MICROSTRUCTURAL FEATURES OF A SUBAQUEOUS LAVA FROM BASALTIC CRUST OFF THE EAST PACIFIC RISE (ODP SITE 1256 , COCOS PLATE)

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Keywords: *subaqueous massive lava, lava pond, lava flow microstructures, 15 Ma-old oceanic crust. East Pacific Rise, Guatemala Basin.*

ABSTRACT

This work examines a massive basaltic lava emplaced in a subaqueous environment and drilled at ODP Site 1256. Site 1256 was drilled on the eastern flank of the East Pacific Rise during ODP Leg 206 (6°44N, 91°56W; Guatemala Basin), located in 15 Ma old oceanic crust created by superfast seafloor spreading (ca. 220 mm/yr). The massive lava lies between thin sheet flows and caps pillow lavas, sheet flows with minor hyaloclastite, breccia and dikes. The massive basalt was encountered in two holes, 1256C and 1256D, which are 30 m apart, and has a thickness of 35 m in Hole 1256C and 75 m in Hole 1256D. It can be interpreted as a ponded lava, originated by rapidly erupted lava accumulated in a off axis >3-5 km depression of a steep paleotopography (Teagle et al., 2004).

The Hole 1256 lava pond has been divided into distinct petrographic units and structural units. Five main structural units with different key flow-related textures and syn-magmatic or late magmatic structures were recognized. Ductile and brittle-ductile structures attributed to the flow gives constraints about the emplacement mechanism of the lava and possibly seafloor topography. Unusual textural features related to the flow kinematics were recognized mainly in the top and in the bottom parts of the lava pond, whereas brittle-ductile and brittle deformations occur throughout the whole ponded body. Microstructures in the base may be interpreted as flow-related deformation of hot ductile coalesced spatter clasts erupted during the first stages of emplacement. Alternatively, they may have been formed during lava drain-back, in the final emplacement stages .

INTRODUCTION

Studies on submarine lava flows have been addressed mostly to their external morphology (Gregg and Fink, 1995; Gregg and Chadwick, 1996; Chadwick et al., 1999); instead detailed analyses of structural and petrographic features refer only to subaerial lava flows (Manley and Fink, 1987; Self et al., 1997; Chadwick et al., 1999; Ventura, 1998; 2001).

This paper presents preliminary results of the study of a massive lava flow emplaced in a submarine environment, close to the East Pacific Rise, drilled at ODP site 1256 during Leg 206 (Wilson et al., 2003). The internal vertical zonation of the massive lava is analyzed in detail from the macroscopic and microscopic point of view. Here we present a description of features that are unusual for lavas with basaltic composition. More details on the petrographic and structural characteristics are described in Crispini et al. (in prep.).

The lava flow studied in this paper was nearly full recovered in Hole 1256C where it has a thickness of 35 m whereas in Hole 1256D it is 75 m thick but the top and the bottom parts were not recovered. The structural analysis has been done on the cut surface of the drilled cores. The top and the bottom part of the lava flow show a complete spectrum of structures linked to the emplacement from ductile lava to brittle rock.

In general, lava flows may be characterized by textural features similar to foliation in metamorphic rocks (Vernon, 1987) and the textures of coherent volcanic rocks show features that can be related to flowage (Smith, 2002). The microstructural analysis of this recovered lava flow is critical for many reasons, in particular to reconstruct the dynamic evolution of the lava flow constrained by ductile and brittle-ductile structures. The transition from ductile to brittle deformation depends mostly on the rheological behaviour of the lava. The brittle deformation occurs when strain rates locally exceed the capability of melt to deform viscously (Dingwell and Webb, 1990). The rheological behaviour and physical properties of a crystallising lava are strongly influenced by its crystals content (% volume crystals or crystallinity). The magma behaves as a brittle material as soon as crystallinity reaches a critical value or a critical melt fraction is present. This value is still poorly constrained and ranges from ca. 25-55% (Barth et al., 1994), up to about 60-65 vol.% of crystallinity (e.g., Geshi, 2001). According to experiments on the Holyoke basalt (Philpotts and Carroll, 1996) 30% of crystallinity is sufficient to produce a mush and at 40% the mush behaves as a solid. The crystallinity value for the formation of a strong crystalline framework depends on mineral assemblage, the shape of crystals (Geshi, 2001), and on the grain size of the minerals (Ildefonse et al., 1999). For these reasons the structural analysis of the lava unit has to be accompanied by a detailed petrographic and textural analysis.

Many lava flows develop textural features that are indicators of the flow kinematics (Smith, 2002); the recognition of such structures helps in the comprehension of the flow history. Ductile and brittle-ductile structures attributed to lava flows have provided constraints about the emplacement mechanisms of lava and the seafloor topography nearby the spreading center (Fink, 1980; Ventura, 2001; Smith, 2002). Some of the textures and microstructures encountered in

Site 1256 lava pond have not been previously described in basaltic lavas.

The occurrence of a thick lava flow at the top of pillow lavas and the recognition of particular internal microstructures may be helpful to identify a style of crustal accretion where the extrusive lavas, pillow lavas and dikes overlay the gabbros. An additional thickness of lavas that flowed from the ridge axis to cover the immediate flanks must be taken into account to determine the real stratigraphy of oceanic crust accreted on-axis and to re-consider the predicted depth of gabbros in a superfast ridge.

GEOLOGICAL BACKGROUND

Drilling at ODP Site 1256 during Leg 206 completed the initial phase of a planned multi-leg project to drill a complete in situ section of ocean crust that will extend through the lavas, the sheeted dikes and down to the gabbros. At Site 1256 (6°44.2'N, 91°56.1'W; Fig. 1), located ~1150 km east of the present ridge axis of the East Pacific Rise (EPR) and ~530 km north of the Cocos-Nazca spreading center, under 3635 m of water in the Guatemala oceanic basin. This crust formed at ~15 Ma on the eastern flank of the EPR and accreted at a superfast spreading rate (~200-220 mm/yr full rate) (Wilson, 1996). The Site 1256 lies across the magnetic Anomaly 5Bn-5Br magnetic polarity transition. The trace of the Cocos/Pacific/Nazca triple junction passes ~100 km to the southeast of Site 1256; the elevated bathymetry of the Cocos Ridge records the trail of the Galapagos plume farther to the southeast (~500 km). Four pilot holes were drilled at Site 1256. Holes 1256A, 1256B, and 1256C provided a complete section of the sedimentary cover, whereas Holes 1256C and 1256D that are 30 m apart were deepened into basement. From ca. 275 meters below seafloor (mbsf), Hole 1256C and Hole 1256D were cored 88.5 m and 502 m into basement, respectively. About 15-20% (~100 m) of the cored extrusive sequence formed during a slightly later time most probably from lavas that flowed significant distances from the axis (~5 km) and were ponded between abyssal hills (Teagle et al., 2004). The cored lava sequence records the transition from a stable, shallowly dipping magnetic field in the axial lavas (~100 to 500 m sub-basement) to a more steeply dipping field (inclination > 70°) in the overlying section. All lavas have normal mid-ocean ridge basalt (N-MORB) chemistry, but the lava pond that dominate Hole 1256C and the top of 1256D are exclusively relatively evolved (Mg # ~53, Cr ~70 ppm), whereas the thin sheet flows deeper in Hole 1256D are generally more primitive (Mg # ~61, Cr ~220 ppm; Teagle et al., 2004).

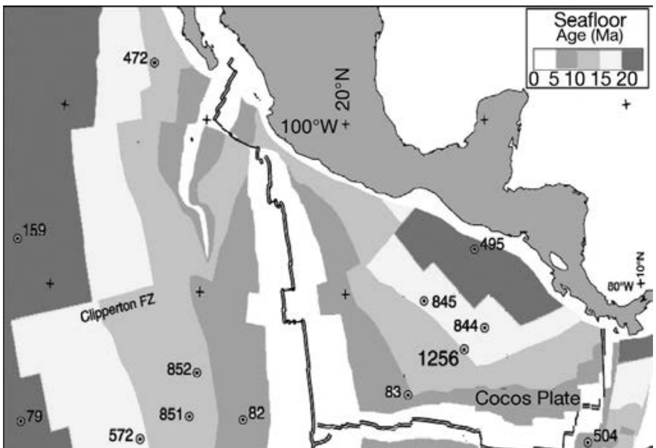


Fig. 1 - Location of ODP Site 1256 (Wilson et al., 2003). Age map of the Cocos Plate and corresponding regions of the Pacific Plate. Selected DSDP and ODP sites that reached basement are indicated by circles. The wide spacing of 10- to 20-m.y. isochrons to the south reflects the ultra fast (200-220 mm/yr) full spreading rate. FZ- fracture zone.

The studied massive lava, drilled in holes 1256C and 1256D, has been used as a clear marker unit for correlations of the igneous stratigraphy (Wilson et al., 2003). The massive lava is covered by thin sheet flows interlayered with some sediments, it lays on pillow lava and thin sheet flows, hyaloclastite, breccia and dikes.

Wilson et al. (2003) suggest that the massive unit originated as a thick lava flow that ponded between steep paleotopography. It has been interpreted as a ponded lava on the following grounds: 1) the absence of inflation-related structures on the upper surface of and within the massive lava, 2) the absence of fine-grained seal zones or lenses which suggests coalesced flow lobe contacts, 3) the largest groundmass grain size and the specific incompatible element concentration in the upper part of the massive lava body suggest the presence of a more differentiated, late solidified melt horizon in the upper one third of the lava body, and 4) the absence or scarcity of subhorizontal vesicle-rich layers and segregated melt lenses that are commonly observed in lower middle of inflated sheet flows elsewhere in Hole 1256D.

The key differences among various submarine flow morphologies are the dimension of individual parcels of lava delivered to the flow front, their inter-connectivity, and the rate of crust formation relative to the rate at which lava moves away from the vent during emplacement (Gregg and Fink, 1995; Perfit and Chadwick, 1998). Rate of extrusion and flow viscosity are the most important influences on submarine lava morphology.

STRUCTURAL AND MICROSTRUCTURAL FEATURES OF ODP-HOLE 1256C LAVA POND

Analytical Methods

In order to characterise the internal structures of the lava flow we examined 30 m of cores from Hole 1256 C and 70 m of cores from Hole 1256 D. We will focus on the cores from Hole 1256 C where the unusual features are mostly concentrated. Detailed description and measurement of the orientation of the main structural features have been performed on the cut surfaces of the cores and oriented thin sections. Thin sections every 10 cm were prepared cut normal to the flow plane where it was recognizable. For particular sites, three mutually perpendicular thin sections were prepared for a 3D examination of the structures of the lava. Determination of the microstructures and semi-quantitative chemical composition of minerals was made with scanning electron microscope (SEM) Philips 515 equipped with an energy dispersive microanalysis system (EDS) (accelerating potential 15 kV; sample current 20 nA) at the University of Genova. Mineral compositions of selected samples were determined by JEOL JXA-733 electron probe microanalyzer (EPMA) at the Center for Instrumental Analysis, Shizuoka University, using corrections from Bence and Albee (1968) and α factor of Nakamura and Kushiro (1970). Accelerating voltage was 15 kV and beam current was 1.2 x 10^{-8} A.

Structural Units of Hole 1256C

On the basis of the groundmass texture and the abundance of primary minerals, we have divided the massive lava in 9 igneous units (Fig. 2) as proposed in Wilson et al. (2003). On the basis of distinct flow-related structures and microstructures, and late to post-magmatic structural features, we further characterize the internal architecture of the flow in five structural units (Fig. 2).

At its top, the massive lava flow cored in Hole 1256C is composed of a holohyaline-cryptocrystalline lava surface with mostly variolitic texture. The lava changes downhole into an intergranular to coarse variolitic fine-grained massive basalt and into a cryptocrystalline, granoblastic basalt. Phenocrysts are dominantly olivine with subordinate amounts of plagioclase and clinopyroxene phenocrysts (mostly augite, rare pigeonite). The average plagioclase composition is An_{58} varying from An_{51} to An_{79}. Many plagioclase microlites are skeletal, which points to rapidly cooled portions of lava. Pyroxenes compositions fall into augite (Wo_{40}, En_{40}, Fs_{20}), and pigeonite (Wo_{10}, En_{55}, Fs_{35}). Diopside (Wo_{60}, En_{34}, Fs_5) occurs in late magmatic veins.

At its base, the massive lava flow has an unusual texture consisting of a variolitic groundmass recrystallized into a very fine grained granoblastic aggregate. Both clinopyroxene and magnetite in the recrystallized basal lava show equigranular textures and a rapid increase in grain size towards the overlying non-recrystallized lava. Plagioclase, on the contrary, tends to preserve its igneous texture at crystal cores even in the most intensely recrystallized sample.

Fig. 3 shows the different chemical composition of plagioclase and pyroxene analyzed in different igneous and structural units of the lava pond. Plagioclases from the groundmass at the base show higher FeO (wt%) than plagioclases from the above and pyroxenes show lower T of crystallization, calculated according to Andersen and Lindsley (1983).

On the basis of the structural and microstructural observations we have divided the lava flow into five structural units (SU) that are: SU1- flow upper crust, SU2 - flow crust, SU3 - core or flow interior, SU4 - core-base transition and SU5 - flow base (Fig. 2). The structural units partly coincide with the magmatic units recognized by Wilson et al. (2003), and include some of them.

SU1 - The upper portion, about 1 m thick, is characterized by a thin glassy breccia that is gradually replaced by hyaloophitic to hyalopilitic basalt; the crystallinity increases downflow. The fabric has strong anisotropy and shows different types of folds. SU1 can be considered as the folded and jumbled surface crust of the lava flow (Wilson et al., 2003).

SU2 - The following 4.5 m of the flow show a medium grain size (0.2-1.00 mm) with variolitic texture; flow fabric is isotropic and the most striking structures are subrounded millimetric vesicles (2 to 5%) and open fractures. Fractures are mainly subhorizontal but nearly vertical joints are also present. SU2 is interpreted as the vesicular crust of the flow.

SU3 - It is the thickest structural unit and it corresponds to the main body of the flow; its thickness varies in the recovered sections from the two holes (1256C and 1256D.) SU3 is divided into three sub-units characterized by the orientation and density of veins and fractures. The upper subunit (3a) is characterized by isotropic fabric and late magmatic veins (0.5-2.5 mm thick) with a density of about 2.5 veins per meter. The total density of open fractures and veins is 8.3 per meter. Late magmatic veins in Subunit 3a are subhorizontal whereas Subunits 3b and 3c show subvertical late magmatic veins with their highest density in Subunit 3b. Subunit 3c is very coarse grained (main size 0.5-2 mm) and characterized by isotropic fabric, with rare late magmatic veins dipping > 45°, and low dipping microfractures. It is important to note that Subunit 3c coincides with an anomalously high K_2O content (an order of magnitude increase, from 0.08 to 0.74 wt% K_2O; Wilson et al., 2003).

SU4 - This unit represents the transition between the core and the bottom of the lava pond. It has an isotropic medium grained fabric (0.7-0.8 mm), no traces of late magmatic veins occur, and shows heterogeneous distribution of fractures.

SU5 - The bottom of the lava is about 1.7 m thick, and consists of cryptocrystalline basalt (grain size < 0.02 mm) with anisotropic flow fabric. It has a unusual texture consisting of recrystallized variolitic groundmass and magmatic veins, which shows synmetamorphic ductile deformation texture. Late magmatic veins occur in different overprinting sets and are folded and disrupted.

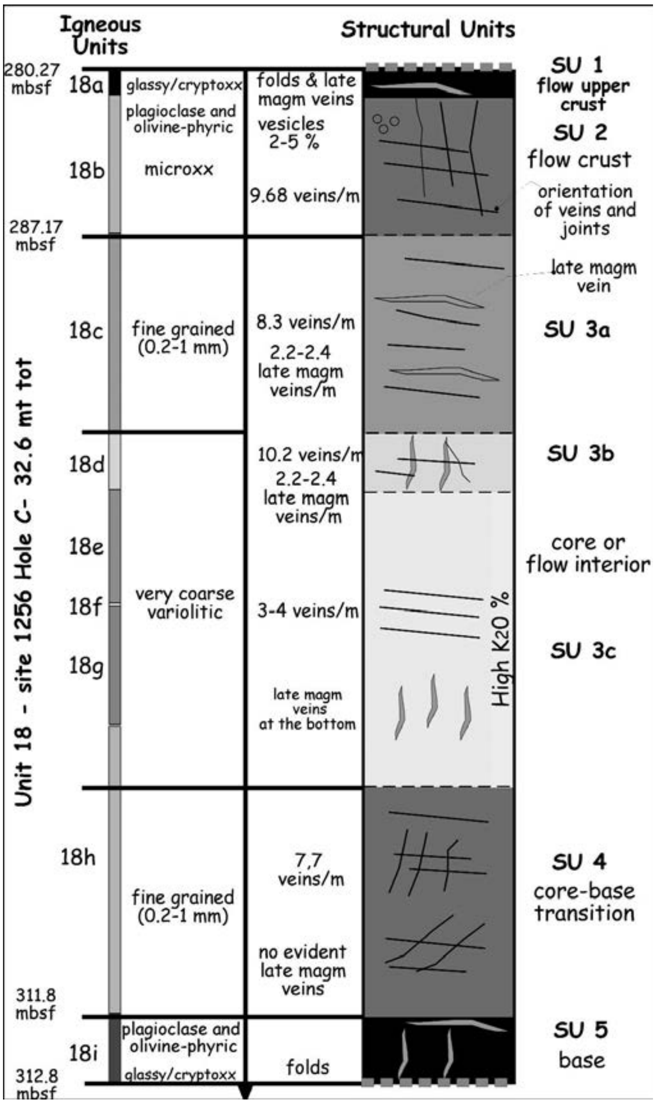
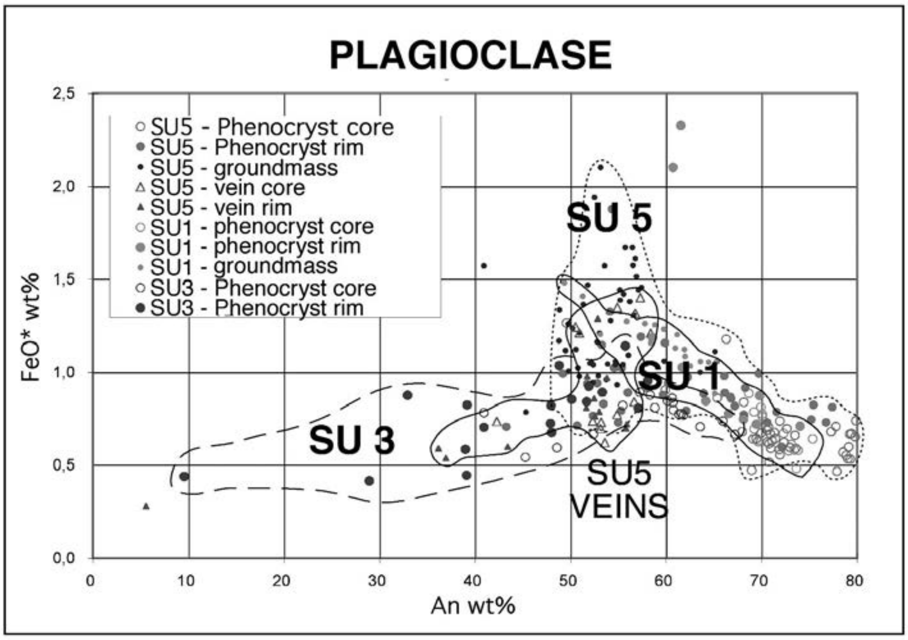


Fig. 2 - Igneous and structural units of Hole 1256C lava pond. The main structural features and occurrences of veins are reported. Lava pond (igneous unit 18 in Wilson et al., 2003) has been defined from core 206-1256C-8R4 (280.27 mbsf) to core 206-1256C-11R7 (312.8 mbsf). Cryptoxx stands for cryptocrystalline, microxx for microcrystalline. For more details see text.



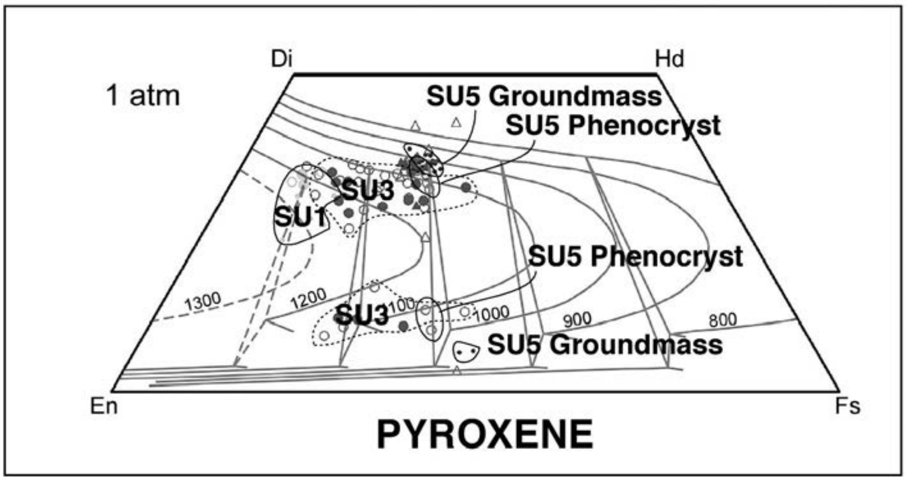


Fig. 3 - Chemical compositions of (a) plagioclase and (b) pyroxene obtained by electron microprobe analyses of samples from different units of the lava pond. Pyroxenes are plotted in the quadrilateral geothermometry of Lindsley and Andersen (1983). The differences in mineral compositions between the core and the recrystallized base of the lava pond are clearly shown. Symbols refer to minerals from different structural units of the lava pond. SU: Structural Unit; for their definition see text and Fig. 2.

Main microstructural features

We observed that microstructures related to ductile deformation are common only at the top and bottom of the lava flow, whereas structures related to brittle-ductile and brittle deformation occur throughout the whole ponded body.

In the upper SU1 and bottom SU5 a variety of textures related to intense flow and compaction can be recognized (Figs. 2 and 4) such as planar alignments of crystals, modal domains and domainal textures (Smith, 2002) deformed by overprinting folds.

The common microstructures related to brittle-ductile and brittle deformations are late magmatic veins filled mainly with plagioclase, quartz, magnetite, clinopyroxene, and granophyric to vermicular intergrowths of sodic plagioclase and quartz (Fig. 4). The geometric features of the vein walls together with their infilling are evidence of development in a partially crystallized lava and they record flow during the transition from ductile lava to brittle rock. Additional features are evidence of the brittle-ductile behaviour during their development: the lack of chilled margins and straight contacts (Fig. 4c), plagioclase laths in the wallrock show both shape- and lattice-preferred orientations parallel to the vein border, segregation pockets are in array of en echelon tension gashes (Fig. 4a), extension fissures are parallel to the folds arc, and veins along shear zones cut magmatic-related shear folds with the same sense of shear.

In the core of the flow, i.e. SU2 to SU4, brittle-ductile structures such as tension gashes, pull-apart veins and fractures are present; no plastic deformation is evident in hand specimen or microscopic scale. In the finer-grained portion of the basalt, clinopyroxene and plagioclase show evidence of both intracrystalline and intergranular deformations, in places, interpreted as sites of strain localization (Agar and Marton, 1995). In plagioclase laths, healed arrays of fluid and/or solid inclusions, interpreted as syn-crystallization features, are reopened or cut by conjugate sets of microcracks. Microcracks are mainly controlled by the crystallographic cleavages and can be interpreted both as cooling or deformation-related features. In SU3-4 one set of microfractures is filled with the late granophyric interstitial minerals, suggesting that this deformation event occurred when lava was not yet completely crystallized. Conversely, intragranular microcracks healed by glass now altered to secondary minerals (e.g., saponite) are interpreted to be late to post-magmatic, as they overprint or reactivate syn-crystallization inclusions and cooling-related microcracks. In the coarse-grained basalt of the flow interior, plagioclase crystals that are clustered in discrete domains rarely show a moderate

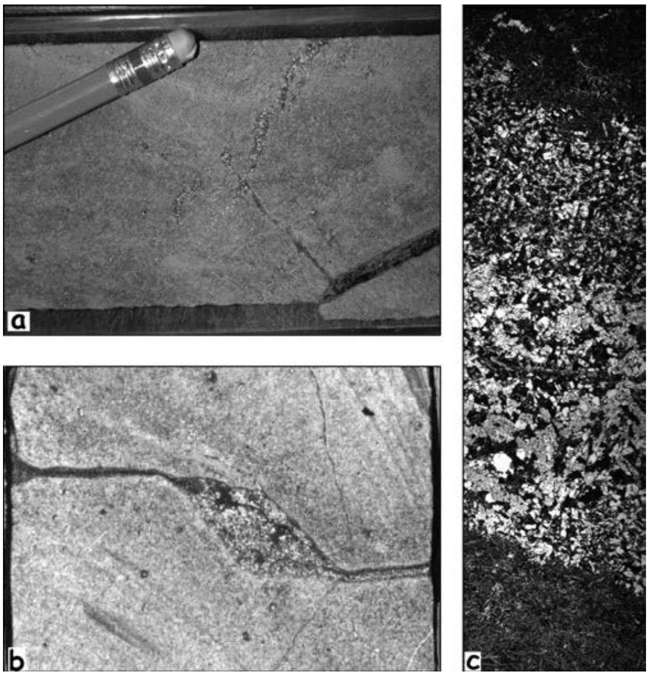


Fig. 4 - Examples of late magmatic structures in Hole 1256C lava pond. a) Array of late magmatic tension gashes filled by plagioclase, clinopyroxene, quartz and apatite. Diameter of the core is 6 cm. b) Centimetric pull apart with late magmatic infilling minerals. Diameter of the core is 6 cm. c) Photomicrograph of a late magmatic vein in SU 5. Sample 206-1256C- 11R-7-9-12 cm. Cross polarized light.

preferred orientation. Some of these crystals show impingements-like features (Nicolas and Ildefonse, 1996), which is evidence of the accomodation of flow in the presence of very low melt fractions.

Microstructures of the flow upper crust (SU1)

The flow upper crust is characterized by the occurrence of multiple generations of ductile folds and superposed brittle-ductile to brittle deformations. These features record the dynamic character of the cooling of this portion of the lava that reflects the changes in mechanical properties of crystallizing lava and the relation between flow and cooling (Gregg et al., 1998).

The flow upper crust SU1 has a glassy portion with patches of fine plumose crystallites form and patches of glass linked to supercooling of lava (Fig. 5 a). The number and density of crystallite patches and the crystal density in individual patches increase downflow and finally coalesce to form the entire groundmass. Clinopyroxene and plagioclase ± Ti-magnetite form spheroidal or fan-shaped crystal aggregates, finer grained varieties of which can be referred to as varioles (Bryan, 1972; MacKenzie et al., 1982; Wilson et al., 2003) (Fig. 5a). Crystallinity increases downflow within the first centimeters of the lava unit; crystallinity records changes also in the portion where varioles prevail but apparently not according to a vertical gradient.

In the top 40 cm of the cored lava pond, very fine varioles and patches of intervening glass are deformed in oblate ellipsoids and aligned in bands. Commonly flattened spherulitic clusters are intercalated with plagioclase and Fe-Ti oxide-rich submillimetric bands bordered by granular pyroxene and platy plagioclase that have a strong preferred orientation (Fig. 4 b). A layering is defined by the shape preferred orientation of minerals, by variations of modal composition, and planar crystal abundance. Some of these textures can be compared to the "boa texture" described in the upper solidification front of the Holoyoke basalt flow described by Philpotts and Dickson (2002). In the "boa texture" ophitic pyroxene-plagioclase clusters form nearly horizontal layer separated by patches of mesostasis every 1-2 mm. SU1 banding differs from the "boa texture" primarily by the flattening of the aligned clusters. SU 1 banding seems to form under pure shear or high flow deformation whereas the "boa texture" seem static or deformed only by gravity (Fig. 5c of Philpotts and Dickson, 2002). According to Philpotts and Dickson (2002) this texture is linked to the roof zone of a lava sheet and its geometry can be related to the shape and evolution of the solidification front. The recognition of these layerings is critical for the understanding of the shape of the solidification front and the physical properties of the crystal mush in the upper solidification front.

Microfolds with different geometries and orientation have been observed in SU1 and SU5 The flow upper crust SU1 has a glassy portion with patches of fine plumose crystallites form and patches of glass linked to supercooling of lava (Fig. 5a). The number and density of crystallite patches and the crystal density in individual patches increase downflow and finally coalesce to form the entire groundmass. Clinopyroxene and plagioclase ± Ti-magnetite form spheroidal or fan-shaped crystal aggregates, finer grained varieties of which can be referred to as varioles (Bryan, 1972; MacKenzie et al., 1982; Wilson et al., 2003) (Fig. 5a). Crystallinity increases downflow within the first centimeters of the lava unit; crystallinity records changes also in the portion where varioles prevail but apparently not according to a vertical gradient.

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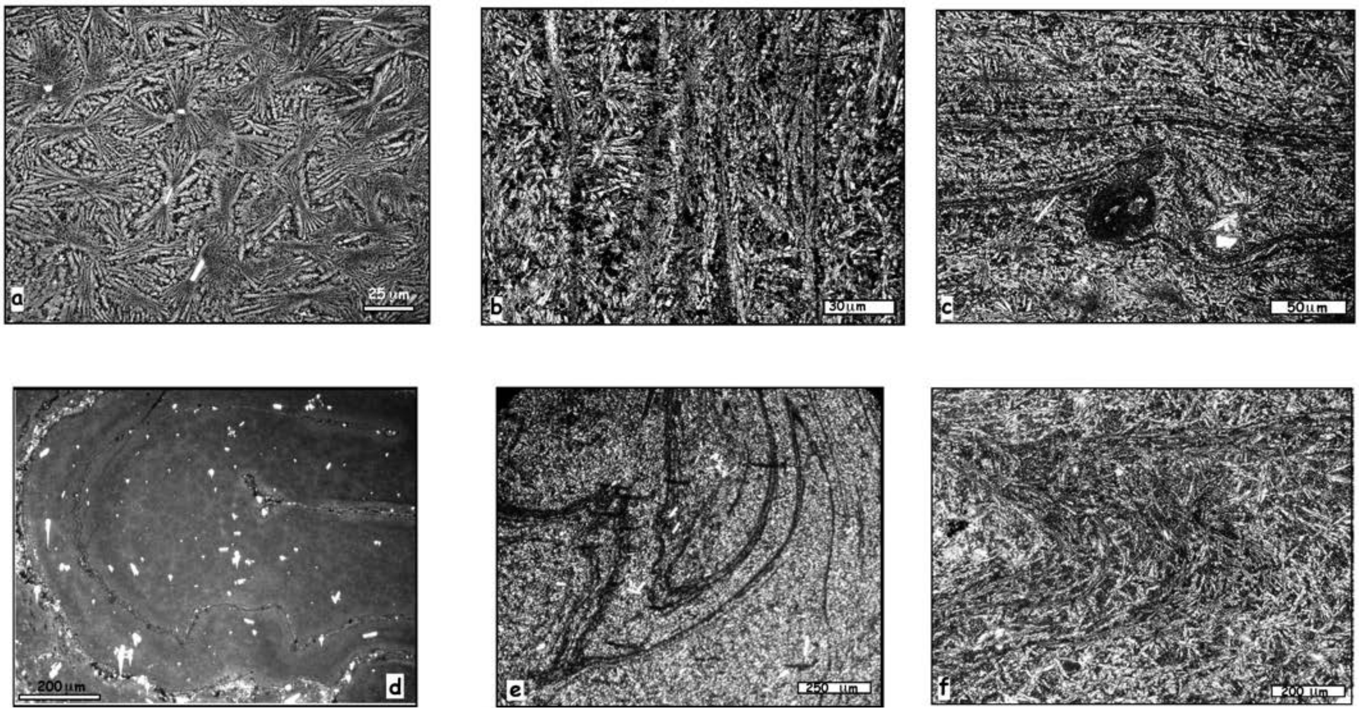

Fig. 5 - Photomicrographs of microstructures from the upper crust SU 1. a) Variety of variolitic texture. Very fine varioles consisting of plumose clinopyroxene intervened with thin plagioclase laths. Plane polarized light. Sample 206-1256C-8R-4-122-125 cm. b) Modal and domainal layerings. Alignments of flattened clusters of plagioclase, pyroxene, and Ti-magnetite alternated with layers of aligned but less flattened clusters of the same minerals. Plane polarized light. Sample 206-1256C-8R-4-108-110 cm. c) Example of asymmetric flow related structures: quarter folds (Passchier and Trow, 1996) around a clinopyroxene-plagioclase glomerocryst. Plane polarized light. Sample 206-1256C-8R-4-122-125 cm. d), e), f) Examples of microfolds in the upper crust (SU1) moving downhole. Sample 206-1256C-8R-4-114-117 cm. Sample 206-1256C-8R-4-117-119 cm. In d) plagioclase crystallites are reoriented lining the profile of the fold. Folded veinlet is pyroxene and garnet bearing.

folds are isoclinal to similar (class 1B of Ramsay, 1967) with subrounded hinge zone (Fig. 5d). The wavelength to thickness ratio of the folded layer and the amplitude to wavelength ratio are high, i.e., 20:1 and 4:1 respectively. The axial plane dips about 30°. The geometric features of the microfolds point to a deformation characterized by a component of subvertical shortening (flattening) combined with a non-coaxial component. Open microfolds deform the low dipping isoclinals; they have subvertical axial planes and very low amplitude/wavelength ratios. The wavelength of the superposed generations of folds decreases with time, due to the increasing crystallization and viscosity.

A change in orientation of the folds has been observed from the upper to the lower layered portion of the SU2 flow crust (Fig. 5e). In the lowest part of SU2 where the degree of crystallinity increases, microfolds are asymmetric similar folds lined by reoriented plagioclase crystals in a variolitic crystal mush (Fig. 5f). The axial plane of the folds dips about 50°. The vertical component of shortening (flattening) is clearly less important than in the above portions of the crust and the flow lines are slightly inclined. From the geometry of these structures we infer that the solidification front (Marsh, 2002) is not a horizontal limit and the weight of the component of pure shear in the development of folds decrease downward. Gravity forces and shearing probably alternated during emplacement of the lava. On the whole, the strain is heterogeneously distributed in SU1 and may be linked to the changes in crystallinity % and the following change from Newtonian to non-Newtonian rheology of the basaltic lava (Smith, 1997). Domainal textures develop where cristallinity is higher and nearly transpose folds in the hinge zones resembling an axial plane cleavage.

In conclusion, we observed that the orientation of the foliation related to lava-flow in SU1 changes from the horizontal to steeply dipping downwards; it may be linked to the prevailing action of non-coaxial shear deformation or the prevailing action of gravity. The structures reflect the modes of emplacement of lava and result from the balance between a gravity transport term and the magmastatic pressure gradient (Bruno et al., 1994) even if the lava flow dynamics can be locally influenced by other factors.

Microstructures of the flow base (SU5)

The base of Hole 1256C the ponded flow has an unusual texture consisting of recrystallized variolitic groundmass (Figs. 6 and 7) and has magmatic veins, which shows ductile deformation textures (Fig. 8). The lowermost part of the entire lava flow, is an aphyric cryptocrystalline basalt with a groundmass texture of equigranular clinopyroxene and equigranular Ti-magnetite (Figs. 7 and 8) with sparse plagioclase laths that reflects recrystallization at near-magmatic temperatures (Fig. 2). While the original variolitic texture is still recognizable in places, the groundmass clinopyroxene and Ti-magnetite are almost completely recrystallized into equigranular neoblasts. The Ti-magnetite crystals show equant, subhedral, skeletal octahedral forms quite different from those in the lava core where Ti-magnetite has dendritic morphology, suggestive of higher cooling rate (Wilson et al., 2003). Larger plagioclase laths are incompletely replaced by neoblasts from their margins; they mainly preserve their igneous texture and are reoriented or microfractured (Fig. 7). Both clinopyroxene and magnetite show rapid increases in grain size toward the overlying massive lava, which seems to be the heat source of recrystallization (see Fig. F 79 in Wilson et al., 2003).

Recrystallization affects the base of the lava unit from its top, i.e. from the contact with the core of the lava (SU4-SU5 transition). It is characterized by a variolitic texture made by plagioclase and pyroxene. Most of the observed variolitic microstructures resemble those developed during the reheating of Kilauea basalt glass (Burkhard, 2001) that evidenced homogeneous areas where spherulitic growth of very fine grained silicates and Fe-Ti oxide at their apices from glass occurred at 919°C in air (Fig. 5 of Burkhard, 2001), similarly to Hole 1256C SU5.

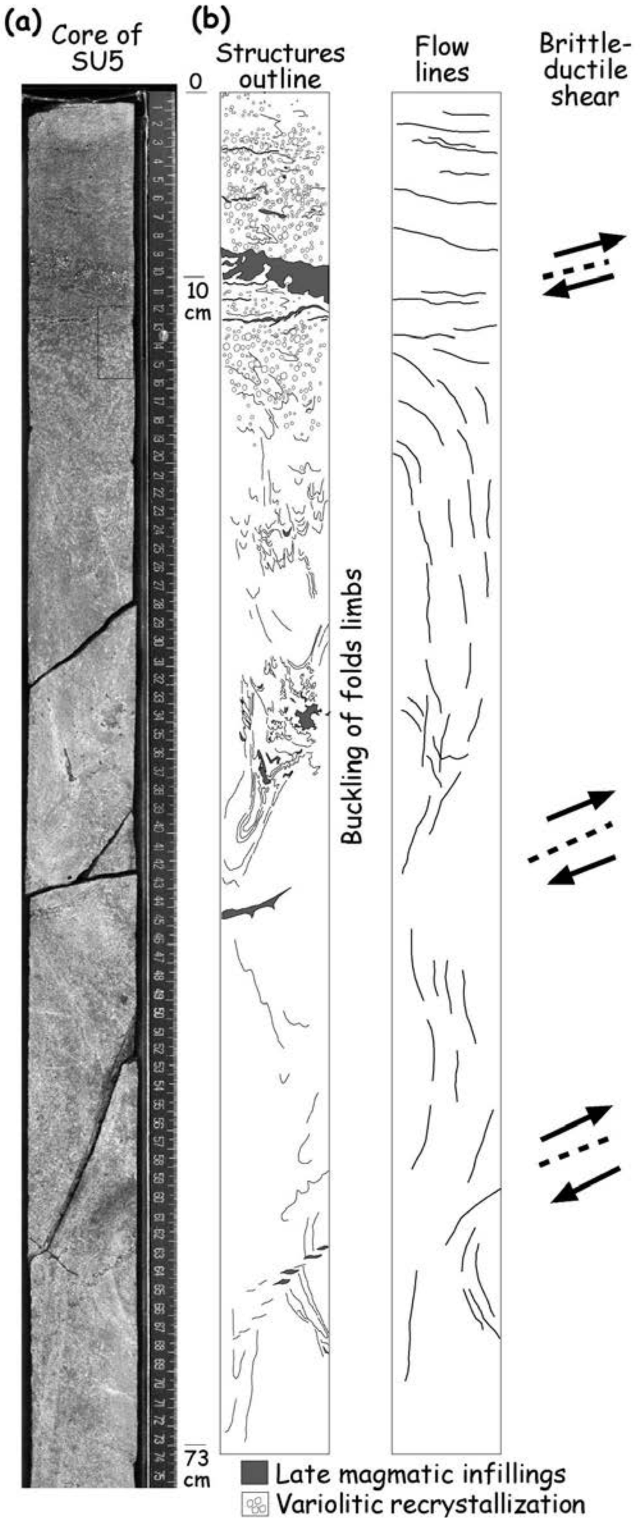

Fig. 6 - Structures at the base of the Hole 1256 massive lava. a) Close-up photo of a piece of core 206-1256C-11R-7. Box refers to the location of the thin section in Fig. 7a. b) Redraw of main structures lined by the veinlets. Late magmatic veins are filled in gray, related shear-senses are shown as well.

In SU5 two main types of layering linked to the lava flow are present. In the upper part, a textural banding is defined by plagioclase abundance (modal layering) and/or their preferred orientation; at sites relics of plagioclase laths within the cryptocrystalline groundmass show a shape preferred orientation and lattice-preferred orientation. Single oriented plagioclase laths (< 0.1 mm) are either scattered throughout the groundmass or are clustered in thin folded bands. At the top of SU5 the foliation (drawing "flow lines" on the cut surface) defined by plagioclase crystals preferred orientation are nearly horizontal; within 20 cm down-hole plagioclase bands become deflected and disrupted. Plagioclase preferred orientation and the axial planes of folded bands turn into nearly vertical orientation down to the base of the flow.

Different sets of veins are present that include veinlets (< 0.5 mm thick) and coarse grained late magmatic veins, all show ductile (folding) and brittle-ductile deformations. Coarse grained veins cut the veinlets. The veinlets have very fine grained infilling minerals and are lined by the high concentration of small magnetite grains (probably linked to the depletion in pyroxene and plagioclase by fractional crystallization) (Figs. 8a, 8b, 8c). Minerals in veinlets are equigranular neoblasts and show evidence of subsolidus intracrystalline deformation such as undulose extinction. The veinlets are deformed in ptygmatic to isoclinal folded profiles (Figs. 8a and 8d). In 3-D the folds are tubular folds with subvertical axial planes and maximum elongation axis plunging about 80° respect to the vertical axis of the core (Figs. 6 and 8). Moreover folds are disrupted and transposed downflow. Buckling of fold limbs occurs in places (e.g., 30-42 cm interval in Fig. 6). Recrystallization in variolitic texture occurs heterogeneously downflow, and partly overprints and replaces some folded and disrupted veinlets.

The folded walls of the veinlets show evidence of subsolidus intracrystalline deformation, and also suggest that the deformation took place when magma was not completely crystallized and partly before the recrystallization of the lava. The geometric relationships suggest that deformation took place prior to or at the same time as the variolitic plagioclase texture development.

Other peculiar microstructures of SU5 are represented by "mantled porphyroclasts" ("porphyrolaths"). In mm-wide layers, fine grained palgioclase and pyroxene are arranged in spiral chains around one inner plagioclase grain, or rarely one magnetite grain (Fig. 7). Supposing that a relative rotation occurred, the arrangement of the crystals indicates a rotation of more than 360°. The orientation of the central crystals is parallel to the main vertical flow plane with different sense of rotation. We interpret tentatively these microstructures as linked to a near turbulent local flow (Ramsay and Huber, 2000) during the lava emplacement. Across the base of the unit we can draw layers with laminar flow surrounding layers with quasi-turbulent flow; the boundary layers being represented by veinlets.

Relationship between recrystallization and deformation in SU5

As described above, the groundmass at the base shows recrystallized variolitic texture and the possible heat source of recrystallization seems to be the core of the lava above (SU 4) as both clinopyroxene and magnetite in the recrystal-

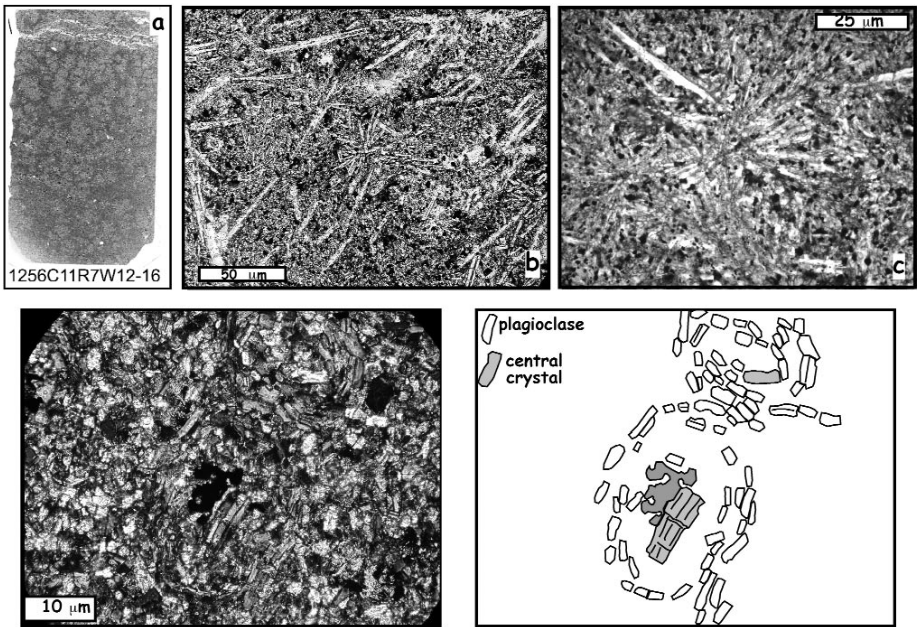

Fig. 7 - Examples of textures from the base of the lava pond SU5. a) Close-up of a thin section located at the top of SU5. Patches of recrystallizations are visible. Sample 206-1256C-11R-7-12-16 cm. b) Variolitic texture replaces pre-existing plagioclase laths with shape preferred orientation. Plane polarised light. c) Detail of the central part of photo 7b). Plane polarised light. d) Microphotograph of faint mantled porphyroblasts. Their geometry is clear only after the analysis and redraw of microprobe images. Crossed polarised light. e) Redraw of the microstructures of Fig. 7d.

lized part show rapid increases in grain size towards it. However, plagioclase tends to preserve its igneous texture at least in its core even in the most intensely recrystallized sample. At the top of SU5 the variolites have a spherical undeformed shape (Fig. 7a), whereas downhole to flattened and disrupted shapes. In the lower part recrystallization is heterogeneously distributed and less pervasive. At the top of SU5 relics of isoriented plagioclase laths suggest that recrystallization occurred after the alignment of plagioclase. Downhole, recrystallization seems to have occurred at the same time with deformation or later than deformation of the veinlets. In the recrystallized groundmass coarser equigranular opaque minerals seem to have flowed inside folded portions of lava (Fig. 8). Coarser magnetite probably recrystallized during flow, whereas finer grains of magnetite partly follow and outline the profile of the folds and probably represent to a later stage of recrystallization (linked to fluids in the veinlets ?).

A thin section taken 35 cm below the top of SU5, shows progressive recrystallization of earlier, more intensely deformed vein minerals that are cut by later, planar veins with chilled margins against the host basalt. Earlier veins are progressively recrystallized into equigranular neoblasts without any evidence of subsolidus intracrystalline deformation such as undulose extinction and kink bands. This, together with the undulating margins of the veins, suggests that either the deformation took place under hypersolidus conditions or the rate of replacement of deformed crystals with neoblasts always exceeded the rate of intracrystalline deformation.

DISCUSSION

Comparison with subaerial massive flow

Structural analysis of subaerial lava flow is reported in several works (e.g., Manley and Fink, 1987; Self et al., 1997; Chadwick et al., 1999; Ventura, 1998; 2001). On the contrary, to our knowledge, structural analyses detailed structural analyses features of complete subaqueous massive lava flows are missing in the literature. Our microstructural and petrographic study of a large subaqueous lava pond drilled in ODP Holes 1256C and 1256D has shown that the most interesting and unusual features occur at the top and the bottom part of the massive lava.

In some way the general features of the massive unit of ODP at Site 1256 (6°44N, 91°56W; eastern flank of the East Pacific Rise) may resemble those of pahehoe lava (Self et al., 1998) except for its very low vesicularity and the unusual structural features of its base. This confirms that the lava cannot be interpreted as an inflated sheet flow but most probably as a lava pond. Nevertheless full petrographic and microstructural analyses on submarine lava pond or lava lake are rare or do not exist in order to make direct comparisons.

As regards the distribution of fractures (Fig. 3), their pattern can be roughly divided into an upper jointed crust (SU1 - SU3a), massive core (SU3b - SU3c) and a basal jointed crust (SU4 - SU5), a distribution that resembles the pahoehoe sheet lobes of the Columbia River Basalts and inflated sheet flows of Oman (Umino et al., 2000).

Significance of microstructures in the flow upper crust of Hole 1256C

The upper flow crust of the lava pond may be interpreted as a folded and jumbled surface crust(Wilson et al., 2003) as described in Gregg et al. (1998). Textures in the upper glassy portion are related to quenching and supercooling of the lava. The variolitic textures in the inner part of the crust SU1 and SU2 resemble the reheating and devetrification texture due to the heat flow from internal portion of the lava. The reheating of glass may be related to the heat supply from hotter lava below the crust; the differential movement of the thin brittle crust with respect to the underlying plastic lava may cause the fracturing and sinking of glassy slabs into hotter lower lava as evidenced by the change in flow lines orientation from nearly horizontal to vertical. The early crystal alignments that delineate the foliation in the lava flows reflect viscosity gradients during fluid-state flow (Smith et al., 1994) and may be interpreted as layers formed parallel to the downward-growing crystallization front in the magmatic state (Philpotts and Dickson, 2002). The structures in the crust indicate also high straining of the groundmass with melt present (Smith, 1997).

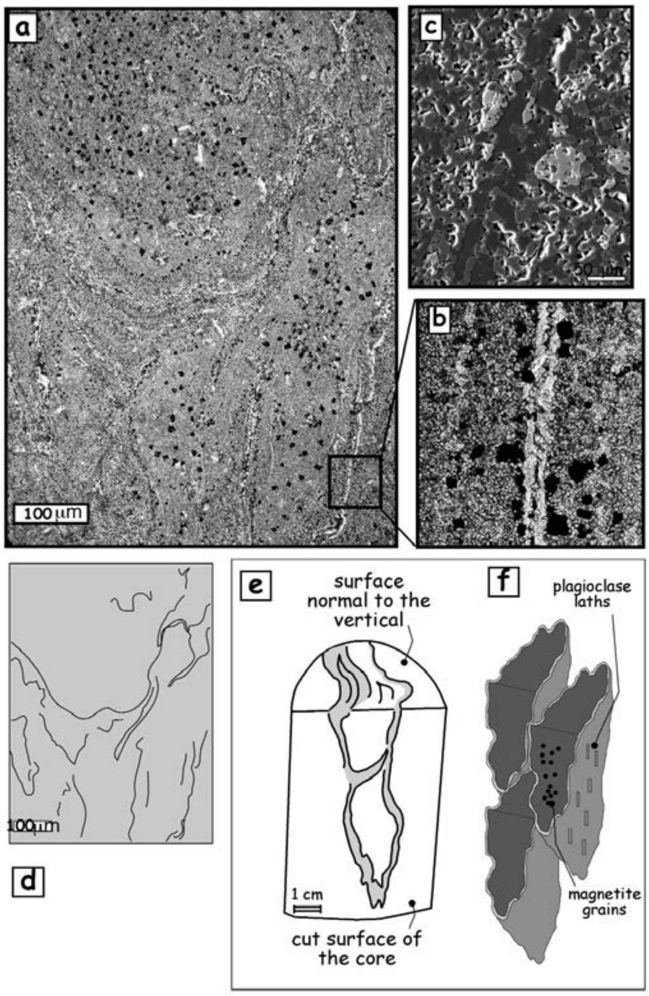

Fig. 8 - Microstructures from the base of the lava pond - SU 5. a) Microphotograph of folded and disrupted veinlets. Veinlets weld and coalesce fluidal droplets of lava where magnetite is partially reoriented. Sample 206-1256C-Box refers to Figs. 8b and 8c. b) Sketch to outline veinlets of photo 8a. c) Detail of the veinlet boxed in 8a. d) Sketches of a fold on a piece of core.

Significance of microstructures in the base of Hole 1256C lava pond.

In order to explain the unusual microstructures in the basal portion of the lava unit, we propose and discuss two opposite interpretations: 1) they represent structures equivalent to spatter deposit developed in a submarine environment, linked to first stages of emplacement of the lava, or 2) they represent structures formed during lava drain-back, during late stages of emplacement of the lava.

1) Sumner et al. (2005) define a spatter in subaerial environment as an accumulation of originally hot, fluid pyroclasts, which agglutinate on landing. The resulting deposit may be an agglutinate or spatter pile, in which the clast outlines are partly or wholly retained, or it may give rise to a spatter deposit that is the first stage in complete coalescence of clasts to form lava in Hawaiian-style fire-fountain eruptions. As outlined by Sumner et al. (2005), at very high accumulation rates, where large volume and close proximity of clasts allow only minimal cooling, immediate coalescence of impacting clasts may lead to fountain-fed lavas and lava ponds. The structures similar to tubular and disrupted folds lined by thin veinlets described in the base of the Hole 1256C lava unit may be interpreted to represent ductile hot spatter clasts (Fig. 8) erupted in the initial stages of the vent opening, but in submarine environment. The still fluid clasts came in contact with each other, flowed, and flattened on a steep paleotopography. The space in between coalesced, and partly recrystallized during the emplacement of the lava. The temperature of the lava at the top of the spatter pile was high enough to create destabilization and recrystallization during deformation. Thus deformation took place prior or at the same time as the variolitic plagioclase texture developed, and before recrystallization of the varioles. Inside clasts local turbulent flows developed, as evidenced by the rotated relics described above (Figs. 7d and 7f).

2) On the fast spreading East Pacific Rise, flows are erupted and confined within a narrow axial summit trough in many places lava (Fornari et al., 1998). If drainback occur, the lava drains back down to its eruptive vent or out through pre-existing holes in the wall of the summit trough (Fornari et al., 1998). In this case we can explain the structures in the base of Hole 1256 lava pond as due to a drainback and so the vertical downflow linked to an abrupt change in the basement morphology. This hypothesis is not supported by the recrystallization vs deformation observations but agrees with the strain distribution. We observed a change of strain path in the base of the lava pond (Fig. 7), which may be explained not only by pulsated inflation but also by the partial collapse of the basement at the bottom of the lava unit with the subsequent abrupt change in the strain rate.

The arrangement and the features of the interfaces of the brittle-ductile microcracks show that similar textures should have been developed when crystallinity reaches about 30-40% and shear thickening led to tearing of the crystal mush (Smith, 2002; Philpotts and Carroll, 1996). Discontinuous sheets of melt between layers of stretched mush probably provided planes of weakness and ductile deformation was enhanced again. Discontinuous sheets of melt provide planes of weakness and the bulk density of the basalt changes; if gravitational instability and the weight of the overlying lava column are more effective then horizontal shear flow, detachment and sinking of differential banding occur. In this case the folded veinlets have to be explained as “real” sheath or tubular folds of pre-existing straight planar anisotropies (rather than coalesced viscous clasts). A new increment of the shear flow caused the brittle-ductile shear gashes that overprinted the vertical flow. The rheological instability of that multilayer caused the disruption and sinking of the flow planes. This may have been enhanced by irregularity or inclination of the basement. Moreover, the analysis of the vertical flow of the Hole 1256C lava pond reveals the occurrence of an inclined boundary that limits the flow as shown by the mostly asymmetrical structures.

CONCLUSIONS

This work provides data on the petrographic and microstructural features throughout a vertical section of a submarine ponded lava cored on a 15 Ma old oceanic lithosphere (superfast seafloor spreading, ca. 220 mm/yr). The lava pond represents an off-axial sequence confined by rugged paleotopography, located directly on pillow lava and covered by thin sheet flows. The unusual microstructures at the base of the lava pond may be interpreted either as hot coalesced spatters erupted in the first stages of the emplacement of the lava, or, less likely as products linked to lava drainback during late stages of the emplacement of the lava.

The base of the lava pond shows unusual textures that can be interpreted as a spatter deposit fed by a subaqueous lava fountain. This may represent the first stage of the emplacement of the lava.

The occurrence of a thick off-axis lava flow at the top of pillow lavas and the recognition of peculiar internal microstructures may be helpful for identifying a style of crustal accretion where the extrusive lavas and dikes overlie the gabbros. An additional thickness of lavas that flowed from the ridge axis to cover the immediate flanks must be taken into account to determine the real stratigraphy of oceanic crust accreted on-axis and to re-consider the predicted depth of gabbros in a superfast ridge.

ACKNOWLEDGEMENTS

We wish to thank the Scientific Party of ODP-Leg 206 for fruitful discussion during the cruise. Ocean Drilling Program is acknowledged for providing the rock samples. Thoughtful reviews provided by Christine Laverne, Giancarlo Molli and Piera Spadea greatly improved this manuscript. Thanks to Lisa Gilbert for revision of the English of the manuscript. This study was supported by MIUR-PRIN 2004 grants Prot. 2004042380 to P.T.

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Received, March 6, 2006
Accepted, November 4, 2006