Variation in peperite textures associated with differing host-sediment properties

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Abstract. Peperites formed by mixing of magma and wet sediment are well exposed along Punta China, Baja California, Mexico, where two sills intrude a section of lava flows, limestones, and volcaniclastic rocks. Irregular lobes and dikes extend from the sills several meters into host sediments, including highly comminuted flow top breccias (lithic lapilli tuff breccias) and shelly micrites, whereas intrusive contacts with lava flows are sharp and planar. Where one sill intruded both coarse-grained volcaniclastic rock and fine-grained limestone, textural differences between the hosts produced strikingly different styles of peperite. Blocky masses of the basaltic intrusions up to 1 m in size were dispersed for distances up to 3 m into host lithic lapilli tuff breccias; the blocks consequently underwent in situ fragmentation as they were rapidly quenched. The high degree of dispersion resulted from steam explosions as the magma enveloped pockets of water in the coarse-grained permeable host. Elutriation of fine-grained material from vertical pipes in tuff breccia above the lower sill provides evidence for meter-scale fluidization of the host. The contact zone between the basaltic magma and the shelly micrite host resembles a mixture of two viscous, immiscible fluids (fluidal peperite). Intrusion occurred behind a stable vapor film which entrained lime mud particles and carried them off "grain by grain" as magma advanced into the host. Thin-section-scale elutriation pipes formed. Microglobular peperite represents a "frozen" example of a fuel-coolant interaction (FCI) between basaltic magma and fluidized micrite host. The intimate intermixing of magma and host at the submillimeter level is attributed to fluid instabilities developed along the magma-vapor-host interface.

Such intimate intermixing of magma and water-bearing fragmental debris is commonly a precursory step toward explosive hydrovolcanism.

Introduction

Peperites are formed by mixing of magma and wet sediment. They are useful for demonstrating contemporaneity of volcanism and sedimentation, but are commonly mistaken for epiclastic breccias or nonintrusive volcanic products. We recently identified peperitic margins on sills at the type locality of the Alisitos Group (Allison 1955) 25 km south of Ensenada (Fig. 1). These sills intruded a 100-m-thick section of volcaniclastic rocks, limestones, and lava flows interpreted here as beach to nearshore deposits. Very complex contact relationships between the intrusions and the wet, unconsolidated volcanogenic and biogenic sedimentary host resulted. We summarize features that can be used to distinguish peperites from younger intrusions emplaced after lithification of sediment. Microglobular peperite is decribed for the first time and interpreted as an example of a "frozen" fuel-coolant interaction (FCI).

Geological setting

Mesozoic metavolcanic and interstratified metasedimentary rocks outcrop over an area of approximately 18000 km^2 in the western wall of the Peninsular Range in northern Baja California. Sections containing Lower Cretaceous biohermal limestones are mapped as Alisitos Group (Silver et al. 1963; Beggs 1983). Near Punta Cabras the Alisitos Group has yielded a U-Pb zircon age of
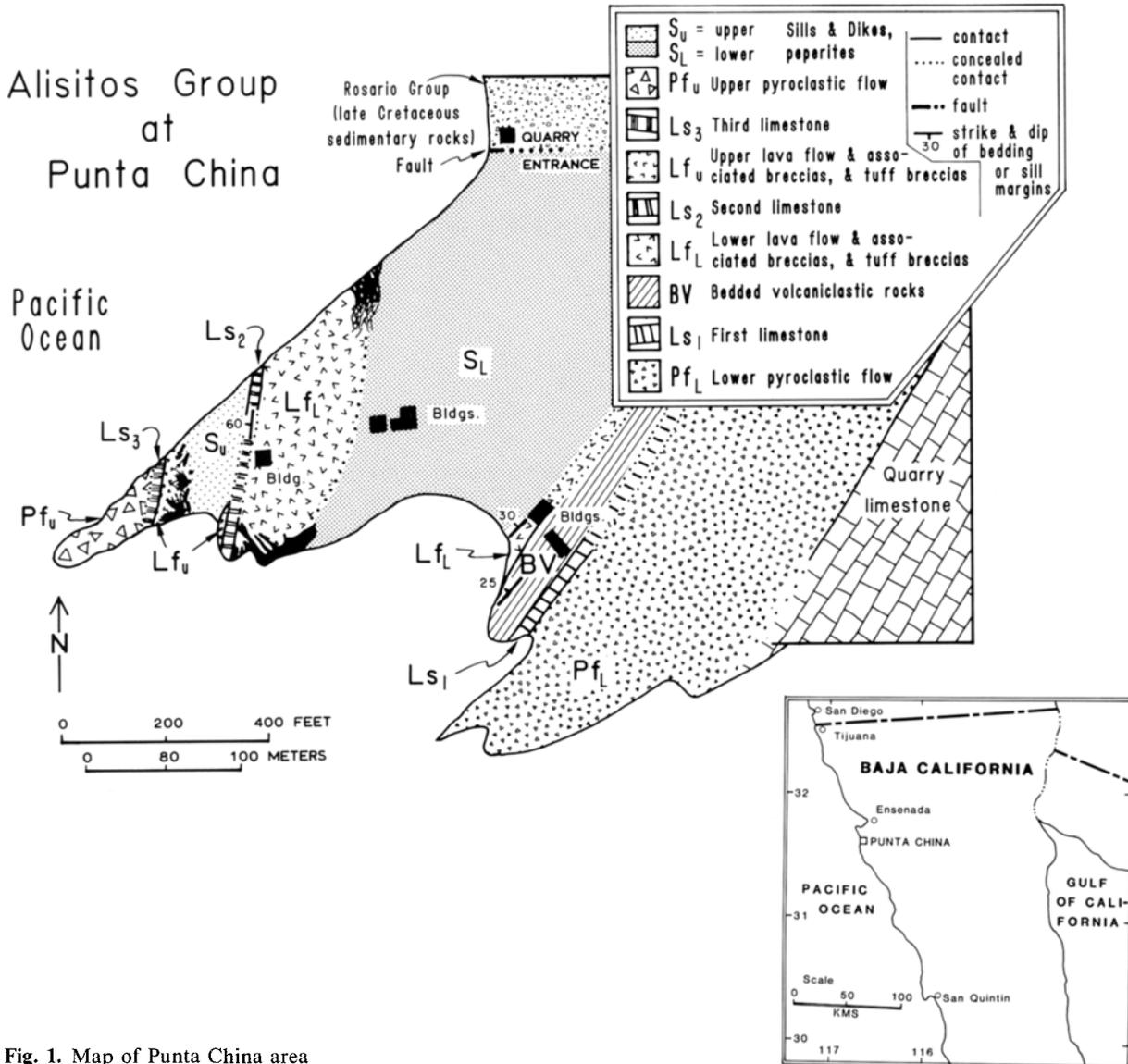
Alisitos Group at Punta China

Fig. 1. Map of Punta China area

127 ± 5 Ma from a tuff and is intruded by an epizonal pluton with a U-Pb zircon age of 115 ± 2 Ma (Silver et al. 1969; Silver et al., in Gastil et al. 1975).

The degree of metamorphism in the Alisitos Group generally decreases from the Peninsular Range batholith westward toward coastal exposures. Rocks in the Punta China area have experienced only diagenetic alteration, and primary microtextures are well preserved (Table 1).

Stratigraphy of volcanic, volcaniclastic, and bioclastic rocks

The peperites at Punta China are developed within the uppermost 100 m of the Alisitos Group

in its type area at Arroyo Santo Tomas. The section overlies 210 m of mid-Albian caprinid limestone and is exposed along the rocky headland of Punta China (Fig. 1). Petrographic, textural, and sedimentological characteristics of this section are summarized in Table 1 and Fig. 2.

Limestones 3–5 m thick dominated by bivalves in growth position with lesser gastropods and minor corals lie near the base, middle, and top of the Punta China section (Fig. 1). Discontinuous layers of shelly micrite and minor shale are also present. The lava flows have thick, irregular pockets of highly comminuted material, referred to here as lithic lapilli tuff breccia (see Fig. 3). Lithic lapilli tuff breccia makes up most of each lava flow unit and is a mixture of blocky to vesicular basalt clasts set in a matrix of more highly com-

Table 1. Petrographic, textural, and sedimentological characteristics of volcanic and volcaniclastic rocks, Alisitos Group at Punta China, Baja California, Mexico (map units of Fig. 3; terminology follows Fisher and Schmincke 1984)

	Textural and field characteristics	Groundmass and alteration products	Accidental fragments
Pyroclastic flow deposits (Pf_u & Pf_l)	Unsorted mixture of basaltic scoria (highly inflated, but not foamy, juvenile fragments) and ash (mostly shards, platy or gently curving, but rarely Y-shaped). Lesser plastically deformed non-vesiculated to scoriaceous oxidized mafic fragments present (spatter). Indistinct alignment of flat clasts, very thick beds (flow units) locally marked by changes in grain size	Scoria (tachylite; mafic glass rendered nearly opaque by iron oxides) or fine-grained smectite-chlorite with lesser intergrown fine-grained hematitic quartz. Some extremely irregular fragments welded or agglutinated to others (spatter), particularly in Pf_u. Phenocrysts (plagioclase)	1. Volcanic lithic fragments with aligned or random plagioclase microlites plus plagioclase phenocrysts 2. (in Pf_u only) minor clasts of myrmekitic granite
Bedded volcaniclastics (BV)	Massive to cross-laminated beds of angular, poorly sorted sand-to-pebble-sized volcanic rock fragments mixed with shells and shell fragments	Scoria (tachylitic) with delicate margins preserved; rare plastically deformed clasts (spatter) in massive beds. Lesser angular to subrounded volcanic rock fragments include mafic to intermediate with trachytic or felted texture and felsic with quartzo-feldspathic mosaic in groundmass	Variety of lithic fragments and absence of shards warrants use of clastic rather than pyroclastic terminology
Lava Flow Lithic Lapilli Tuff Breccia Units (Lf_u & Lf_l)	Reddish-black scoriaceous to vesicular mafic lava flows with irregular, highly comminuted material: matrix-supported lithic lapilli tuff breccias or clast-supported agglomerates (blocks up to 1 m in size). Lf_u has some plastically deformed clasts (spatter) near the top, and clasts at the top are locally rounded	Sparse phenocrysts of plagioclase, flow alignment of plagioclase microlites	Amygdule fillings are calcite + laumontite or chlorite-smectite linings filled with calcite or fine-grained quartz-albite intergrowths (same as linings filled with laumontite)
Penecontemporaneous intrusions (lower sill and upper sill)	Massive horizontally and vertically jointed sills with extremely irregular upper contacts (peperites). No amygdules. Interiors brown, peperite margins black	Sparse phenocrysts of plagioclase and minor clinopyroxene; higher phenocryst content in upper sill than lower sill. Groundmass is tachylitic at peperite margins only; microlites of plagioclase and lesser clinopyroxene, chlorite-smectite alteration	

minuted basalt. Plastically deformed clasts (spatter) occur at the top of the lithic lapilli tuff breccia on the lower flow unit. The basalt flows bear sparse plagioclase phenocrysts and show flow alignment of plagioclase microlites.

Both lava flows were intruded by basalt sills that formed peperites where they came into contact with unconsolidated, water-saturated lithic lapilli tuff breccia and shelly micrite. Except along peperitic margins, the sills are somewhat coarser grained than the flows, lack vesicles, and

show weakly developed cooling joints. In addition to plagioclase phenocrysts, the sills contain clinopyroxene phenocrysts and thus cannot represent the liquid interiors of the same flows. The groundmass of the sills is tachylitic at the peperite margins; elsewhere it shows plagioclase and clinopyroxene microlites.

Very thick, nonstratified horizons of unsorted scoria and ash are interpreted here as pyroclastic flows (Pf_L and Pf_u, Fig. 1 and Table 1). These locally contain scoria that agglutinated during em-
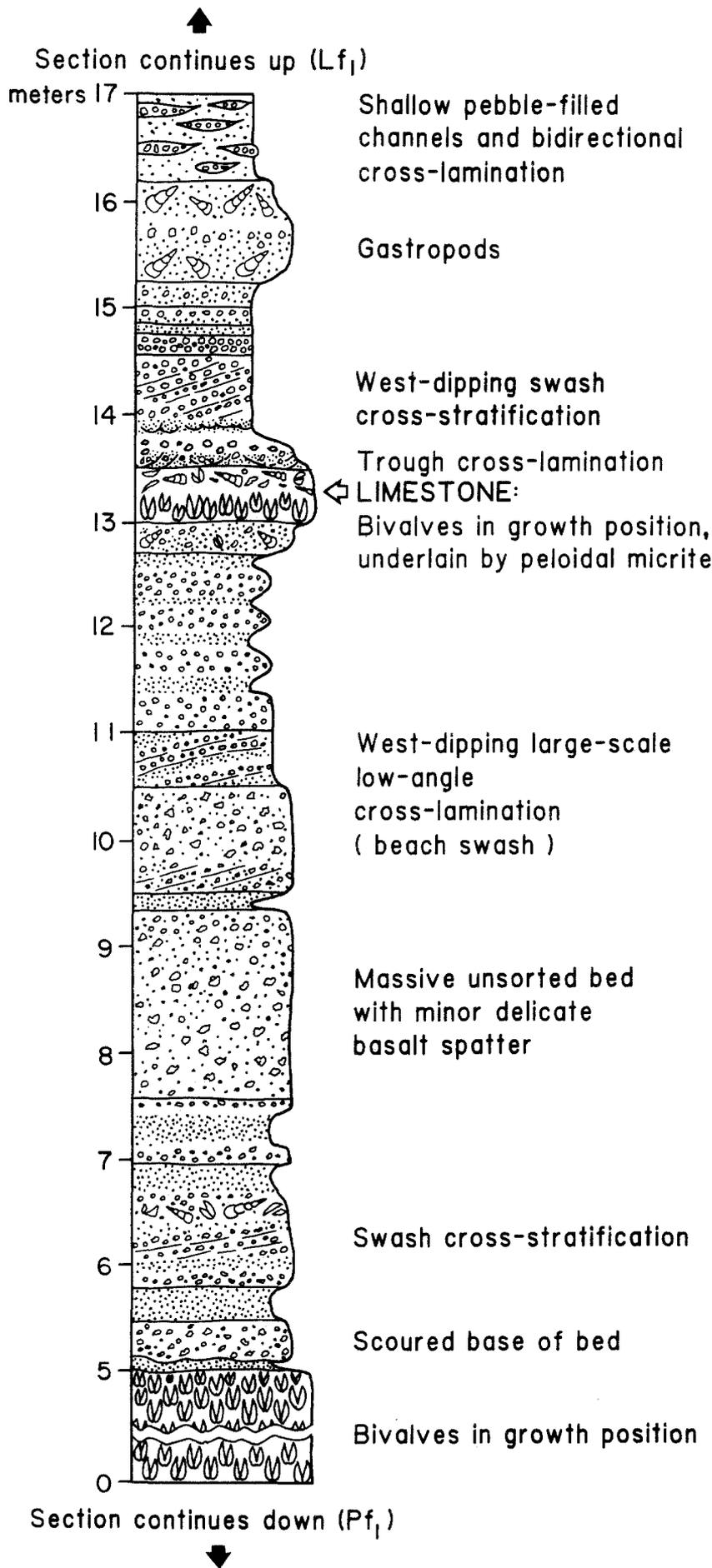
Section continues up (Lf₁)

meters 17

Shallow pebble-filled
channels and bidirectional
cross-lamination

16

Gastropods

15

West-dipping swash
cross-stratification

14

Trough cross-lamination
⇦ LIMESTONE:
Bivalves in growth position,
underlain by peloidal micrite

13

12

West-dipping large-scale
low-angle
cross-lamination
(beach swash)

11

10

Massive unsorted bed
with minor delicate
basalt spatter

9

8

7

Swash cross-stratification

6

Fig. 2. Measured section of bedded vol-
caniclastic rocks along the coast at Punta
China (map unit BV). Angular sand-to-
pebble-sized black and reddish orange
aphanatic volcanic rock fragments, mixed
with shells and shell fragments, form
poorly sorted, medium to thick beds that
are massive to cross laminated. Sorting
improves and stratification and cross-
stratification increase upsection

Scoured base of bed

5

Bivalves in growth position

0

Section continues down (Pf₁)

Fig. 3. Clast-supported lithic lapilli tuff breccia developed by comminution of the top of the lava flow

placement as molten ejecta (spatter; see Table 1). The bedded volcaniclastic section (Fig. 2) records reworking of volcanic detritus, supplied largely by pyroclastic (scoria) flows, in a fluctuating nearshore to beach environment. Detritus accumulated too quickly to allow much rounding or sorting of clasts or buildup of reefs, and minor spatter in the massive, unsorted beds near the base of the bedded section indicates contemporaneous volcanism. Intense fragmentation of the lava flow units occurred as the flows, already highly vesiculated by magma volatiles, interacted with water in the littoral environment. Carbonate deposition rates reported in Wilson (1975) suggest that each limestone bioherm in the Punta China section could have accumulated in fewer than 1000 years. Rapid development of the relatively rigid limestone bioherms above loosely compacted micritic muds controlled the pathways of magma intrusion at very shallow levels, as discussed below.

Penecontemporaneous intrusions

Both basalt sills at Punta China intruded lava flow-lithic lapilli tuff breccia units (Lf_L and Lf_U, Fig. 1). In each case, the base of the sill is in sharp, planar contact with relatively unfragmented lava flow whereas the top intrudes highly comminuted material (agglomerate and lithic lapilli tuff breccia) and is extremely irregular, with peperite developed. The lower sill also penetrated the lower lava flow to form peperite in a shelly

micrite horizon that lies between the flow and an overlying rudistid reef (Ls_2, Fig. 1). Peperite developed in the fine-grained micrite host is strikingly different from that in the volcaniclastic host. The fact that the sill produced peperite at the base of this bedded, otherwise undisturbed limestone provides further evidence that the sill does not simply represent the liquid interior of a flow penetrating its own debris. The sill was produced during a second magmatic episode, which occurred after the growth of a several meter thick bivalve biotherm. Differences in peperite style associated with the different hosts at Punta China are summarized in Table 2.

Peperites in agglomerate and lithic lapilli tuff breccia host

The upper contact of the lower sill locally intrudes brecciated rock and clast-supported breccias (lava flows and agglomerates) with irregular pockets of highly communited material (lithic lapilli tuff breccia). The contact is a 12-m-thick, complexly diked and silled zone (Fig. 1) with intrusions that thicken, thin, twist, and turn over distances of meters. The margins of the dikes were fragmented in situ as they quenched. Anastamosing brecciated zones with "jigsaw puzzle clasts" cut the dikes; these consist of jagged polyhedral fragments, millimeters to decimeters in size, that have moved so little with respect to one another that they could be fitted back together into their prefragmentation configuration. The fine-grained

Table 2. Peperite characteristics observed at Punta China, Baja California, Mexico, with inferred processes of development. More detailed explanations in text

	Fluidal peperites microglobular	globular	Blocky, hydroclastic peperites blocky	dispersed
Host	unconsolidated micrite, very fine grained, well sorted		lithic lapilli tuff breccia, coarse-grained, poorly sorted but generally ash poor	
Peperite fragment shape	small (mm scale) microfluidal	medium (cm-dm scale) macrofluidal	small (mm scale) angular fragments	large (dm-m scale) angular blocks
Fluidization pipes		millimeterscale only		meter-scale pipes
Host permeability		very low (millidarcys?)		very high (tens of darcys*)
Host water content		high (40%) diffuse		high (30%) localized
Peperite fragment-forming mechanism	fluid interface instabilities	fluid interface instabilities (?)	dynamic stressing, granulation	steam explosions
Mixing mechanisms	immiscibility, fluidization, "oscillation-pumping"	immiscibility, fluidization, fluid density differences	dynamic or unmixed	steam explosions, fluidization

* Permeability estimate for lithic lapilli tuff breccia extrapolated form values for uncompacted modern sands (Pettijohn et al. 1972)
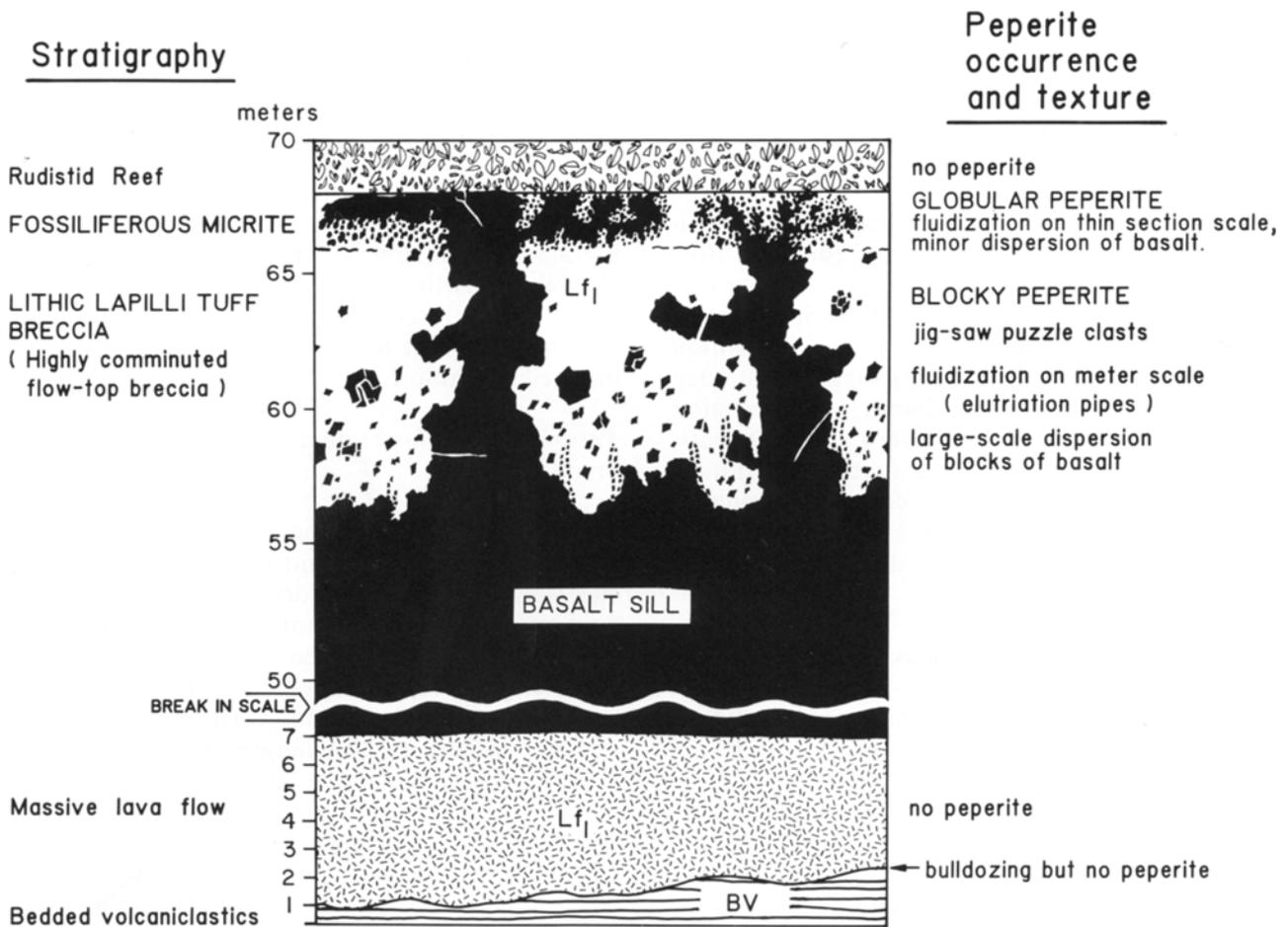

Fig. 4. Schematic illustration of peperite textures at Punta China, top of unit S_L (Fig. 1)

material between the jigsaw puzzle clasts varies from host material, which injected the dikes, to sill material, which granulated during interactions between magma and water.

The upper contact of the lower sill elsewhere intrudes matrix-supported lithic lapilli tuff breccia. Irregular lobes of the sill extend several meters into the host, and blocky masses of the sill up to 1 m in size were dispersed up to 3 m farther into the host (Fig. 4). These masses consequently underwent in situ fragmentation to form jigsaw puzzle clasts as they were quenched. Dikes emanate from the sill, and dike margins and terminations are also very irregular. Discontinuous dikes that emanate upsection from the upper contact of the sill are encased in and associated with vertical elutriation pipes developed in the lithic lapilli tuff breccia host (Fig. 4). In these pipes, ash-sized material was winnowed away, leaving behind a concentration of larger clasts (Fig. 5). Dikes extending from the main sill have cracks injected with host sediment (Fig. 4).

Near the tip of Punta China (Fig. 1), the upper contact of the upper sill intrudes clast-supported breccia (agglomerate) that passes upward into matrix-supported breccia (lithic lapilli tuff breccia). Complex relations become more intricate upsection, with bulbous fingers and stringers, as the grain size of the host decreases.

Peperites in shelly micrite host

Dikelike protrusions from the lower sill rise verti-cally through 10 m of lithic lapilli tuff breccia to penetrate an overlying 2-m-thick shelly (fossiliferous) micrite horizon (Fig. 4). The magma was apparently unable to penetrate the bivalve biotherm that overlies the micrite horizon, probably because the bioherm formed a rigid framework due to interlocking of shells or early cementation, or both. Instead, the magma spread laterally along the base of the bioherm and dribbled back down into the shelly micrite in irregular droplets, shown schematically in Fig. 4.

At outcrop scale, the contact zone between the intrusion and the shelly micrite host sediment resembles a mixture of two immiscible fluids of similar viscosity with "globules" of basalt enclosed in micrite and vice versa (Fig. 6). Tachylitic basalt glass intrudes and surrounds micrite that shows absolutely no recrystallization or other alteration at the tachylite/micrite contacts. These textures are similar to globular peperite described by Brooks et al. (1982); spalled margins, blocky fragments, and jigsaw puzzle clasts are absent or very poorly developed within it. Microglobular peperite (Fig. 7) locally occurs within the zone of globular peperite at Punta China. The "microglobules" of micrite within basalt are similar in appearance to sedimentary or authigenic infilling of vesicles, but examination of thin sections reveals no geopetal structures or unfilled vesicles, nor are cement-filled vesicles present. Furthermore, globules of basalt occur in the micrite, which is not vesicular.

There is much less dispersion of magma

Fig. 5. Fluidization elutriation ("drilling") pipes developed above main body of S_L within lithic lapilli tuff breccia host. Lightcolored zones have been elutriated of fines by upward-flowing steam. *Dark areas* represent clast concentrations between elutriated zones. Drilling is best developed in coarse, permeable lithic lapilli tuff breccia host near the main body of the intrusion

Fig. 6. Peperite with globular texture developed where sill S_L intrudes shelly micrite. Note extremely irregular peperite margins and absence of blocky, hydroclastic fragments
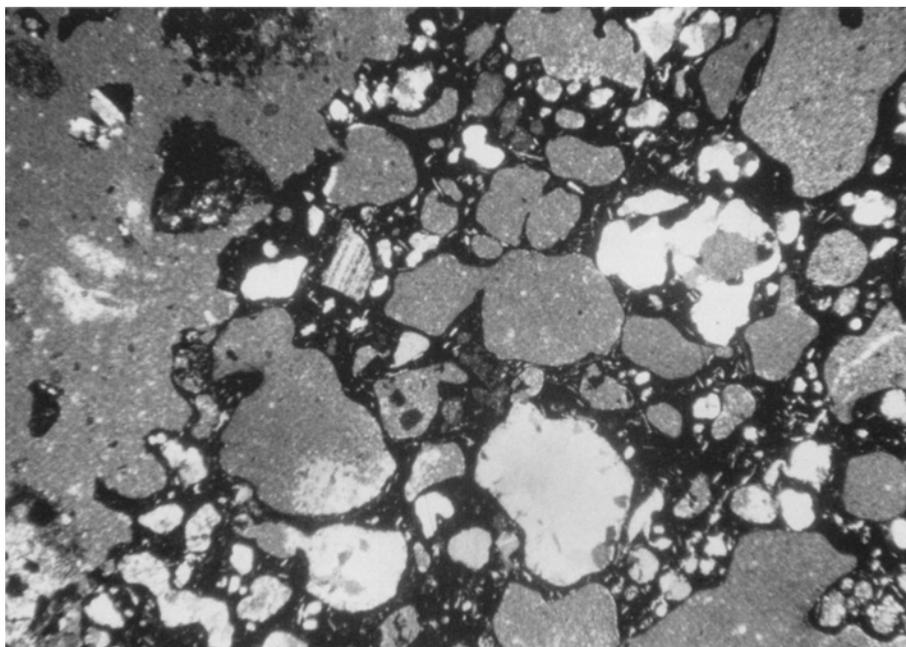

Fig. 7. An extremely well-developed microglobular peperite from Punta China, Baja California, Mexico. The envelopment of micrite by highly fluidal magma is accomplished by fluidization of the host sediment at the magma-wet sediment interface. Micrite particles are removed grain by grain along the interface in a steam and sediment carapace that also serves to insulate the magma against sudden cooling (hence the absence of quench fragmentation). Coarse-grained calcite is neomorphic spar formed by recrystallization of micrite. The photomicrograph (crossed polars) is 6.2 mm in long dimension

through the host sediment away from the intrusive bodies in the shelly micrite host than in the underlying lithic lapilli tuff breccia host (Fig. 4). Elutriation pipes are not apparent at the outcrop, but in thin section concentrations of shell fragments, elutriated of micrite, form pipelike structures above and along millimeter-thin stringers of basalt.

Discussion

The broad class of peperites includes products of any form of magma-wet sediment mixing. Hydroclastic peperites have blocky clasts formed by fragmentation of water-chilled magma. Fluidal (globular) peperites have clasts shaped by effects of surface tension into droplike bodies. Fluidal

peperites form only if a water-vapor film can be maintained more or less continuously at the magma-sediment interface, effectively insulating the magma. The vapor film prevents the magma from being hydroclastically fragmented by thermal shocking, which results from rapid contraction upon cooling.

Peperites described in the literature fall largely into two categories, i.e., those with blocky, jigsaw puzzle fragments (Hanson and Schweickert 1983; Brooks et al. 1982; Kokelaar 1982; Smedes 1966), and those with "pillowy", globular ones (Brooks et al. 1982; MacDonald 1939; Kokelaar 1982; Smedes 1966). In most cases, both blocky and globular fragments are reported, with pillowy fragments mixed with smaller blocky fragments derived in part from brecciation of the pillows (Schmincke 1967; Brooks et al. 1982; Kokelaar 1982).

Fluidal (globular) peperite

Fluidal peperites can be interpreted in terms of "frozen" fuel-coolant interactions (FCI's) with tiny, transportable particles of the sedimentary host viewed as essentially accidental components of the (fluid) coolant. Fuel-coolant interactions occur when a hot liquid (fuel) contacts a cooler liquid (coolant) whose vaporization temperature is less than the fuel temperature. The spectrum of fuel-coolant interactions ranges from nonexplosive vaporization of coolant along the fuel-coolant interface, to highly explosive interactions in which mixing of the fuel and coolant accompanies rapid transfer of heat from the fuel to the coolant, resulting in sudden vaporization of the coolant and explosive disruption of the system (Wohletz 1986).

The intact stratigraphy (fragmented lava flow overlain by shelly micrite overlain by pelecypod bioherm; Fig. 5) in which the Punta China fluidal peperites developed suggests that magma emplacement was relatively passive. In order for fluidal, nonexplosibe globular peperite to develop during passive emplacement of magma into wet sediment, a vapor film must form and persist at the magma-wet sediment contact. Kokelaar (1982) describes the specific process of fluidal penetration of magma into wet sediment and suggests that it occurs by displacement of host material within the vapor film. This process works especially well in fine-grained, well-sorted, loosely packed sediment (such as micritic muds) in which grain-by-grain particle entrainment can occur

within the vapor film. Sediment displacement occurs as sediment is removed along the vapor film at the magma-wet sediment interface. Displaced sediment moves laterally along this contact until lower temperatures allow the steam generated at the contact to condense and deposit its entrained sediment. Steam which "attempts" to move away from the contact into cold host sediment condenses. Steam moving laterally along the contact is thus preferentially preserved, and it accounts for the bulk of steam movement and sediment transport.

The interfacial steam-sediment slurry may locally "drill" outward into the host, producing relatively coarser-grained fluidization pipes which have been elutriated of fine material by the through-flowing steam (Kokelaar 1982). In some cases, thin stringers of magma are also stretched out within the outward-rushing slurry. In the shelly micrite host at Punta China, such fluidization pipes are very small (thin-section scale). "Drilling" can occur only if the host penetrated by the drilling is near boiling temperature, "otherwise the vapour generated ... would (condense)" (Kokelaar 1982, p. 28). The fluidization pipes could only have formed where the host was in a state of quiescent fluidization (Kunii and Levenspiel 1969); that is, where upward fluid flow supported the grains to the extent that particles were free to move, but little mixing occurred.

Fluidization of micrite close to the magma-host contact not only faciliated "drilling", but also allowed microglobular peperite to form by fluidal mixing. Experimental data show that when magma encounters a fluid coolant, oscillation of the vapor film along the magma-host interface distorts the magma's surface into an irregular, wavy surface, parts of which may grow and detach themselves as tiny, fluidal magma "fragments" (Wohletz 1986). The intimate intermixing of magma and micrite at Punta China suggests that the same process can occur within magma-fluidized host systems. Repitition of the oscillations produces more and more fragments, which are mixed by this "oscillation pumping" into the coolant and are explosively ejected en masse if the system is dynamically triggered or reaches the homogeneous boiling point (Wohletz 1986). Low-viscosity magmas should mix more rapidly with (fluidized) host sediment by this process than would magmas with higher viscosities (cf. Wohletz 1986).

Microglobular peperite was preserved at Punta China because the system remained metastable and was never raised to temperatures ade-

quate for spontaneous superheat vaporization (homogeneous boiling; Wohletz 1986), nor was it shaken, prodded, or otherwise triggered by earthquakes or other external forces. The water/magma mass ratio in a roughly 1:1 volume mix of uncompacted micrite and magma is about 0.16–0.24 (range derived from visual estimation of lava and micrite proportions within the microglobular peperite zone only). The relatively low ratio of magma to water available in the zone of interaction may have provided insufficient heat to bring upon superheating and dynamic mixing (Wohletz and McQueen 1984); hence it did not explode.

Blocky, hydroclastic peperites

Fluidal peperite did not develop within the lithic lapilli tuff breccia host, despite being intruded by the same magma as the shelly micrite host. Differences in confining pressure, magma temperature, rate of supply, viscosity, composition, etc., must have been negligible in sites stratigraphically separated by only a few meters and intruded by the same sill apophyses. We therefore propose that the difference in peperite characteristics must have been controlled in this instance by different properties of the hosts. The most obvious differences between the shelly micrite and lithic lapilli tuff breccia hosts are the latter's much greater average grain size, poorer sorting, and greater permeability.

Fragmentation due to thermal contraction is termed "granulation" (Fisher and Schmincke 1984). Dynamic stress fragmentation is a different hydroclast-forming process, whereby continued movement of fluid magma breaks apart its chilled, rigid outer carapace (Kokelaar 1986). Both of these hydroclastic processes occurred much more readily within the lithic lapilli tuff breccia host than in the micrite host. This is probably related to the host's greater permeability and to an inability to maintain a continuous steam envelope when many host clasts are too large to entrain in a vapor film at the magma-host interface. The result was rapid quenching and increased brittleness.

Large basalt blocks dispersed decimeters to meters from apophyses cannot be explained by simple quench granulation or dynamic stressing of chilled magma surfaces. This high degree of dispersion is probably the result of explosive expansion of water-laden host sediment engulfed in the magma by the process of "clast blocking" (Fig. 8). The lithic lapilli tuff breccia host is a
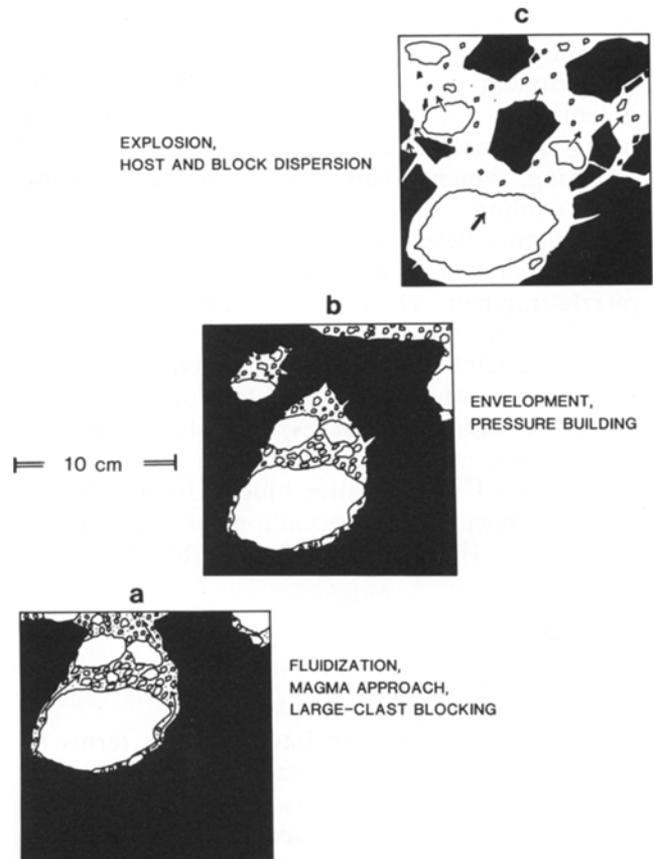

Fig. 8. Schematic diagram illustrating "clast blocking". A large clast within a permeable, poorly sorted lithic lapilli tuff breccia is enveloped by magma, along with a small pocket of wet tephra in its "shadow". The surface of the magma cools rapidly during intrusion into coarse-gained, permeable host material and is broken into blocks and dispersed into the host when water enclosed within tephra pockets is vaporized

highly comminuted lava flow, rather than a pyroclastic flow, with a relatively low percentage of ash-sized matrix and abundant blocks. The intruding magma frequently encountered large clasts, which it engulfed, along with water-laden matrix in "shadows" behind the clasts (Fig. 8a). The enclosed water was thus somewhat confined in zones behind such large "blocking clasts" (Fig. 8b), and simple vaporization of pockets of interstitial water violently broke apart the rapidly chilling magma into blocks and mixed it with partially fluidized host sediment (Fig. 8c). The scale of dispersion (perhaps as much as 3 meters) is greater for these peperites than for others described in the literature, but this is an unusually coarse-grained host.

"Drilling" on a much larger scale than that observed in the fluidal peperite occurred at the contact of the lithic lapilli tuff breccia host with the

main body of the lower sill (Fig. 4). Peperite has drilled approximately two meters into the host, elutriating fine sediment along the fluidization paths. This process is probably enhanced in coarse-grained, highly permeable host sediment. Coarser-grained, high-permeability hosts are more easily brought to quiescent fluidization than finer-grained hosts (Woolsey et al. 1975). Proximity to the main body of the intrusion must also have played a role in the process, since large fluidization pipes are only evident at that contact (Fig. 5). Peperites developed in shelly micrite show fluidization channeling only at a microscopic scale, reflecting that host's much lower permeability.

Host-filled fractures cut the sill apophyses both within the lithic lapilli tuff breccia host and in the shelly micrite host. Kokelaar (1982) interprets similar features to have resulted from injection of fluidized host into cooling fractures. Host material injecting these fractures may have been fluidized at the time of fracture develoment as a result of abrupt pressure decrease within the fracture during opening (Kokelaar 1982; Walton and O'Sullivan 1950).

Conclusions

Peperites form by mixing of magma with wet sediment. Explosive, localized steam generation together with quench granulation and dynamic stressing of chilled margins produces blocky peperites. Globular peperites form where a vapor film, in which host material is entrained and flows nonexplosively away from the magma-wet sediment interface, is maintained more or less continually during peperite development. Fluidal intermixtures of the microglobular type reported here may be rarely preserved. They are produced by fine-scale mixing of magma with a fluidized host, and thus result from the same fuel-coolant contact instabilities that commonly lead to explosive disruption of basalt in contact with shallow water. Explosive disruption of the fluidal intermixture may have been inhibited by small system size, inadequate water/magma ratios, or absence of an external triggering mechanism (cf. Wohletz 1986).

Careful textural study allows differentiation of peperites from other volcanic/sedimentary rocks less useful for demonstrating magma/sedimentation contemporaneity. The specific properties of intruding magmas (fluidal vs viscous, different rates of supply, etc.) interacting with different

host types (coarse-grained or fine-grained, permeable or impermeable, cohesive or noncohesive), in environments where neither great confining pressure nor overly limited environmental water impose limits on the interaction, should produce a predictable spectrum of peperite textures. The microglobular peperite described herein probably represents an end-member condition of interaction between highly fluidal magma and fine-grained, noncohesive sediment. With coarser-grained hosts, fluidization, elutriation, and dispersion by localized steam explosions become more important. Host grain size is an important determinant of peperite style because large clasts cannot be entrained along the magma-wet sediment interface, a process necessary for production of fluidal, sediment-displacive peperites.

References

Allison EC (1955) Middle Cretaceous Gastropoda from Baja California, Mexico. J Paleontol 29:400–432

Beggs JM (1983) Stratigraphy, petrology, and tectonic setting of the Alisitos Group, Baja California, Mexico [unpub PhD diss]. U Calif Santa Barbara, pp 1–201

Brooks ER, Wood MM, 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

Fisher RV, Schmincke H-U (1984) Pyroclastic Rocks. Springer Berlin Heidelberg New York Tokyo pp 1–472

Gastil G, Phillips PR, Allison EC (1975) Reconnaisance geology of the State of Baja California. Geol Soc Am Mem 140, pp 1–170

Hanson RE, Schweickert RA (1983) Chilling and brecciation of a Devonian rhyolite sill intruded into wet sediments, northern Sierra Nevada, California. J Geol 90:717–724

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

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

Kunii D, Levenspiel O (1969) Fluidization Engineering. John Wiley and Company New York

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

Pettijohn FJ, Potter PE, Siever R (1972) Sand and Sandstone. Springer Berlin Heidelberg New York, pp 1–618

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

Silver LT, Stehli FG, Allen CR (1963) Lower Cretaceous pre-batholithic rocks of northern Baja California, Mexico. Am Assoc Pet Geol Bull 47:2054–2059

Silver LT, Allen CR, Stehli FG (1969) Geological and geo-chronological observations on a portion of the Peninsular Ranges batholith of northwestern Baja California, Mexico. Geol Soc Am Spec Paper 121:279-280

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

Walton MS, O'Sullivan RB (1950) The intrusive mechanics of a clastic dike. Am J Sci 248:1-21

Williams H, McBirney AR (1979) Volcanology. Freeman San Francisco, pp 1-391

Wilson JL (1975) Carbonate facies in geologic history. Springer Berlin Heidelberg New York 1-471

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

Wohletz KH, McQueen RG (1984) Experimental studies of hydromagmatic volcanism, in Boyd FR et al, Explosive Volcanism: Inception, Evolution, and Hazards. Nat Acad Press Washington DC, pp 158-169

Woolsey TS, McCallum ME, Schumm SA (1975) Modeling of diatreme emplacement by fluidization. Phys Chem Earth 9:29-42