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# Peperitic textures of Ordovician dacitic synsedimentary intrusions in Argentina's Puna Highland: clues to emplacement conditions

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## Abstract

Synsedimentary crystal-rich dacitic sills, laccoliths and cryptodomes emplaced in early Ordovician submarine thin-bedded silt/sandstone sequences show a variety of magma–water interaction features. Megapeperites occurring along the igneous contact contain angular dacitic megaclasts that are dispersed in dominantly structureless host sediment. They result mainly from quench fragmentation of magma and dynamic stressing of cooling magma bodies on contact with wet sediments, combined in some instances with fluidization of the sediments or minor explosive expansion of water incorporated by magma breaching the sediment–water interface or stopping of water-saturated roof sediments by shallowing intrusions.

Globular peperites, having bulbous to globular dacitic clasts immersed in the host sediment with evidence of fluidization along the contact zone, are also recognized at the top and base of sills. In this case, a vapor film might have formed at the magma–sediment interface; insulating the magma from direct contact with the sediment and suppressing quench fragmentation and steam explosions. The diversity of peperite textures observed in the same intrusive and sedimentary rocks appears to be mainly the result of different levels of emplacement of the synsedimentary dacitic intrusions. Scarcity of peperites related to mafic sills is attributed to their having been emplaced late during the evolution of the basin. © 2002 Elsevier Science B.V. All rights reserved.

*Keywords:* peperites; submarine volcanism; synsedimentary dacitic intrusions; Ordovician; Central Andean Puna Plateau

## 1. Introduction

Textural diversity in peperites has been explained on the basis of variation in disruption processes where magma interacts with unconsolidated water-saturated sediments. Disruption and intermixing of magma and sediments during pe-

perite formation are thought generally to result from non-explosive processes, such as quench fragmentation and dynamic stress fragmentation or from phreatomagmatic activity involving steam explosions, or from a combination of these (Brooks et al., 1982; Hanson and Schweickert, 1982; Kokelaar, 1986; Wohletz, 1986; Hanson, 1991; Cas, 1992). Fluidization of host sediment also has been considered as a mechanism controlling magma–sediment interaction, with fluidal or globular peperites produced when a water vapor

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film is established at that interface suppresses quench fragmentation and steam explosions (Kokelaar, 1982; Busby-Spera and White, 1987). Textural features of host sediment have been regarded as important in the control of the type of peperite formed (Busby-Spera and White, 1987).

Although different mechanisms for peperite generation have been proposed in previous studies, there are few detailed evaluations of the physical controls on textural characteristics of peperites, particularly in the case of voluminous silicic magmatic complexes, with the notable exceptions of Snyder and Fraser (1963) and Hanson and Wilson (1993).

In this paper, we describe in detail various types of peperite related to crystal-rich dacitic sills, lac-

coliths and cryptodomes, and scarce spilitic sills, intruded into a single sedimentary rock type (fine-grained siliciclastic submarine turbidites). These synsedimentary intrusions, together with volcanic members (hyaloclastites and lava flows) and sedimentary units, represent the Cochinoqa–Escaya magmatic–sedimentary (CEMS) complex. This large Early Ordovician submarine complex, dacitic and basaltic in composition, crops out in the Argentina Puna Highland (Central Andes) between 22–24°S and 66°W (Fig. 1), and represents part of the Early Paleozoic SW Gondwana margin.

Diverse peperites from blocky megapeperites to microglobular peperites are well exposed in several sections of the CEMS, particularly along margins of dacitic intrusions into pelitic sedimen-

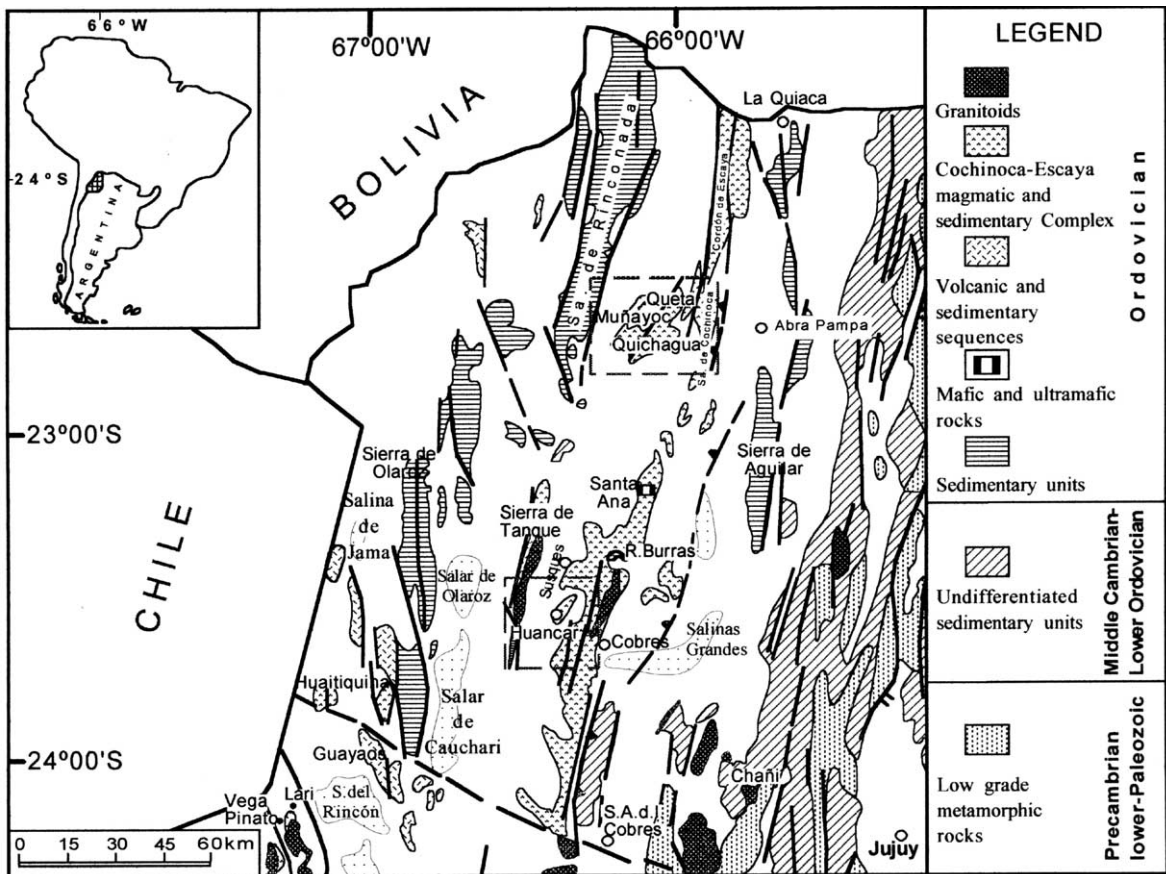


Fig. 1. Map of part of Northern Argentina showing the distribution of Ordovician igneous and sedimentary units in the region of modern Central Andean Puna plateau.

tary rocks. This diversity makes it possible to analyze and evaluate disruption processes that took place between the same magmatic and sedimentary members during their formation and also to discriminate among controlling factors. On these bases, different levels of emplacement of the sedimentary intrusions are proposed. Causes of the observed scarcity of peperites related to mafic intrusions of the complex are also considered.

## 2. Regional geology

The CEMS complex represents an Early Ordovician, submarine, bimodal volcanic system emplaced contemporaneously with outer shelf-slope basin sedimentary sequences. These sedimentary sequences consist of oxygen-poor basin-slope turbidites and storm- and wave-influenced shelf sediments (Martínez et al., 1999), which developed along an oblique left-lateral transpressional subduction zone (Coira et al., 1999).

Porphyritic lava flows and hyaloclastites, to-

gether with dikes, sills, laccoliths and cryptodomes of peraluminous dacitic composition, with a weak arc signature, are the major magmatic units of the complex. Subordinate basic, subalkaline to alkaline, massive and pillowed flows, sills and dikes accompany them. The dacitic and mafic members are near-vent non-explosive submarine volcanic and subvolcanic units.

Ductile to brittle deformation and low-grade metamorphism have modified the complex, making it difficult to recognize original igneous textures and relations and leading to contrasting interpretations of the origin and emplacement of its members. The identification, in less deformed sections of the complex, of dacitic hyaloclastites associated with lava flows (Coira and y Koukharsky, 1994), as well as of spilitic pillow lavas intercalated with submarine turbidites (Coira and y Koukharsky, 1991), produced the first arguments for the existence of synsedimentary submarine volcanism during Ordovician time in the northeastern Puna. More recently, the recognition of peperites at the interface of dacitic intrusions

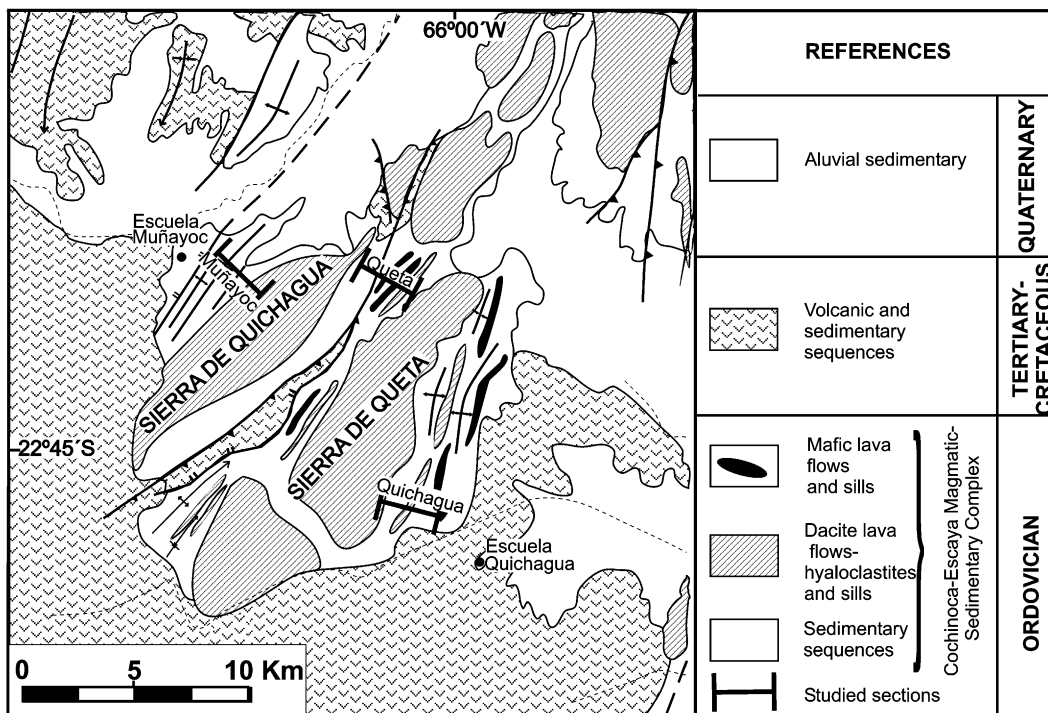


Fig. 2. CEMS complex at Sierras de Quichagua-Queta.

with siliciclastic turbidites of the complex (Coira and Pérez, 1998) corroborates the syndimentary emplacement of the magmatic units.

### 3. Syndimentary intrusions

Abundant crystal-rich dacitic intrusions constitute a distinctive feature of the CEMS complex. They are composed of porphyritic dacites with 20–35% phenocrysts of oligoclase ( $An_{15-20}$ ), quartz, and biotite between 0.3 and 2 cm in diameter, and megacrysts of alkali feldspar ( $Ab_{70-60}$ ) up to 5 cm across, in a gray-green perlitic, devitrified microgranular groundmass that contains ag-

gregates of quartz, alkali feldspar, chlorite and sericite.

Contacts of these intrusions with the sedimentary host rocks are commonly characterized by the development of mixed rocks (igneous and sedimentary) with diverse clastic textures, from blocky shaped igneous clasts which preserve in places a jigsaw fit arrangement, to lobate or globular igneous bodies, both dispersed in massive and usually indurated sedimentary rock. The mixed rocks grade into the unmixed coherent intrusions and also into the sedimentary host rock which show its typical and distinctive laminated structure in contrast with the structureless mudstone matrix in the mixed rock.

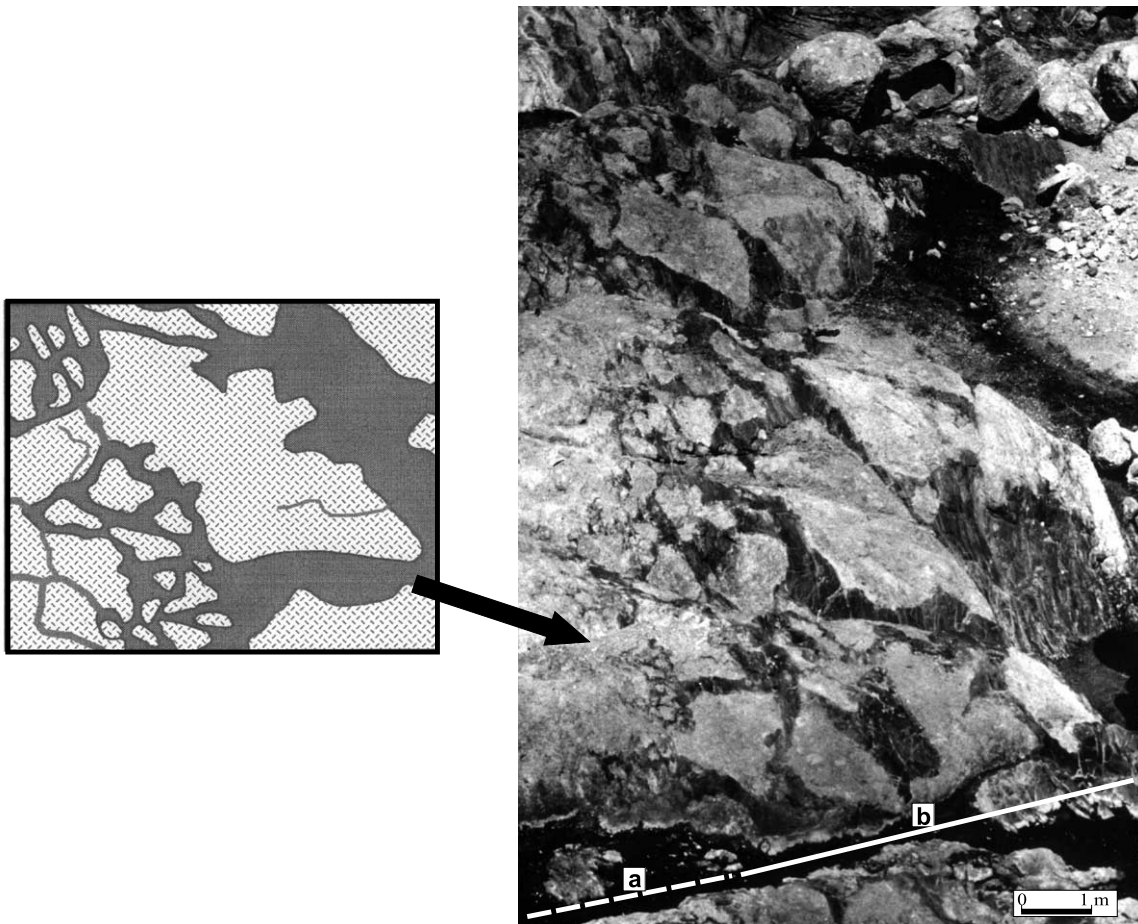


Fig. 3. Megapeperites on top of Muñayoc cryptodome (base on left): a, closely packed; b, unpacked. Base on left: note arrowed late finger-like dacitic intrusion and close-up showing dispersion of subangular dacitic fragments adjacent to large dacite blocks.

Subalkalic basalt-spilites, doleritic basalts and alkali basalts-basanites also occur as sills and laccoliths in the complex. The subalkalic basalts, as well as the alkali basalts and basanites, are aphyric to scarcely porphyritic and commonly vesicular. The subalkalic basalt groundmass, generally variolitic, consists of albite, chlorite (penninite), epidote (pistacite) and minor calcite. In some cases, titanite-augite, tremolite-actinolite, ilmenite and magnetite occur.

Doleritic-basaltic dikes and sills are composed of patches of clinopyroxene and andesine-labradorite laths distributed in a scarce chloritic matrix (up to 15% in volume).

Alkali basalts and basanites include among their mafic minerals augite, kaersutite and, in some cases, biotite.

In a few cases, on top of spilitic sills, there is breccia composed of polyhedral spilitic clasts only slightly separated from one another and surrounded by indurated sedimentary host rock.

### 3.1. Case studies

#### 3.1.1. Muñayoc cryptodome

At Muñayoc profile, located on the western

flank of the Quichagua Range (Fig. 2) a series of massive dacitic lava flows, marginal cogenetic in situ hyaloclastites and domes crops out, associated with siliciclastic sequences bearing a Middle Arenig graptolite fauna (Martínez et al., 1999) in the upper section. A conspicuous level of large dacitic clasts set in a sedimentary massive matrix, 8–10 m thick, and related to a dacitic cryptodome, forms the top of that magmatic sequence and grades from the cryptodome by an increase in clast separation and sediment content (Fig. 3). The coherent cryptodome dacite passes towards the roof, gradually, to matrix-poor in situ hyaloclastite with jigsaw fit to slightly rotated subangular partly curvilinear fragments 0.5–2 m across.

Along the side of those hyaloclastic dome facies, angular to subangular dacitic fragments, 0.5–3 m across, which are slightly displaced with respect to one another and separated by minor (0–4%) silicified silty matrix, form a close-packed breccia level, 4 m thick (see a in Fig. 3). Occasional small finger-like dacitic intrusions, 0.20–0.30 m across, cut and partly obliterate the texture of those breccias. Upwards, closer to the sedimentary host rock, the close-packed breccia is gradually succeeded by a more loosely packed

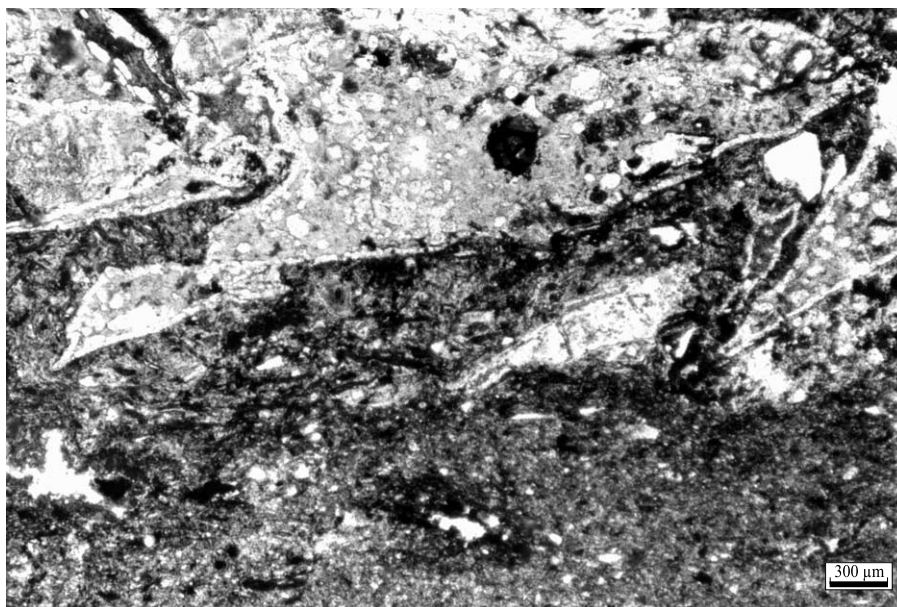


Fig. 4. Microphotograph of a ragged dacite clast margin of Muñayoc mudstone dacite mega breccia. Angular dacitic microfragments and crystal chips are dispersed in a slightly silicified sedimentary matrix near the dacite contact.

breccia 6 m thick (b in Fig. 3), characterized by subangular dacitic blocks, 0.2–1.2 m across, some with partly rounded margins, enclosed in a silicified siltstone matrix (15–25% by volume). They are distributed in a way that suggests detachment of dacitic fragments from the cryptodome and dispersion into the sedimentary host-rock, which is a mainly structureless siltstone that shows lamination away from the contact.

In detail, small blocky, subangular dacitic fragments and angular crystals (0.3–5 cm in diameter) are dispersed into the mudstone matrix, at the margins of large dacitic clasts (close view, Fig. 3). Microfragmentation of the dacite at the margin of the clasts is also identified in thin sections, which reveal highly angular dacite microblocks 0.5–4 mm in diameter and scattered crystal fragments dispersed in a structureless mudstone matrix (see Fig. 4).

These macro- and micro-textures are clearly exposed especially at the transition from the lower close-packed to upper more loosely packed section.

In restricted sectors of the upper breccia level (see Fig. 5), it is possible to recognize disturbances

in the arrangement of the clasts, with evident rotation of some (0.5–1 m in diameter and scale dispersion as much as 1.5 m). Also identified, within certain limited areas, are zones of rounded-clast breccia cross-cutting zones of blocky-clast breccia, the latter characterized by in situ brecciation.

On the flanks of the cryptodome roof volcanoclastic silt/sandstone sequences crop out, each 0.3–4 m thick and characterized by fine parallel laminae (3 mm to 16 cm in thickness) with normal grading. The sandy layers, which gradually pass upward into pelitic laminae, are composed of abundant crystals and subordinate amounts of equant, non-vesicular vitroclasts and quartz–feldspar microaggregates. Silty layers are silicified.

### 3.1.2. Sills and laccoliths of Quichagua River

Small laccoliths (up to 25 m across) and dacitic sills (5–8 m thick), enclosed in Early Ordovician siliciclastic host-rocks, crop out in the northern Quichagua River valley (Fig. 2). Conspicuous mudstone–dacite breccias are recognized along dacite–sedimentary host rock contacts, particularly on the upper margins of the intrusions.

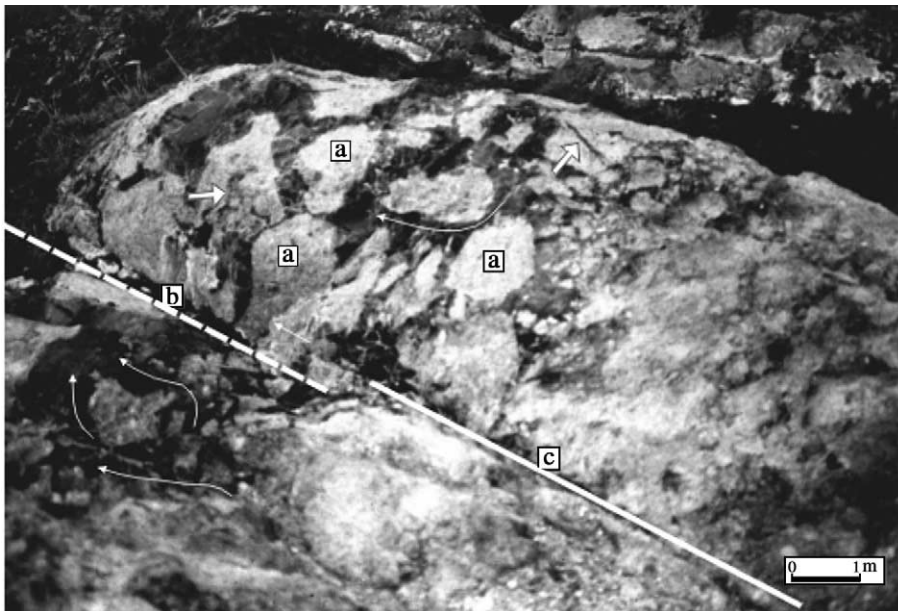


Fig. 5. Muñayoc megapeperite: b, loosely packed section; c, closely packed section. Thick arrows point to products of in situ fragmentation and injection of the late dacite clasts by mudstone along fractures. Thin arrows indicate rotation of clasts (a) corresponding to subrounded clasts.

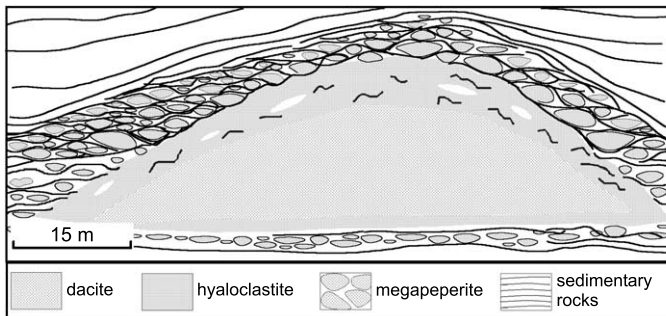
The sedimentary host rock is penetratively foliated and folded, whereas the dacite intrusive bodies show contrasting deformation and are only slightly stretched, with immediately enclosing sedimentary layers lying parallel with their contacts.

The largest laccolith (25 m thick) shows (Fig. 6a) a gradual transition from a massive dacite interior into 7–8-m-thick hyaloclastites along its base and domed roof.

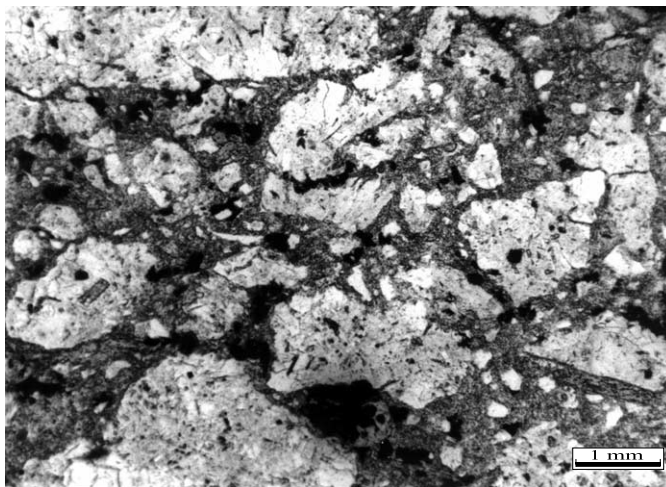
Hyaloclastite is composed of blocky to slightly lenticular dacitic fragments 5–20 cm in diameter

enclosed in a scarce (5–10%) silicified matrix that contains millimetric granules of the same composition and locally abundant crystal fragments. Structureless and silicified sedimentary inclusions up to 5 cm across are recognized in the marginal hyaloclastites.

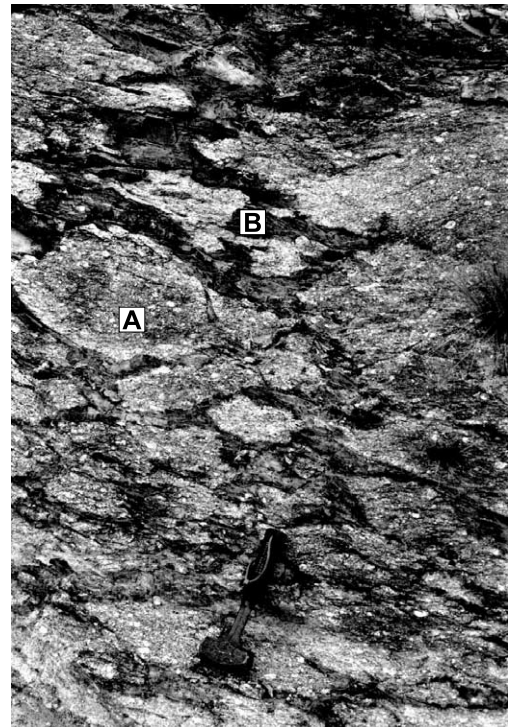
A 5–6-m-thick breccia composed of elongate and lensoidal dacite blocks (0.2–2 × 0.5–3 m) dispersed in a mudstone matrix (8–25% in volume) (Fig. 6a,b) surrounds the laccolith. The dacitic blocks show in detail spalled margins (Fig. 6c). Small dacitic blocky and equant fragments 0.5–5



a



c



b

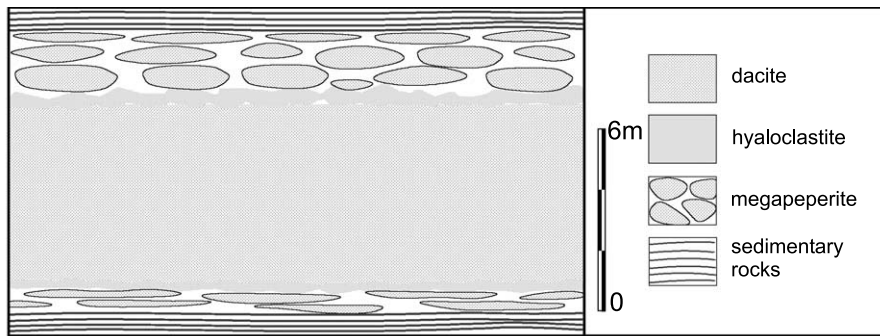
Fig. 6. (a) Quichagua laccolith. Note in the sketch transition from massive dacite to surrounding hyaloclastite and marginal megapeperite. (b) View of marginal megapeperite of the Quichagua cryptodome. (A) Lensoidal and slightly ragged dacite blocks closely packed in a sparse structureless mudstone matrix (B). Hammer lies roughly perpendicular to stretching direction of dacite clasts. (c) Hyaloclastic margin of dacitic blocks of Quichagua laccolith megabreccia. Plane polarized light photomicrograph. Blocky angular to subangular dacite fragments display closely packed jigsaw fit texture. In detail, the boundaries of larger clasts are fragmented into microgranules and crystals (in situ microfragmentation).

cm in diameter and crystal chips are dispersed in the siltstone host rock. Sedimentary matrix textures in this part of the host rock are obliterated and/or partially masked by diffuse and vein-like superimposed silicification.

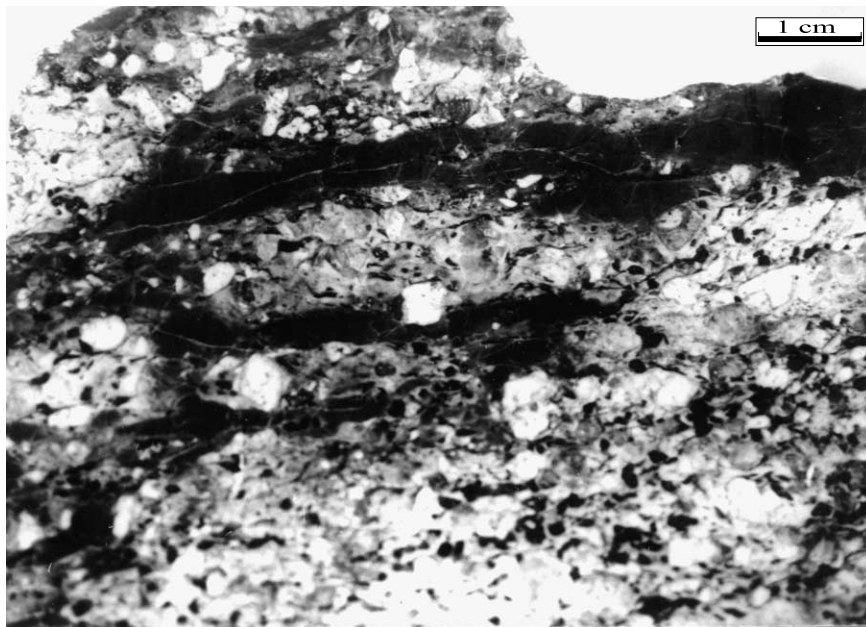
At the flat base of the laccolith, a thinner brecciated level (up 2 m across) is recognized. It comprises subangular, elongate dacitic fragments, 0.3–0.6 m across with roughly subparallel orienta-

tions, enclosed in a structureless indurated siltstone matrix (5–10% in volume).

One of the dacitic sills (6 m thick) displays along its roof a 2-m-thick breccia with subangular and lensoidal dacitic fragments, 0.1–0.4 m in diameter, roughly subparallel to its top and surrounded by a scarce (8–12% in volume) silicified mudstone matrix (Fig. 7a). The dacite fragments exhibit spalled margins with detached microfrag-



a



b

Fig. 7. (a) Sill at Quichagua River sections. Note lensoidal shape of dacite clasts on the upper megapeperite margin and their tongue-like arrangement at the thin basal peperite. (b) Detail at the base of Quichagua sill. Elongate, tongue-like, dacite clasts are delimited by almost unmodified laminae of the siltstone host rock.

ments 0.4–3 cm in diameter. This breccia passes gradually downwards into a massive dacitic sill. At the base of the sill, the dacitic fragments have tongue-like shapes, are 0.01–0.2 m thick, and are enclosed in a siltstone matrix with their long axis roughly parallel to the sedimentary host rock lamination (Fig. 7b).

3.1.3. *Huancar Hill dacitic sills*

At Huancar Hill, located 24 km south of Susques (see Fig. 8), a 260-m-thick section of the CEMS complex is exposed. It is represented by a succession of dacitic lava flows (30–60 m thick) and hyaloclastites (30–35 m thick) with intercalations of siltstones and fine sandstones (1–40 m thick) and intruded by sills, 15–18 m thick, of the same composition and characterized by columnar jointing. This sequence, on the basis of the recognized graptofauna association (Brussa and Coira, unpublished data), could correspond to early representatives of the CEMS complex.

At the top and base of the sills, there are a matrix supported (50–60% in volume) globular clasts in a layer 0.03–0.10 m thick. Dacite globules, comprising drop-like or bulbous fragments with irregular outlines and varying in size from 2 to 15 mm in diameter, are isolated within an indurated siltstone host rock and show a weak incipient alignment (Figs. 9 and 10). Those dacitic fragments are oriented perpendicular to the basal contact and lie some distance (2–3 cm) from the contact with the dacite body. They are characterized by quartz, feldspars and biotite phenocrysts in a quartz, feldspar and chlorite microgranular groundmass and exhibit, in thin section, fine scale irregularities along the margins. Near dacitic sill contacts, the sedimentary matrix is homogeneous and structureless, and this feature is particularly evident near dacite projections (Fig. 10). Vesicles and vuggy cavities, 150–400 μm in diameter, and irregular channels or micropipes, representing in part interconnected vesicles 100–500 μm across, are identified in the mudstone matrix at the contact with the sill.

3.1.4. *Spilitic sill of Quebrada Colorada, western flank of Sierra de Queta*

On the western flank of Sierra de Queta (Fig. 2),

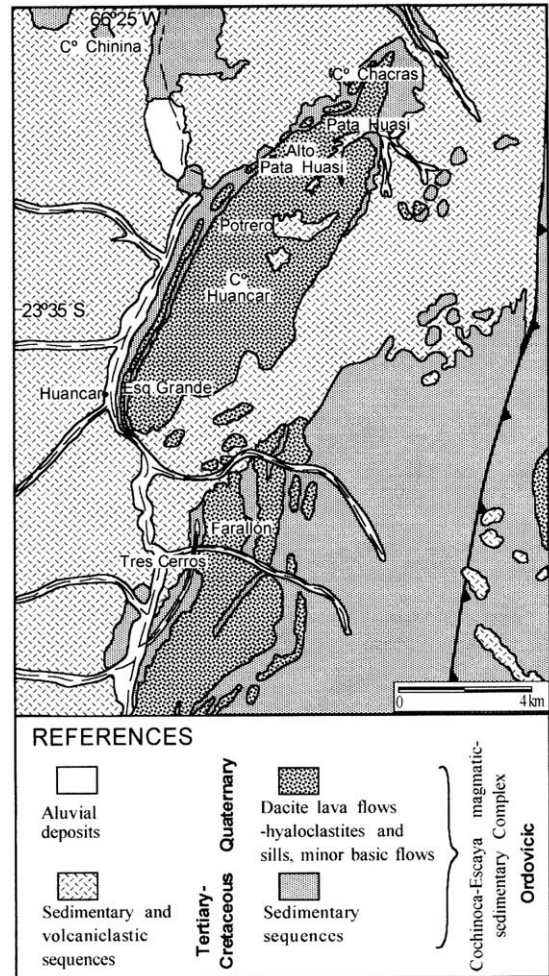


Fig. 8. Ordovician igneous and sedimentary sequences at C° Huancar region. C° = Cerro.

along Quebrada Colorada, the CEMS complex is represented by spilitic and doleritic basalt sills associated with siliciclastic turbidites. These give way gradually upward to dacite lava flows and sills, which become dominant at the summit.

A spilitic sill from the lower part of this sequence crops out in the core of an anticline. It shows at the roof a breccia composed of blocky and polyhedral spilitic fragments of variable size (from a few centimeters to 40 cm in diameter) and having rough, irregular margins, slightly separated with respect to one another by a mudstone matrix (up to 20% in volume; Fig. 11). This breccia, up to 1 m thick, is discontinuous along the sill

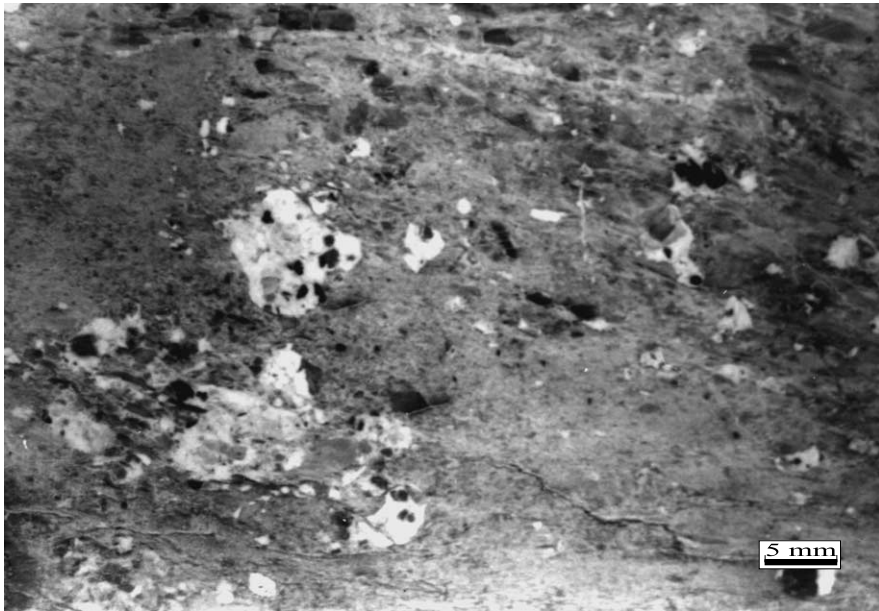


Fig. 9. Dacite globules and equant fragments of variable size detached from the Huancar dacite sill and dispersed in the siltstone host rock.



margin and grades into the spilite, which shows a concentration of vesicles and parallel rough banding toward that margin.

Sedimentary host rocks are strongly silicified on top of the igneous body and show in places, at the contact with the spilite, contorted and convolute lamination. These structures are not observed along whole sedimentary sequence, being recognized only along the boundary with the sill (see Fig. 10). They are of centrimetric size and do not exhibit any preferred orientation or relation to the tectonic cleavage. The spilite sill also shows, towards the roof, fractures up to 30 cm long and 2–20 cm thick filled with siliceous mudstone host rock (Fig. 12).

The spilite sill also shows, towards the roof and at the contact with the sedimentary host rock,

Fig. 10. Detail of dacitic sill contact in Cerro Huancar. Note distinct loss of lamination of the sedimentary host rock near the small projection on the dacitic intrusion. Microglobular dacitic fragments and crystals are dispersed within the texturally homogeneous mudstone.



Fig. 11. Blocky breccia on top of spilite sill. Mudstone (A) enclosing spilite clasts (B) which show irregular margins and slight displacement from one another.

fractures filled with homogeneous siliceous mudstone host rock from less than 0.30 cm long and 0.02 m thick to 1.5 m long and 0.20 m thick, which show straight to irregular fracture surfaces (Fig. 13).

#### 4. Interpretation and discussion

##### 4.1. Megapeperite formation: emplacement conditions of Muñayoc cryptodome and Quichagua laccolith and sills

The large-scale massive mudstone dacite breccias that occur in the Muñayoc and Quichagua profiles are characterized by the large size of their blocky and subangular clasts, enclosure of these clasts in a structureless sedimentary matrix, and their conspicuous volume (areal extent of 2–4 km<sup>2</sup>).

The arrangement of the dacite clasts, which suggests various degrees of ‘in situ’ fragmentation at macro and micro-scale, together with the disruption of sedimentary component in contact with them and the close association and gradational

contacts with coherent intrusions, indicate that the breccias are peperites, applying this term in a genetic sense, as was proposed by White et al. (2000). In sum, their compositional and textural characteristics indicate interaction between a magmatic component and poorly consolidated or unconsolidated wet sediments. Thermal stress processes, such as quench fragmentation and dynamic stressing of cooling magma bodies, together with some sediment fluidization controlled by cooling fractures, are clearly registered in them.

Taking into account the distinctive large size of the clasts and conspicuous volume of the bodies of peperite, characteristics that hint to its particular formation conditions, we consider it useful to term them ‘megapeperite’, a term which makes reference to the large clasts and large volumes of the peperite bodies.

Interaction of large volumes of siliceous magma with wet sediments to form large-scale peperites was analyzed and discussed in detail by Snyder and Fraser (1963), Hanson (1991), Hanson and Wilson (1993), Morgan (1997), and Hanson and Hargrove (1999). These previously documented examples provide important points of reference

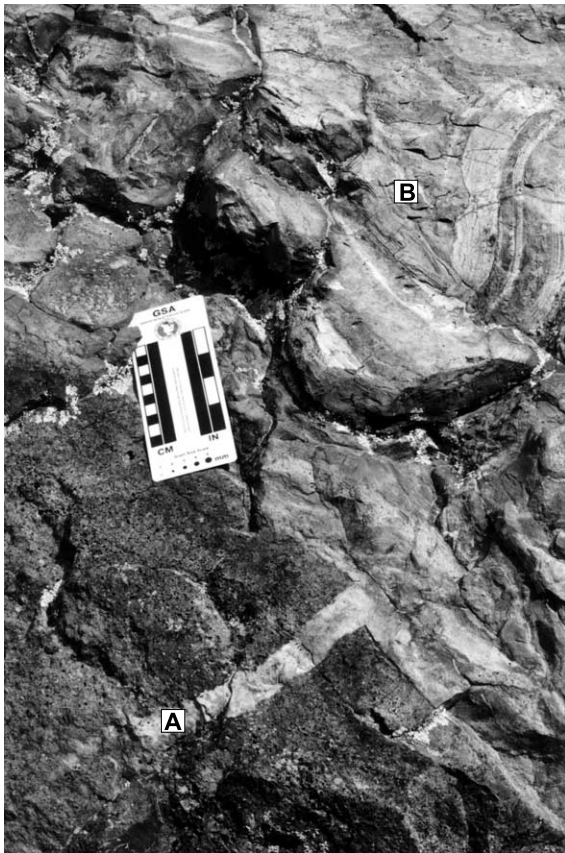


Fig. 12. Closeup view of Quebrada Colorada spilitic sill/sedimentary host rock contact with scale on that boundary of a siliceous mudstone-filled fracture in the spilitic. Note narrowing of the fracture inwards the magmatic body (A). Siliceous mudstone with contorted and convoluted lamination (B) developed at the contact.

for interpretation of the main processes that control megapeperite formation, and for establishing the types of settings favorable for production of such peperite.

In the case of the Muñayoc megapeperites, the arrangement of the angular-subangular blocky clasts with jigsaw fit textures is preserved in places, particularly in the lower close-packed section, and the microscale fragmentation of the clasts, with angular dacite shards spalled from their margins and intermixed with the sediment, indicate that thermal stress processes such as dynamic stressing of the cooling magma body and quench fragmentation were decisive in the generation of

the rocks. Dynamic stressing of the earlier emplaced parts of the dome by continued injection of magma is corroborated by the occurrence of dikes 0.20–0.40 m thick (Fig. 3) cutting closed packed megapeperite section. On the other hand, cooling contraction granulation (Kokelaar, 1986), evidence for which is especially observed at the margins of the clasts, could have taken place after their release from larger masses of disrupted magma. The dispersion of the dacitic fragments in certain areas of the loosely packed upper section, where they lie in the sedimentary matrix, as far as 1.5 m from their sources, with chaotic textures and clear rotation, is interpreted to reflect minor steam explosions. Such explosions could be another mechanism that contributed to forming these rocks. It is likely that they could have been caused by vaporization of water incorporated by the growing cryptodome as it initially breached the sediment/seawater interface (bulk interaction steam explosivity, Kokelaar, 1986) or to explosive expansion of included water-saturated roof sediments in the dome. Reworked hyaloclastites observed on top of, and laterally outward from the dacitic cryptodome, as was described by Cas et al. (1990), testify to dome ascent and its breaching of the sediment–water interface. Following breaching of the seafloor, the dome's quenched margins spalled and the spall debris was resedimented by grain-flow redeposition and avalanching on the flanks of the dome.

There are other peculiarities of these megapeperites, such as the mixed shapes of clast (subrounded and blocky) observed in certain areas of the loosely packed section, which have the same sedimentary matrix as the rest (see Fig. 5). These clast-shape variations indicate local cooling of the intruding dacite across the ductile/brittle transition during intrusion of the magmatic body into wet sediments. Such variations may have resulted from variation in the confining pressure during its shallowing, or from variations in the volumetric rate of magma supply (water/magma mixture ratio) relative to available water.

The intermixing between a structureless homogenized sedimentary matrix, with bedding only preserved in limited areas, and the blocky dacitic fragments, with various degrees of in situ frag-

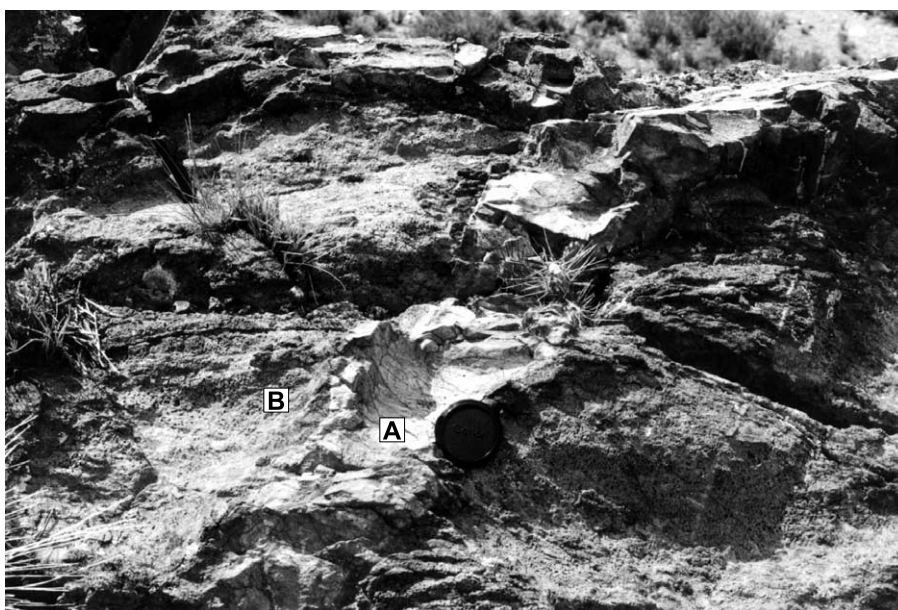


Fig. 13. Roof of Quebrada Colorada spilite (B) sill with a siliceous mudstone filled fracture. Note partly irregular form of the fracture and homogeneous nature of the sediment enclosed in it (A).

mentation and fractures mudstone filled, observed in the upper dispersed peperite (Fig. 5), indicate that the sedimentary matrix must have been amenable to fluidization. Effects of such fluidization are particularly evident along thermal cracks of the quench-fragmented dacite, as was described by Hanson and Wilson (1993) in a detailed study of large-scale rhyolite peperites.

Similar megapeperites were also recognized in the Quichagua River section, but without the direct evidence of subsurface emplacement of the related sills and laccoliths in the same sedimentary lithofacies that exists in the Muñayoc region.

The conspicuous *in situ* hyaloclastic margins of the dacite laccolith in Quichagua River, and the jigsaw fit texture of the dacitic blocks of the surrounding megapeperite, with blocky and equant ( $> 100 \mu\text{m}$  in diameter) shards spalled from their margins into the host sediment (Fig. 6c), reflect the importance of thermal stress processes, particularly cooling contraction granulation (Kokelaar, 1986) related to interaction of the dacitic magma with wet sediment. The shape and size ( $> 100 \mu\text{m}$  in diameter) of the hydroclasts are similar to type I clasts, the result of non-explosive quenching processes in experimental studies of Wohletz

(1983). The size of these fragments is inferred to indicate a water to magma ratio  $> 1$  which has been correlated with low intensity magma–water interactions (Frazzetta et al., 1983; Sheridan and Wohletz, 1983).

At the Quichagua River site, shallow subsurface emplacement of magma into water-saturated sediment, under conditions of reduced confining pressure, allowed rapid expansion and mobilization of heated pore water, disrupting the coherence of the sediment adjacent to the contact. Under these conditions vapor expansion produced tensile stresses and fluid instabilities of the vapor film and began to fragment the melt (Corradini, 1981; Buchanan, 1974; Buchanan and Dullforce, 1973).

In the case of the Quichagua sill, the relations observed in the megapeperite level on top of the intrusion between sedimentary host rock and dacite clasts, with development of lensoidal closely packed textures and spalled laccolith margins with blocky microfragments ( $> 200 \mu\text{m}$ ) dispersed in the indurated mudstone matrix, indicate that quenching processes operated on the margin of the laccolith body during its intrusion in wet sediments. The absence of a hyaloclastite envelope

around the igneous body, in contrast with the conspicuous development of hyaloclastite at the Quichagua laccolith, suggests less shallow, slightly more confining conditions for their intrusion, with more restricted expansion and mobilization of pore fluids and consequent reduction of cooling-contraction granulation processes. In contrast, fluidization of the sediment apparently increased at the contact with magma. The thin subparallel lobes and tongues of dacite observed in the basal peperite, delimited by laminated sedimentary host rock, also hint at a more fluidal behavior of the dacite sill, such that apophyses or tongues could cause displacement of the sediment away from them with little disturbance of the remaining host sediment. These characteristics point also to slightly more confined conditions for the emplacement of the sill, which could control the onset of fluidization of the sediments, with formation of stable insulating vapor film around the intruding magma apophyses (Kokelaar, 1982).

In all the examples analyzed here, voluminous crystal-rich dacitic magma interacted with uniformly fine-grained sedimentary host rock, under shallow and less confined emplacement conditions. The poorly consolidated sediments, high availability of water in the system, and high viscosity of the magma constitute the key factors in the formation of these blocky megapeperites.

#### 4.2. Huancar fluidal peperite formation

Peperites in Huancar Hill section are finer grained, have globular clasts and are less voluminous than the blocky megapeperites described above.

It is possible to recognize features formed by fluidization in the sedimentary host-rock, suggesting entrainment of sediment particles away from the dacite contact as it was introduced (Fig. 10). Fluidization is suggested by irregular vesicles and micropipes developed in the host sedimentary rock (Kunii and Levenspiel, 1969). Also, globular and drop-like dacitic clasts floating in the structureless siltstone matrix show displacement in a direction subperpendicular to the contacts, and the sedimentary host rock lacks lamination around intrusive dacite micro-projections (Figs.

9 and 10). Small fluidal magma fragments are inferred to have detached themselves as a result of vapor film oscillation along the magma–host sediment interface (Wohletz, 1986).

The different textural patterns recognized indicate that the systems were never heated to temperatures adequate for spontaneous superheat vaporization (Wohletz, 1986), and that sufficient volumes of pore water were not heated rapidly enough to trigger explosive hydroclastic fragmentation. Instead the sedimentary host material was entrained and flowed non-explosively away from the magma–wet sediment interface during passive emplacement of magma.

Taking into account all of the characteristics of these globular peperites, it is possible to assign a deeper level of emplacement and more confined conditions for the Huancar dacite sill than for Muñayoc and Quichagua dacite bodies, consistent with their lower position in the CESM complex. Confinement appears to increase the efficiency of non-explosive mingling, with magmatic volatile retention accompanied by a decrease of dacitic magma viscosity. As another alternative, this type of fluidal-clast peperite could also result from the intrusion of sills in somewhat dewatered or more compacted sediments with less pore water, but not with so little water that fluidization cannot occur.

#### 4.3. Mechanisms of megapeperite generation along basic sills

The blocky texture and the evidence of mobilization and injection of wet sediments into spilite fractures observed in the megapeperite of Quebrada Colorada are indicative of multiple processes at the magma–wet sediment interface during its formation.

The angular and polyhedral clasts of spilite with jigsaw fit textures recognized in that peperite are diagnostic of non-explosive hydroclastic mechanisms resulting from cooling and solidification of mafic magma with brittle disintegration along contraction joints. Meanwhile, structureless host sediment within spilite fractures is interpreted as the result of pervasive injection of highly mobile fluidized sediment (Kokelaar, 1982) along

thermal contraction cracks of the quenched spilitite and triggered by the opening of cooling fractures, as was also proposed by Hanson and Wilson (1993) explain large-scale peperite formation.

## 5. Conclusions

The identification of peperites along the dacitic intrusions of the CEMS complex corroborates their interaction with water-saturated sediments. The dacites were emplaced into a thick sedimentary basin pile, which favored shallow intrusions rather than extrusive eruptions. This is consistent with a basin evolution model in which an oblique left-lateral transpressional subduction regime existed during Early Ordovician time, as proposed by Coira et al. (1999) for the northern Puna. The CEMS complex sections offer excellent opportunities for analysis of textural diversity of peperites developed between dominantly silicic magmas and sedimentary host of consistent composition and textural characteristics.

Large peperites with blocky textures occur very commonly in the studied area as products of interaction between dacitic crystal-rich intrusions and fine-grained siliciclastic sediments. The main processes inferred on the basis of detailed textural and facies analysis are: quench fragmentation of magma on contact with wet sediments, and dynamic stressing of earlier chilled body margins by continued injection of magmas, together, in some cases, with fluidization of the wet sediments controlled by pressure reduction during opening of cooling cracks in the body. In the case, particularly, of the emergent Muñayoc cryptodome, it is possible to infer, in addition to the previous processes, minor explosive expansion of water incorporated to the system (bulk interaction steam explosivity, Kokelaar, 1986). In all of these examples, there are direct or indirect indications of high availability of water in the system, and of shallow levels of emplacement of large volume of dacite magma interacting with wet sediments to form those blocky megapeperites.

The blocky texture of some peperites has previously been argued to have formed due to prop-

erties of the host sediment, such as coarse grain sizes, poor sorting and high permeability (Busby-Spera and White, 1987). In the cases studied here, however, large-scale blocky, as well as small globular peperites formed as a result of dacitic magma interaction with identical fine-grained sedimentary host rock (siliciclastic siltstones). These examples show that the textural variation of peperites cannot always, or necessarily, be related to the granulometry and sorting of the sedimentary host rock.

The globular peperite identified in Huancar Hill developed from the same magmatic and sedimentary constituents as did the Muñayoc and Quichagua megapeperites, but shows textural signs of fluidization processes, with evidence of passive emplacement of magma without hydroclastic fragmentation. Instead the magma and host showed fluidal behavior, with detachment of globules of magma as result of oscillation of vapor films along the magma–wet sediment interfaces and accompanied by bulk sediment transport away from the contacts. This texture of peperite suggests emplacement of the dacitic sills deeper beneath sea level, where confining pressure was sufficient to suppress steam explosions, but not so high as to prevent achievement of a certain minimum vapor flow velocity required for fluidization (Kokelaar, 1982). Also, the viscosity of the magma was decreased, favoring its mixing with fluidized wet sediment (Wohletz, 1986).

In the case of the mafic magmas, the scarcity of peperites related to the intrusions is probably attributable to their being emplaced late during the evolution of the basin, when pore water in the sedimentary pile had been lost by compaction.

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