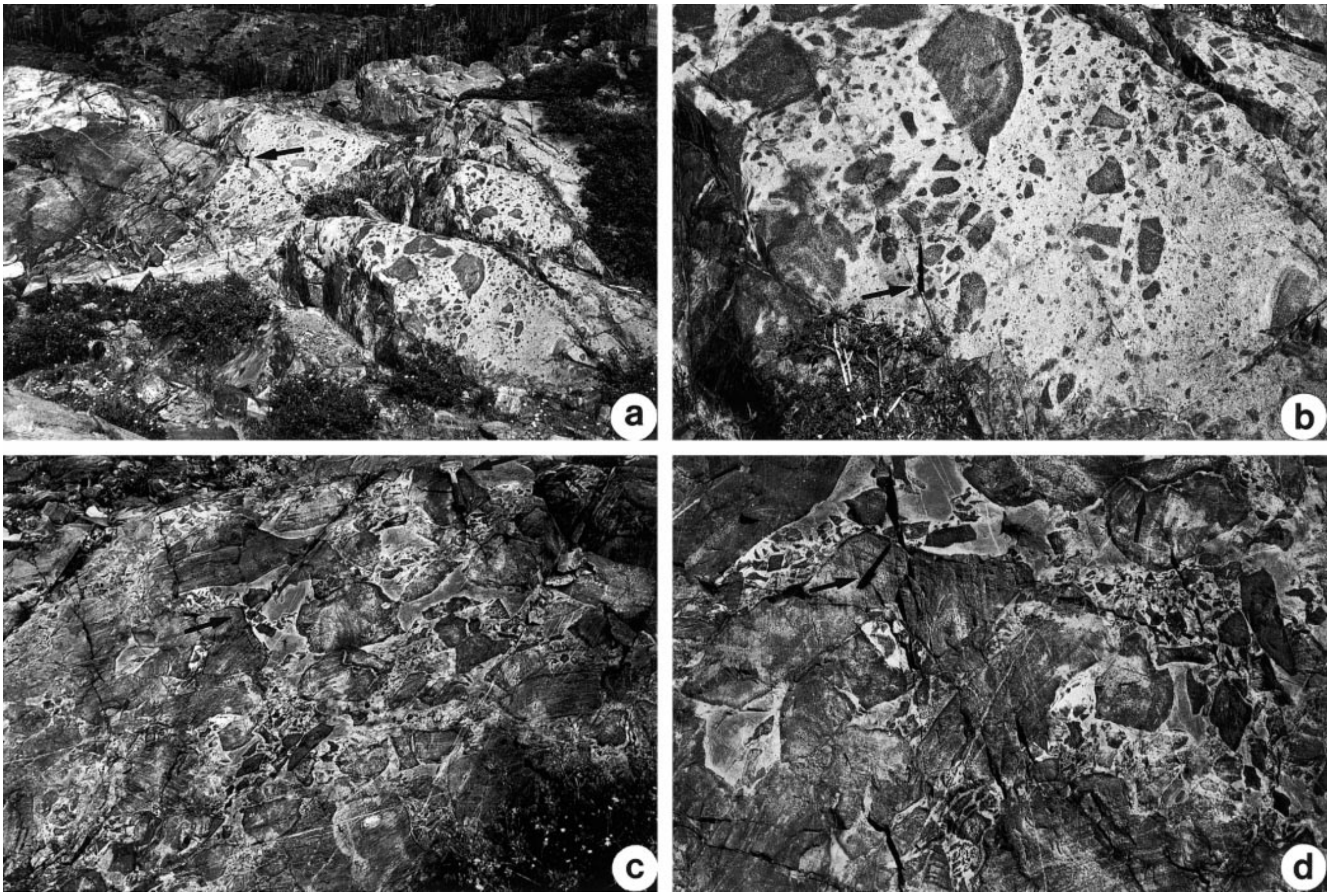

Fig. 4 **a** Blocky augite-phyric andesite peperite. *Hammer* (*arrow*) lies near right margin of large andesite tongue. *Light-coloured host sediment* is tuff. **b** Closer view of lower right part of previous figure. *Pencil* (*arrow*) lies on angular andesite clasts preserving jigsaw-fit texture. Note highly irregular fragment a short distance left of pencil. **c** Mixed blocky and fluidal augite-phyric andesite peperite, with andesite clasts set in lighter grey host tuff. Many larger clasts have partly fluidal outlines. Numerous examples of jigsaw-fit texture are visible. *Hammer* in upper right (*arrow*) for scale. Other *arrow* indicates position of pencil in **d**. **d** Closer view of central part of previous figure. *Pencil* (*arrow*) points to edge of andesite body showing in situ fragmentation. The other *arrow* (*upper right*) points to thin, irregular, tuff-filled fracture penetrating another andesite body. An excellent example of jigsaw-fit texture is visible at bottom centre. *White areas* in host tuff are due to alteration

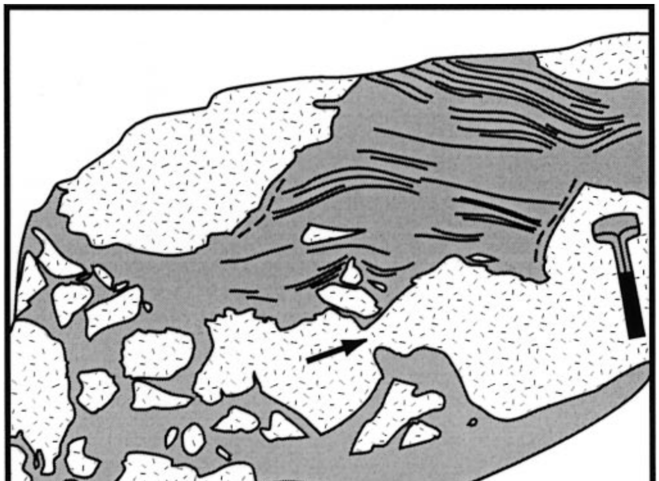

Fig. 5 Sketch taken from a photo of mixed blocky and fluidal augite-phyric andesite peperite. Andesite clasts and irregular bodies (*light pattern*) are set in host tuff (*dark grey*) showing preserved planar lamination truncated at contacts with andesite. Thin zones along some contacts where lamination has been destroyed are indicated by *dashed lines*. *Hammer* lies on a fluidal andesite body connected to another body to the left by a thin neck (*arrow*)

suggest that fluidization of fine-grained sediment occurred during peperite formation (Kokelaar 1982).

Plagioclase-phyric andesite peperite

The northern half of the Huntley Mill Lake complex consists largely of a distinctive type of peperite in which intrusive plagioclase-phyric andesite occurs primarily as decimetre-scale, ellipsoidal, elongate, or angular, polyhedral clasts within sediment. In contrast to the largely coherent augite-phyric andesite to the south, magma in this part of the complex has undergone more complete disruption and commingling with sediment. Bedding is typically not recognizable in the host sediments, which consist dominantly of tuff-breccia and lapilli-tuff debris-flow deposits; however, tuff interbeds are locally preserved between the coarser deposits and are generally concordant with regional bedding trends.

For mapping purposes, the plagioclase-phyric andesite peperite is divided into two types based on the degree of separation of intrusive andesite clasts (Fig. 2). Dispersed peperite contains intrusive clasts that are separated by ≥1.5 m of sediment, vary in abundance in an irregular fashion, and in many places are sparse or absent. Clasts in closely packed peperite are ≤1.5 m apart and in some cases are separated by only a few centimetres of host sediment. In some places a single subphase of andesite characterized by uniform phenocryst content makes up all of the intrusive clasts over areas up to hundreds of square metres in extent. In other areas the clasts consist of two or more distinct subphases that have been intermixed in a chaotic fashion.

Eight mappable, coherent intrusions of plagioclase-phyric andesite occur within the peperite, and several are rimmed by zones of closely packed peperite that grade outward into dispersed peperite (Fig. 2). The same zonal pattern occurs along the northern margin of the large mass of diorite in the central part of the Huntley Mill Lake complex (Fig. 2). Moreover, the diorite has a chilled margin several metres wide of plagioclase-phyric andesite lithologically identical to intrusive clasts in the adjacent peperite. This relation and the close petrographic similarities between the plagioclase-phyric andesite and the diorite (Table 1) indicate that the diorite is a more slowly cooled equivalent of the andesite. The zonal patterns developed in the peperite outward from both the diorite and the small, coherent andesite intrusions suggest a direct link between emplacement of these intrusions and formation of the peperite.

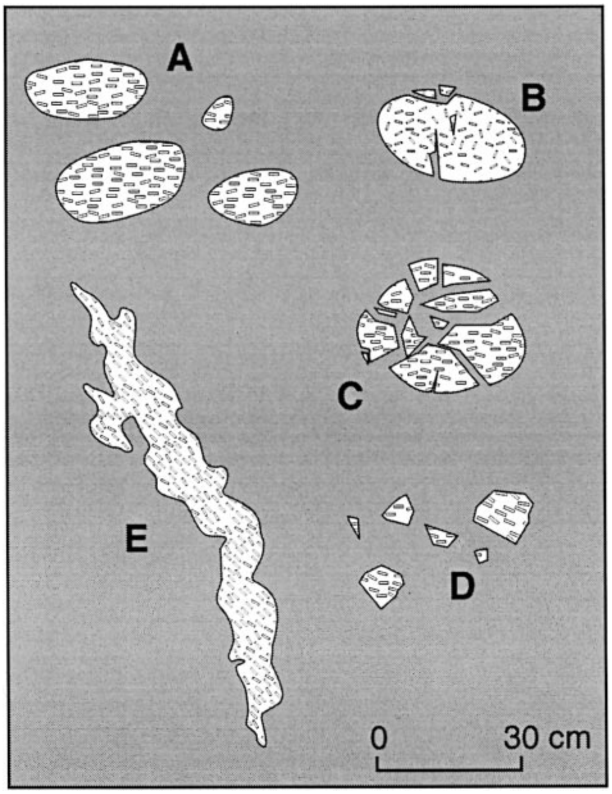

Fig. 6 Characteristic features of andesite clasts in plagioclase-phyric andesite peperite (*small rectangles* in andesite schematically represent plagioclase phenocrysts; *dark grey areas* indicate host tuff-breccia). *A* ellipsoidal clasts with internal phenocryst alignment truncated at margins; *B* ellipsoidal clast showing marginal in situ fragmentation; *C* jigsaw-fit cluster of andesite clasts derived from in situ fragmentation of an ellipsoidal clast. *D* cluster of angular, plagioclase-phyric andesite fragments. *E* elongate, tongue-like andesite clast

Characteristics of intrusive andesite clasts

Plagioclase-phyric andesite clasts most typically have ellipsoidal outlines from a few centimetres to several metres in length and average ~30 cm (Figs. 6, 7a). There is no regular pattern to the size variation, and clasts several metres long are randomly dispersed among the more common, smaller clasts. Inspection of outcrop surfaces at a variety of angles shows that most of the clasts are roughly equidimensional in three dimensions; elongate, tongue-like forms (Fig. 7b) are less common. Connections between clasts have not been observed, even in areas of closely packed peperite.

The intrusive clasts generally do not photograph well, and their characteristic features are depicted schematically in Fig. 6. Margins of the ellipsoidal clasts vary from smooth and rounded to partly subangular, and amoeboid forms of the type seen in fluidal augite-phyric andesite peperite are absent. Irregular fractures filled with fine-grained sediment penetrate some clasts; in other places, the clasts have fragmented in place, forming jigsaw-fit clusters of small, angular fragments. Numerous examples are present where small, angular shards derived from the margins of clasts have spalled short distances into the adjacent matrix. These textures record in situ brittle fragmentation. Angular plagioclase-phyric andesite clasts that cannot be matched with adjacent clasts indicate more chaotic dispersal of disrupted andesite.

Plagioclase phenocrysts show a well-defined flow alignment in a significant number of the andesite clasts. This commonly parallels one or more margins of a clast but is truncated by the other margins, or by irregularities in the margins (Fig. 6). The alignment generally becomes less pronounced or disappears inward, especially in the larger clasts. Where the alignment is well developed, the phenocrysts tend to show a regular decrease in size toward the margins.

Closely packed plagioclase-phyric andesite clasts locally truncate tuff interbeds within the host sequence

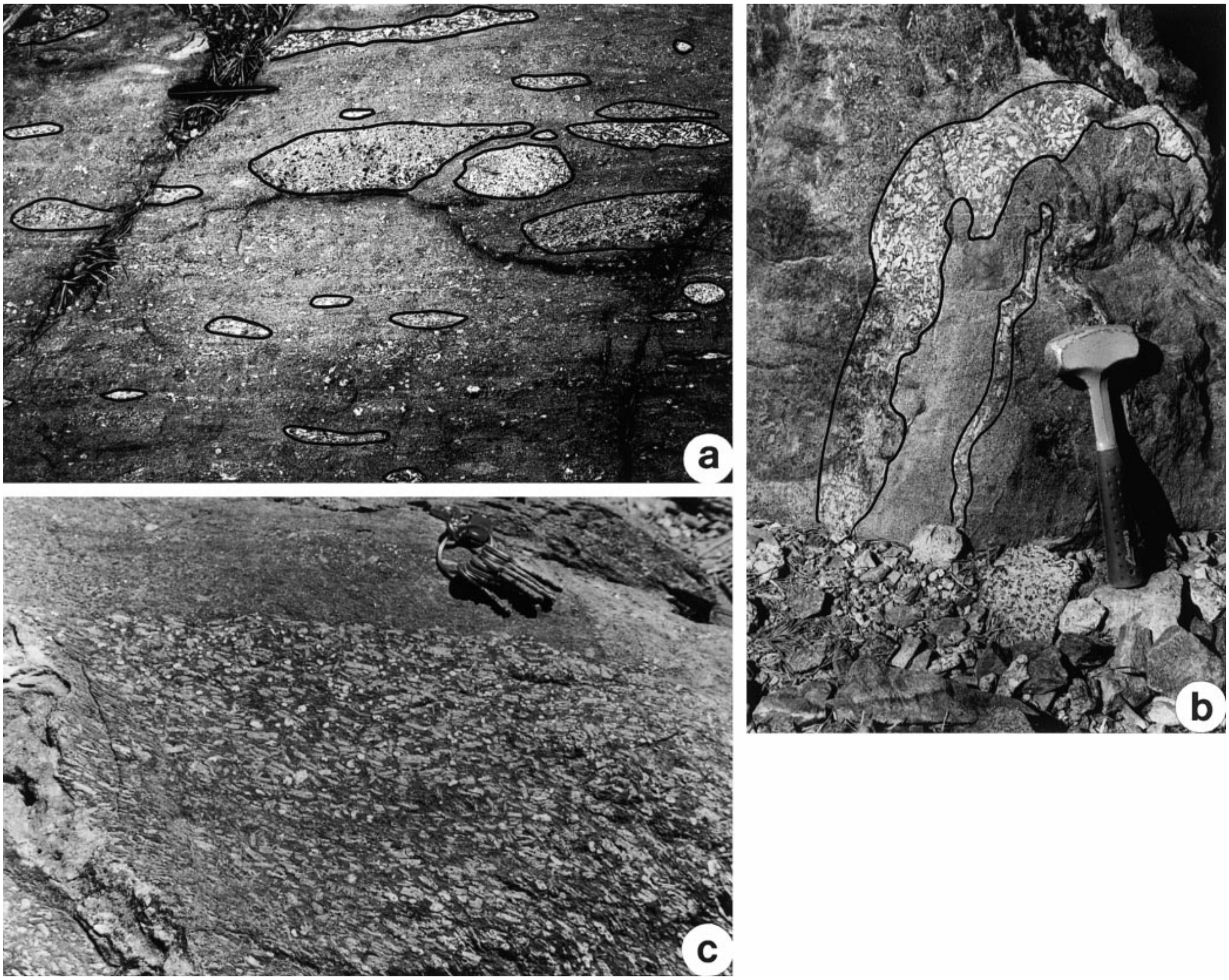

Fig. 7 a Closely packed plagioclase-phyric andesite peperite, within zone of ductile deformation along eastern contact of Huntley Mill Lake intrusive complex. Andesite clasts (*outlined*) have been tectonically flattened but still preserve rounded margins. Abundant plagioclase and augite phenocrysts are visible inside andesite clasts, and several subphases of andesite with different sizes and proportions of phenocrysts are present. *Pencil* for scale. **b** Small, elongate, tongue-like andesite clasts (*outlined*) in plagioclase-phyric andesite peperite. Coarse plagioclase phenocrysts are visible inside clasts. **c** Edge of ellipsoidal andesite clast in plagioclase-phyric andesite peperite. Note alignment of plagioclase phenocrysts parallel to margin. Quartz amygdules appear as small, white, ovoid spots between plagioclase phenocrysts. To the left, a light-coloured, epidote-rich vein cuts the clast. Shapes of andesite clasts in Fig. 7b and c have not been modified by deformation

along irregular intrusive contacts, and the tuff forms matrix between jigsaw-fit fragments in such cases. Intrusive relations are less obvious where the plagioclase-phyric andesite clasts are widely dispersed within host tuff-breccia and lapilli-tuff. However, the high content of coarse plagioclase phenocrysts in this phase of andesite is distinctive (Table 1), and we have not observed transported clasts of this type in debris-flow deposits elsewhere in the Tuttle Lake Formation (e.g. Templeton 1991; Mielke 1996). The close petrographic similarities to adjacent, coherent plagioclase-phyric andesite and diorite intrusions, and zonations in abundance of the andesite clasts away from the margins of these intrusions indicate an intrusive origin for the plagioclase-phyric andesite clasts. Moreover, jigsaw-fit textures in a significant number of clasts imply in situ quenching of magma during intrusion; such textures are not shown by transported clasts elsewhere in Tuttle Lake debris-flow deposits.

Large, elongate andesite bodies

Large, elongate, sinuous andesite bodies 5 m to ≥30 m long (Figs. 8, 9) occur in numerous places within both dispersed and closely packed peperite, as indicated in Fig. 2. Margins are highly irregular and crenulate, and lobes and elongate tendrils extend into the adjacent sediment (Figs. 8b, 9b). Small, angular fragments have moved short distances from the margins into the adja-

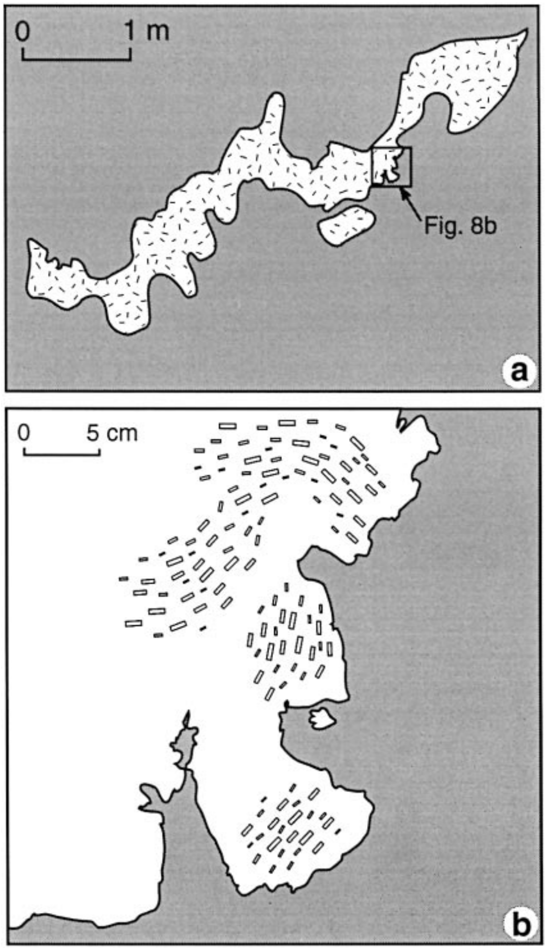

Fig. 8 **a** Outcrop sketch of large, elongate andesite body (*light pattern*) within plagioclase-phyric andesite peperite. **b** Detailed sketch from a photograph of irregular margin of elongate body. Internal alignment of plagioclase phenocrysts is shown schematically

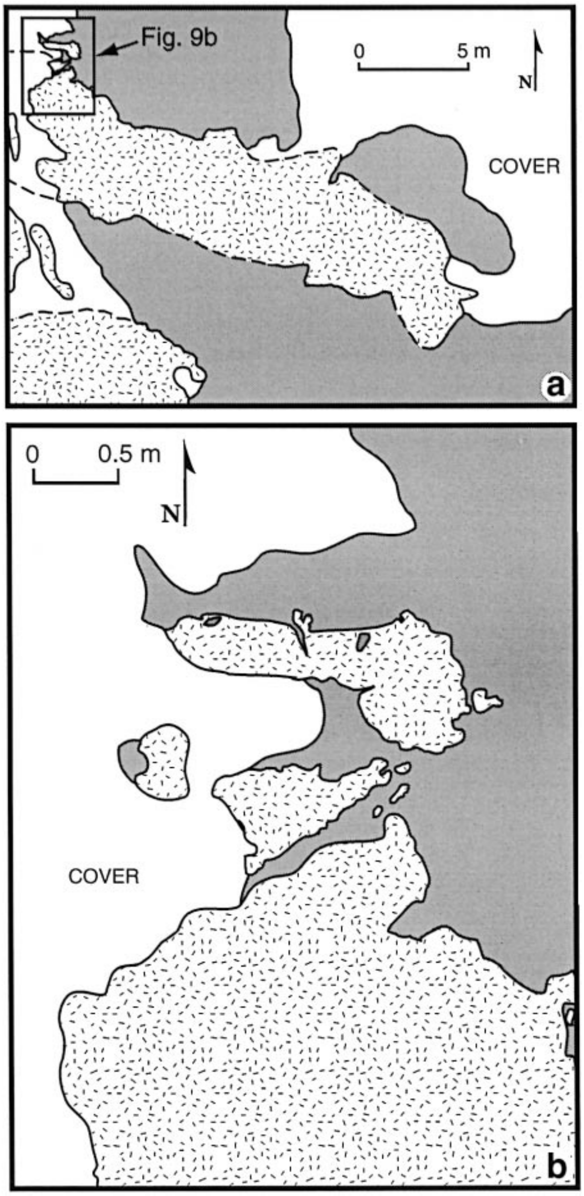

Fig. 9 **a** Tape-and-compass map of large andesite body (*light pattern*) within plagioclase-phyric andesite peperite. Corner of a second large body is visible at *lower left*. **b** Detailed sketch of irregular margin of body

cent sediment. Ellipsoidal to highly irregular, fluidal bodies down to a few centimetres long occur in close proximity to the larger bodies (Fig. 9b) and are inferred to represent small lobes or tongues connected to the larger bodies in three dimensions.

Plagioclase phenocrysts are typically aligned near the margins and in some places show a decrease in size toward the margins similar to that present in the smaller andesite clasts. As in the smaller clasts, the alignment is truncated in places by irregularities in the margins (Fig. 8b).

In general, no pattern is present in the distribution or orientation of the elongate andesite bodies. One exception occurs northwest of Huntley Mill Lake, where bodies 20–30 m long occur separately or in small groups spaced 100–250 m apart along a northwest trend (Fig. 2). Long axes of the bodies are aligned along this trend, implying that the bodies originally may have been continuous.

Interpretation and discussion

Emplacement of the Huntley Mill Lake intrusive complex

The Huntley Mill Lake complex records progressive emplacement of discrete magma batches to form a composite, high-level intrusion. Abundant development of peperite indicates that the host Tuttle Lake sediments were still wet and unconsolidated at the time of intrusion. The different intrusive phases have typical hypabyssal textures, except for the diorite. Intrusive relations in general indicate that the central diorite was emplaced after the augite-phyric andesite in the southern part of the complex. Because the plagioclase-phyric andesite to the north is directly related to the diorite, we infer that it also largely postdates the augite-phyric andesite. It is unknown whether the small augite-phyric andesite intrusions in the northern part of the complex were emplaced early and were engulfed by plagioclase-phyric andesite peperite, or whether they represent late-stage intrusions. In any case, we infer that the diorite solidified late in the development of the complex, after the host sediments had largely been dewatered. This allowed the diorite to develop a coarse-grained, phaneritic texture at shallow levels in the arc sequence.

Exact interpretations of the three-dimensional shape of the complex and the mechanisms involved in creating space for the intruding magma are impossible, because most of the crucial contacts either are not exposed, inaccessible, or have been cut out by younger plutons. Laterally extensive, mappable horizons of peperite at different levels in the augite-phyric andesite (Fig. 2) are consistent with progressive emplacement of this part of the complex as a thick, composite sill or laccolith. These horizons may represent septa of host sediment preserved during intrusion of a series of vertically stacked, partly coalescing, sill-like bodies (cf. Walker and Francis 1987).

In general, there is little evidence that forceful displacement of the host sediments was an important factor in making room for the intrusive complex (cf. Duffield et al. 1986). An exception is in the easternmost exposed part of the augite-phyric andesite, where emplacement of magma appears to have warped the adjacent sediments into a synform (Fig. 2). As discussed herein, there is evidence that fluidization of fine-grained host sediment along contacts with magma (cf. Kokelaar 1982) was at least locally important in facilitating intrusion during development of fluidal augite-phyric andesite peperite.

Formation of augite-phyric andesite peperite

Formation of fluidal andesite bodies

Highly irregular contacts between intrusive andesite and host sediment characterize fluidal and mixed blocky and fluidal peperite in the augite-phyric andesite. Such relations are interpreted to reflect an interplay between magma pressure, which provides the impetus for intrusion, and quenching of the magma, which impedes intrusion. Repeated outbreak of magma from new points creates a network of complexly shaped lobes, tongues, and apophyses separated and supported by the host sediment.

Globular forms of the type shown in Fig. 3b and c are similar to those described in other examples of fluidal peperite (e.g. Snyder and Fraser 1963; Brooks et al. 1982; Kokelaar 1982; Busby-Spera and White 1987; Riggs and Busby-Spera 1990; McPhie 1993; Rawlings 1993) and are also common in peperites elsewhere in the Tuttle Lake Formation (Templeton 1991; Mielke 1996). These globular bodies resemble pillows in some respects but are substantially smaller on average than normal pillows, and lack the elongate, cylindrical forms typical of pillows. Many of the intrusive bodies probably grew by expansion of a chilled, ductile crust, as occurs in small pillow buds (e.g. Moore and Lockwood 1978; Walker 1992). However, their formation is likely to differ in detail from growth of extrusive pillow buds because of marked contrasts in physical properties of the respective quenching agents (wet sediment vs water). Contact instabilities between dynamically interacting magma and wet sediment are inferred to play a major role in developing the complex intrusive geometries in fluidal peperite (cf. White 1996). We do not use the term "intrusive pillow" in referring to the small, globular intrusive bodies, in order to distinguish them from bodies formed where magma intruding wet sediment develops interconnected tubes similar in size and shape to normal extrusive pillows (e.g. Kano 1991).

Busby-Spera and White (1987) point out that development of fluidal peperite represents a type of fuel-coolant interaction in which magma invading wet sediment is insulated by a thin film of vapourized pore water (see also Kokelaar 1982; White 1996). This allows the magma to develop complex, fluidal or globular forms without undergoing brittle quench fragmentation, at least initially (Fig. 10a). During fuel-coolant interactions, oscillations in the vapour film along fuel (magma) surfaces may cause the fuel surface to develop small-scale instabilities, with detachment of fluidal droplets of fuel and intermixing with adjacent coolant (e.g. Wohletz 1986; Zimanowski et al. 1991). Such phenomena are believed to occur on the millimetre or submillimetre scale during phreatomagmatic interactions. They may provide an explanation for fine-scale irregularities along the margins of globular andesite bodies in fluidal augite-phyric andesite peperite, but they cannot account for the complex intrusive relations developed on a larger scale, which represent "coarse mixing" between fuel and coolant in the sense of White (1996). Coarse mixing of this type requires an external driving force (such as magma pressure), in contrast to fine-scale interactions driven by heat exchange between fuel and coolant (White 1996).

Development of fluidal peperite appears to be favoured where the host sediment is fine grained. In such cases fluidization of the sediment may occur (Kokelaar 1982; Busby-Spera and White 1987; Branney and Suthren 1988; Boulter 1993; Brooks 1995). Fluidization destroys sediment cohesion and may cause entrainment of the sediment particles in heated pore fluid streaming along intrusive contacts. This enables intricate, fine-scale intrusive relations between sediment and magma to develop (e.g. Fig. 3d). Progressive displacement of fluidized sediment allows intrusion to proceed without

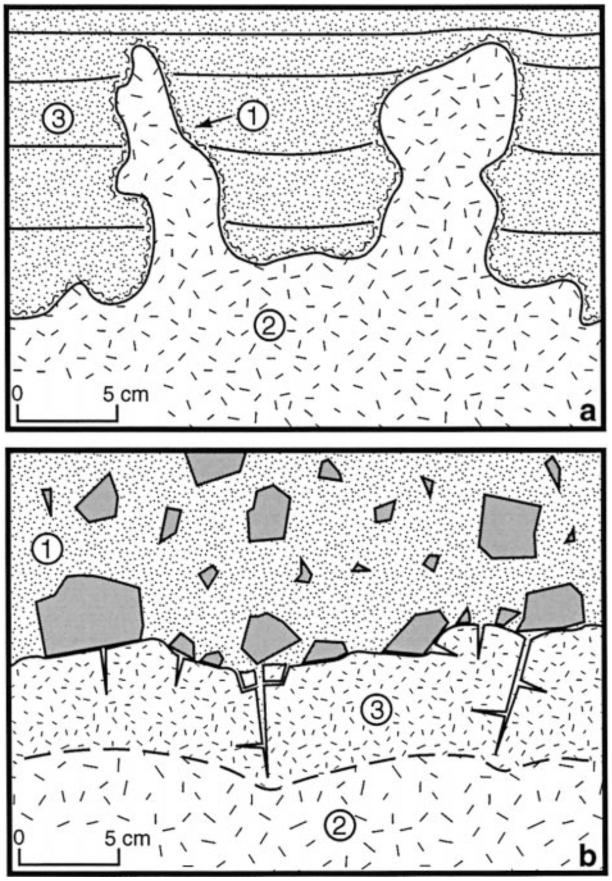

Fig. 10a, b Processes involved in formation of augite-phyric andesite peperite. **a** Formation of fluidal peperite. Thin, weak zone of fluidized sediment (*1*) develops along unstable contact between fluidal magma (*2*) and wet, fine-grained host sediment (*3*). This favours intrusion of magma as small, globular, interconnected bodies. Note truncation of relatively undisturbed lamination in host sediment. **b** Formation of blocky peperite. Coarse clasts (*dark grey*) in host tuff–breccia (*1*) inhibit fluidization of host sediment and impede advance of magma (*2*); chilled margin (*3*) undergoes fragmentation

disturbance to the remaining sediment host. Evidence for this process is the termination of laminae in host tuff against narrow zones of structureless tuff along intrusive margins (Fig. 5); these zones represent sites where sediment adjacent to intruding magma was homogenized. Identical relations have been described by Kokelaar (1982) and Branney and Suthren (1988), and examples also have been documented from peperites elsewhere in the Tuttle Lake Formation (Templeton 1991; Mielke 1996).

Formation of blocky and mixed blocky and fluidal peperite

Textures in blocky peperite record fragmentation of magma resulting from cooling across the brittle/ductile transition. In mixed blocky and fluidal peperite, shapes of the igneous clasts indicate that fluidal behaviour during initial contact with wet sediment preceded brittle fragmentation. The abundance of jigsaw-fit textures in this peperite type implies that quench fragmentation was an important clast-generating process (e.g. Hanson 1991; McPhie et al. 1993), probably occurring together with dynamic stressing of chilled margins (Kokelaar 1986). In typical blocky peperite, in contrast, fluidal forms are absent, and jigsaw-fit texture is only locally preserved. Mechanisms for generating chaotic textures in blocky peperite include minor steam explosions and/or progressive disruption of previously formed peperite masses during forceful emplacement of new magma pulses.

In the situation described by Busby-Spera and White (1987), fluidal peperite is restricted to areas where magma intruded fine-grained sediment, whereas blocky peperite formed where the same magma intruded lapilli-tuff and tuff-breccia. Analogous relations between peperite type and host sediment are present in the augite-phyric andesite. Busby-Spera and White (1987) suggested that the absence of fluidal peperite in coarse-grained sediment in their study area was due partly to the relatively high permeability of the ash-poor host, which allowed rapid escape of heated pore fluids and thereby inhibited formation of stable, insulating vapour films around intruding magma bodies. A permeability control was not important in our study area, because the high content of fine-grained tuff in the matrix of Tuttle Lake lapilli-tuffs and tuff-breccias would have given these beds similar low permeabilities to the tuff that hosts fluidal peperite. Direct grain-size effects are interpreted to be the main control on formation of blocky vs fluidal peperite in the augite-phyric andesite, reflecting the fact that coarser-grained sedimentary particles cannot be entrained in the streaming vapour films surrounding intrusive bodies (Fig. 10b; Kokelaar 1982; Busby-Spera and White 1987). This prevents development of an intricate network of small, fluidal intrusive bodies accommodated by weak, fluidized, fine-grained host sediment. The coarser clasts may impede advance of the magma, which develops a relatively thick chilled margin that undergoes brittle fragmentation by quenching and dynamic stressing (Fig. 10b).

Formation of plagioclase-phyric andesite peperite

Ellipsoidal andesite clasts in plagioclase-phyric andesite peperite are superficially similar in overall shape and size to globular andesite bodies in fluidal augite-phyric andesite peperite, but differ in a number of respects:

1. They lack amoeboid outlines, fine-scale crenulations along the margins and visible interconnections.
2. Plagioclase crystals in many of the clasts show an internal alignment parallel to some margins but truncated by other margins. The alignment may be accompanied by a decrease in phenocryst size near the margins.

3. The plagioclase-phyric andesite clasts show a zonal arrangement, in which areas of closely packed clasts generally surround coherent andesite intrusions or are developed along the northern margin of the central diorite. These areas grade outward into extensive masses of dispersed peperite, in which clasts are widely separated within host sediment.

We interpret the alignment of plagioclase phenocrysts to be the result of flow alignment of crystals within moving magma prior to disruption, and we interpret the decrease in size of phenocrysts near the margins to reflect flowage differentiation, in which mechanical forces acted to shunt coarser crystals inward from the margins during laminar transport of magma (Bhattacharji and Smith 1964). We infer that early stages in the development of this part of the Huntley Mill Lake intrusive complex involved penetration of the host Tuttle Lake sediments by networks of interconnected conduits through which andesite magma was transported to areas presently occupied by plagioclase-phyric andesite peperite (Fig. 11a). The large, elongate andesite bodies, which also show flow alignment and marginal flowage segregation of plagioclase phenocrysts, are interpreted to represent partly preserved segments of the magma conduits.

Some of the ellipsoidal andesite clasts probably were derived from lobate protrusions that developed along intrusive contacts during initial stages of magma-sediment interaction. Truncation of internal flow alignment along irregular margins of large, elongate andesite bodies (e.g. Fig. 8b) indicates places from which clasts were detached during disruption and dispersal of the andesite. Non-explosive disruption of interconnected feeder conduits and lobes by quench fragmentation and foundering within less dense host sediments, and sinking of detached fragments, may have played a role in mixing clasts of intrusive andesite within host sediment. However, had this been the sole mechanism of clast dispersal, intermediate stages of disruption of the interconnected feeder networks should be preserved. The absence of such features, and the common occurrence of widely dispersed clasts in host sediment far removed from obvious feeder conduits, argue for an explosive mechanism of clast dispersal. We infer that networks of interconnected feeder conduits were blasted apart by flashing of pore water in the host sediment to steam (Fig. 11). This is consistent with the absence of observed interconnections between ellipsoidal clasts, even where closely packed. The chaotic intermixing of two or more different subphases of plagioclase-phyric andesite within certain areas is interpreted to reflect explosive disruption of separate feeder systems that transported different magma batches into the same area. We infer that localized steam explosions affected different parts of the peperite mass at different times during its development. Local bedding in the host sediments parallel to regional bedding trends, partial preservation of larger, elongate andesite bodies, and local alignment of the long axes of these bodies suggest that steam explosions did not completely disrupt and homogenize the entire mass of plagioclase-phyric andesite peperite.

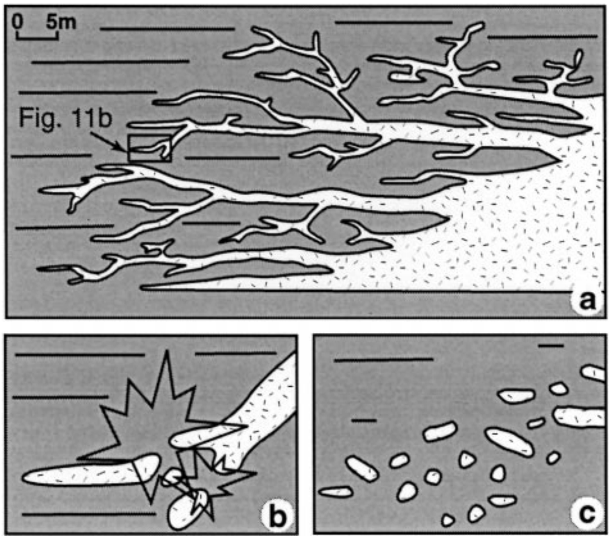

Fig. 11a–c Inferred mode of formation of plagioclase-phyric andesite peperite. **a** Initial propagation of andesite into host tuff–breccia as a branching network of feeder tubes and conduits. Horizontal lines indicate bedding in tuff–breccia. **b** Localized steam explosions in host sediment disrupt feeder network. **c** Resulting dispersal of andesite clasts and remnants of conduits within disrupted host sediment. Non-explosive quench fragmentation and foundering of magma conduits into less dense sediment may have contributed to disruption of conduits

Elongate, tongue-like clasts (Fig. 7b) may have been derived from small apophyses extending from feeder conduits. In many ellipsoidal clasts, the internal flow alignment is truncated at rounded margins (Fig. 6). We infer that these clasts were derived from magma in the feeder conduits that was only partly solidified at the time of conduit disruption, so that the clasts developed rounded margins due to surface-tension effects prior to complete cooling. Release of fragments of partly fluid magma preserving an internal flow alignment of crystals was possibly favoured by the high volume of coarse plagioclase phenocrysts (Table 1), which would help stiffen the magma during disruption (e.g. Arzi 1978). Preservation of jigsaw-fit texture in some clasts, and the presence of small pieces of andesite spalled from margins of larger clasts into the adjacent matrix, indicate that brittle failure affected many of the larger clasts following initial disruption.

Mappable, coherent intrusions of plagioclase-phyric andesite and diorite are interpreted to represent the main feeder conduits for the peperite. This is consistent with the zonal map pattern in the peperite, where closely packed peperite grades outward into dispersed peperite away from the margins of these intrusions. Such a distribution reflects disruption of smaller magma conduits and tongues that became progressively less abundant away from the main feeders.

Conclusion

The Huntley Mill Lake intrusive complex is one of only a limited number of published examples of large-scale magma/wet sediment interaction involving formation of extensive peperites or related intrusive hydroclastic breccias with volumes up to several cubic kilometres (e.g. Snyder and Fraser 1963; Hanson 1991; Hanson and Wilson 1993; Morgan 1997). Intermingling of magma and sediment on this scale requires environments in which thick sequences of wet sediment accumulate and are penetrated by large volumes of magma prior to lithification. Likely settings include the proximal, subaqueous parts of island arcs (as for the Huntley Mill Lake complex), volcanically active rift or pull-apart basins, and incipient spreading centres in back-arc basins or in narrow, Gulf-of-California-type ocean basins (e.g. Einsele et al. 1980). In such settings buoyancy factors associated with emplacement of magma into thick, unconsolidated sediments favour formation of shallow intrusions rather than extrusion of lava (McBirney 1963). Whether coherent hypabyssal intrusions or peperites develop probably depends on a variety of factors, including rate of magma supply, depth of intrusion and the physical properties of the magma and sediment/pore-fluid system. In any case, given the abundance of favourable settings in diverse tectonic environments, large-volume peperite is likely to be more common than generally appreciated and important in the facies architecture of many submarine volcanic sequences. Because of its complex internal make-up, large-volume peperite may be difficult to recognize in rocks that are poorly exposed or strongly deformed and metamorphosed. The abundance of peperite, including several large-scale examples, in the submarine Paleozoic and Mesozoic arc succession in the Northern Sierra terrane (e.g. Brooks et al. 1982; Hanson 1991; Templeton 1991; Hanson et al. 1996; Mielke 1996) is a case in point. Recognition of large-scale peperite and related intrusive hydroclastic breccia in this terrane has been favoured by excellent, glaciated exposure and structural simplicity.

Peperite in the Huntley Mill Lake intrusive complex displays a variety of features that reflect different styles of magma/wet sediment interaction. Fluidal peperite in the augite-phyric andesite developed small, globular andesite bodies, many of which were probably connected by thin necks. This peperite type was favoured by non-explosive intrusion of magma into fine-grained sediment susceptible to fluidization (cf. Busby-Spera and White 1987). Mixed blocky and fluidal peperite reflects an increase in the role of brittle fragmentation processes, involving both quench fragmentation and dynamic stressing of chilled margins (Kokelaar 1986). Such processes probably predominated in the formation of blocky peperite, which shows little evidence for precursor fluidal forms; possibly disruption of magma in this peperite type involved some steam explosivity.

Steam explosivity probably played an important role in formation of the extensive plagioclase-phyric andesite peperite making up the northern part of the Huntley Mill Lake intrusive complex. Because this peperite type shows wide dispersal of much of the disrupted intrusive andesite within coarse-grained host sediment, an intrusive origin is generally not obvious in single outcrops. Detailed mapping was required to demonstrate the intrusive origin of the plagioclase-phyric andesite clasts in this part of the complex.

We infer that initial stages in development of the plagioclase-phyric andesite peperite involved intrusion of magma into the host sediments as a series of interconnected, at least partly tubular, conduits. Similar intrusive magma tubes or tongues are associated with peperite in other parts of the Tuttle Lake Formation (Templeton 1991; Mielke 1996), and also occur in other examples of large-scale magma/wet sediment interaction (Hanson 1991; Hanson and Wilson 1993). In some cases, such feeder conduits are directly associated with compositionally similar but larger coherent hypabyssal intrusions, as in the Huntley Mill Lake complex, and these intrusions probably represent the main feeders for the associated peperitic masses. This is likely to represent a general pattern in large-scale peperite complexes, which may facilitate recognition of other examples in the stratigraphic record.

Acknowledgements This research was supported by NSF grant EAR 92–19096 to R. Hanson and D. Harwood. We are indebted to C. Jones for access to the Snow Mountain area, much of which is on his private property, and for his hospitality during the field work. D. Harwood first recognized that the hypabyssal rocks in this part of the Tuttle Lake Formation deserved further study and unselfishly shared his knowledge of the area with us, including results of his unpublished mapping. We acknowledge expert preparation of thin sections by W. Van Lohuizen. Thorough reviews by J. McPhie and J. White greatly improved the manuscript.

References

Arzi AA (1978) Critical phenomena in the rheology of partially melted rocks. Tectonophysics 44:173–184

Bhattacharji S, Smith CH (1964) Flowage differentiation. Science 145:150–153

Boulter CA (1993) High-level peperitic sills at Rio Tinto, Spain: implications for stratigraphy and mineralization. Trans Inst Min Metall 102:B30–B38

Branney MJ, Suthren RJ (1988) High-level peperitic sills in the English Lake District: distinction from block lavas, and implications for Borrowdale Volcanic Group stratigraphy. Geol J 23:171–187

Brooks ER (1992) Geology of the Eastern Belt of the northern Sierra Nevada. In: Schiffman P, Wagner DL (eds) Field guide to the geology and metamorphism of the Franciscan Complex and Western Metamorphic Belt of northern California. Calif Div Mines Geol Spec Publ 114:54–78

Brooks ER (1995) Paleozoic fluidization, folding, and peperite formation, northern Sierra Nevada, California. Can J Earth Sci 32:314–324

Brooks ER, Wood MW, Garbutt PL (1982) Origin and metamorphism of peperite and associated rocks in the Devonian Elwell Formation, northern Sierra Nevada, California. Geol Soc Am Bull 93:1208–1231

Busby-Spera CJ, White JDL (1987) Variation in peperite textures associated with differing host-sediment properties. Bull Volcanol 49:765–775

Duffield WA, Bacon CR, Delaney PT (1986) Deformation of poorly consolidated sediment during shallow emplacement of a basalt sill, Coso Range, California. Bull Volcanol 48:97–107

Einsele G et al. (1980) Intrusion of basaltic sills into highly porous sediments, and resulting hydrothermal activity. Nature 283:441–445

Fisher GR (1992) The Mt. Tallac roof pendant and its implications for the role of the Sailor Canyon basin in Jurassic Cordilleran tectonics. PhD thesis, University of Nevada, Reno, pp 1–265

Goto Y, McPhie J (1996) A Miocene basanite peperitic dyke at Stanley, northwestern Tasmania, Australia. J Volcanol Geotherm Res 74:111–120

Gradstein FM, Agterberg FP, Ogg JG, Hardenbol J, van Veen P, Thierry J, Huang Z (1994) A Mesozoic time scale. J Geophys Res 99:24051–24074

Hannah JL, Moores EM (1986) Age relationships and depositional environments of Paleozoic strata, northern Sierra Nevada, California. Geol Soc Am Bull 97:787–797

Hanson RE (1991) Quenching and hydroclastic disruption of andesitic to rhyolitic intrusions in a submarine island-arc sequence, northern Sierra Nevada, California. Geol Soc Am Bull 103:804–816

Hanson RE, Elliot DH (1996) Rift-related Jurassic basaltic phreatomagmatism in the central Transantarctic Mountains: precursory stage to flood-basalt volcanism. Bull Volcanol 58:327–347

Hanson RE, Schweickert RA (1982) Chilling and brecciation of a Devonian rhyolite sill intruded into wet sediments, northern Sierra Nevada, California. J Geol 90:717–724

Hanson RE, Schweickert RA (1986) Stratigraphy of mid-Paleozoic island-arc rocks in part of the northern Sierra Nevada, Sierra and Nevada Counties, California. Geol Soc Am Bull 97:986–998

Hanson RE, Wilson TJ (1993) Large-scale rhyolite peperites (Jurassic, southern Chile). J Volcanol Geotherm Res 54:247–264

Hanson RE, Girty GH, Girty MS, Hargrove US, Harwood DS, Kulow MJ, Mielke KL, Phillipson SE, Schweickert RA, Templeton JH (1996) Paleozoic and Mesozoic arc rocks in the Northern Sierra terrane. In: Girty GH, Hanson RE, Harwood DS, Schweickert RA (eds) The Northern Sierra terrane and associated Mesozoic magmatic units: implications for the tectonic history of the western Cordillera. Pacific Section SEPM Book 81:25–55

Hargrove US (1995) Geology of the Huntley Mill Lake sill complex: a multiphase peperitic sill intruded into wet sediments, Jurassic, northern Sierra Nevada, California. BA thesis, Texas Christian University, Fort Worth, pp 1–80

Harwood DS (1992) Stratigraphy of Paleozoic and lower Mesozoic rocks in the Northern Sierra terrane, California. US Geol Surv Bull 1957:1–78

Kano K (1989) Interactions between andesitic magma and poorly consolidated sediments: examples in the Neogene Shirahama Group, South Izu, Japan. J Volcanol Geotherm Res 37:59–75

Kano K (1991) Miocene pillowed sills in the Shimane Peninsula, Japan. J Volcanol Geotherm Res 48:359–366

Kokelaar BP (1982) Fluidization of wet sediments during the emplacement and cooling of various igneous bodies. J Geol Soc Lond 139:21–33

Kokelaar BP (1986) Magma–water interactions in subaqueous and emergent basaltic volcanism. Bull Volcanol 48:275–289

Kokelaar BP, Bevins RE, Roach RA (1985) Submarine silicic volcanism and associated sedimentary and tectonic processes, Ramsey Island, SW Wales. J Geol Soc Lond 142:591–613

Korsch RJ (1984) The structure of Shapeless Mountain, Antarctica, and its relation to Jurassic igneous activity. N Z J Geol Geophys 27:487–504

Kulow MJ (1996) Geology, petrology, age, and intrusive relations of Cretaceous plutons in the Donner Lake–Cisco Grove area, northern Sierra Nevada, California. MS thesis, Texas Christian University, Fort Worth, pp 1–122

Lorenz BE (1984) Mud-magma interactions in the Dunnage Mélange, Newfoundland. In: Kokelaar BP, Howell MF (eds) Marginal basin geology. Geol Soc Lond Spec Publ 16:271–277

Macdonald GA (1939) An intrusive peperite at San Pedro Hill, California. Univ Calif Publ Geol Sci 24:329–337

McBirney AR (1963) Factors governing the nature of submarine volcanism. Bull Volcanol 26:455–469

McPhie J (1993) The Tennant Creek porphyry revisited: a synsedimentary sill with peperite margins, Early Proterozoic, northern Territory. Aust J Earth Sci 40:545–558

McPhie J, Doyle M, Allen R (1993) Volcanic textures: a guide to the interpretation of textures in volcanic rocks. Center for Ore Deposit and Exploration Studies, University of Tasmania, Hobart, pp 1–196

Mielke KL (1996) Paleovolcanology, petrology, stratigraphy, and structure of Jurassic and Cretaceous island-arc rocks in the Webber Peak and Meadow Lake areas, Nevada and Sierra Counties, Northern Sierra terrane, California. MS thesis, Texas Christian University, Fort Worth, pp 1–109

Mielke K, Hanson R, Girty G, Girty M, Schweickert R (1995) Paleovolcanology and regional stratigraphic significance of Jurassic and Cretaceous island-arc rocks in the Webber Peak Quadrangle, Northern Sierra terrane, California. Geol Soc Am Abstr Programs 27:64

Moore JG, Lockwood JP (1978) Spreading cracks on pillow lava. J Geol 86:661–671

Morgan EJ (1997) Early Devonian subaqueous andesitic volcanism in the New England Fold Belt, eastern Australia. Aust J Earth Sci 44:227–236

Rawlings DJ (1993) Mafic peperite from the Gold Creek Volcanics in the Middle Proterozoic McArthur Basin, Northern Territory. Aust J Earth Sci 40:109–113

Riggs NR, Busby-Spera CJ (1990) Evolution of a multi-vent volcanic complex within a subsiding arc graben depression: Mount Wrightson Formation, Arizona. Geol Soc Am Bull 102:1114–1135

Schmincke H-U (1967) Fused tuff and peperites in south-central Washington. Geol Soc Am Bull 78:319–330

Schweickert RA (1996) Tectonic setting of the Triassic to Jurassic magmatic arc and its basement. In: Girty GH, Hanson RE, Harwood DS, Schweickert RA (eds) The Northern Sierra terrane and associated Mesozoic magmatic units: implications for the tectonic history of the western Cordillera. Pacific Section SEPM Book 81:57–75

Smedes HW (1966) Geology and igneous petrology of the northern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana. US Geol Surv Prof Pap 510:1–116

Snyder GL, Fraser GD (1963) Pillowed lavas. I. Intrusive layered lava pods and pillowed lavas, Unalaska Island, Alaska. US Geol Surv Prof Pap 454-B: 1–23

Templeton JH (1991) Submarine volcanism and volcaniclastic sedimentation in a Jurassic island-arc environment, northern Sierra Nevada, California. MS thesis, Texas Christian University, Fort Worth, pp 1–134

Templeton JH, Hanson RE (1991) Extensive magma/wet-sediment interaction in a Jurassic island-arc setting, northern Sierra Nevada, California. Geol Soc Am Abstr Programs 23:A395

Walker BH, Francis EH (1987) High-level emplacement of an olivine–dolerite sill into Namurian sediments near Cardenden, Fife. Trans R Soc Edinburgh Earth Sci 77:295–307

Walker GPL (1992) Morphometric study of pillow-size spectrum among pillow lavas. Bull Volcanol 54:459–474

White JDL (1996) Impure coolants and interaction dynamics of phreatomagmatic eruptions. J Volcanol Geotherm Res 74:155–170

White JDL, Busby-Spera CJ (1987) Deep marine arc apron deposits and syndepositional magmatism in the Alisitos Group at Punta Cono, Baja California, Mexico. Sedimentology 34:911–927

Wohletz KH (1986) Explosive magma–water interactions: thermodynamics, explosion mechanisms, and field studies. Bull Volcanol 48:245–264

Yamagishi H (1991) Morphological and sedimentological characteristics of the Neogene submarine coherent lavas and hyaloclastites in Southwest Hokkaido, Japan. Sediment Geol 74:5–23

Zimanowski B, Frölich G, Lorenz V (1991) Quantitative experiments on phreatomagmatic explosions. J Volcanol Geotherm Res 48:341–358