BASALTIC BRECCIAS IN THE UPPER OCEANIC CRUST, HOLE 504B (COSTA RICA RIFT, PACIFIC OCEAN)

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ABSTRACT

DSDP/ODP Hole 504B is located in the Panama Basin, eastern Pacific ocean, 200 km south of the Costa Rica Rift, which is a 171-km-long east-west trending segment of the Cocos-Nazca Spreading Center. Hole 504B penetrates 2.1 km into 5.9 m.y. old oceanic crust consisting, from the top to the bottom, of pillow lavas (571.5 m) covered by 274.5 m of sediments; a transition zone (209 m), and a lower zone composed of diabasic dikes (1056 m). Basaltic breccia is a significant component of the volcanic section, down to the upper part of the sheeted dike complex. Six main types of breccias were recognized through core and petrographic observations. Only jigsaw-puzzle breccias can be interpreted as tectonic. Although overall pore-fluid pressures slightly lower than hydrostatic were measured at Hole 504B, jigsaw-puzzle breccias may have formed under local conditions of suprahydrostatic fluid pressure, mostly beneath impermeable barriers such as massive basaltic flows. High fluid pressure conditions were favoured by a structural setting allowing the action of a fault-valve. Highly fractured zones identified by core observations and geophysical logs at depths of about 400-550 mbsf and 800-1100 mbsf, respectively, likely correspond to faults, creating the conditions for a fault-valve mechanism. Breccias of the stockwork zone were produced by focused fluid flow associated with a discharge hydrothermal cycle. All the other breccias recognized in the studied section are interpreted as deriving from either *in situ* fragmentation of basalts or sedimentation of basaltic debris.

INTRODUCTION

Deep Sea Drilling Project/Ocean Drilling Program (DSDP/ODP) Hole 504B (Costa Rica Rift, Eastern Pacific Ocean) represents by far the deepest penetration into oceanic crust, extending through 274.5 m of sediments and 1836.5 m into basement. It is the only hole which clearly penetrates through the extrusive pillow lavas and into the sheeted dike complex predicted from studies of ophiolites (Cann et al., 1983; Anderson et al., 1985; Becker et al., 1988; Dick et al., 1992; Alt et al., 1993).

Although structural and microstructural studies have only recently been systematically carried out in ODP drill cores from the oceanic crust (since Leg 118; Robinson et al., 1989), the occurrence of breccias in the crustal section drilled at Hole 504B is well documented in core descriptions (Cann et al., 1983; Anderson et al., 1985). During DSDP Legs 69 and 70 at Site 504, autoclastic breccias cemented by clays were recognized at the base of the hole (about 770 mbsf). In the section drilled during DSDP Leg 83, highly brecciated material has been described as hyaloclastite in pillows and as rubble surfaces of massive flows (Anderson et al., 1985). More detailed descriptions of breccias, together with other structural features, have been provided by Agar (1990, 1994) and Tartarotti et al. (1998) for Hole 504B. During ODP Leg 148 (Alt et al., 1993), various types of breccias were observed in core sections at Hole 896A, located 1 km south of Hole 504B. They have been described by Harper and Tartarotti (1996), who revealed the occurrence of jigsaw-puzzle breccias as one of the most common breccias of probable tectonic/hydrothermal origin. The occurrence of breccias identical to those found at Hole 896A was reported also at Holes 504B by Alt et al. (1996).

In spite of the abundant records of breccias at Hole 504B and analogous holes, a methodical description of all the recovered breccias and a definite interpretation of their origin namely, sedimentary vs. tectonic, is still lacking: this is not only due to the fact that structures in the oceanic crust in core material have not been systematically investigated until now, but also to the fact that in rock portions of reduced dimension as those of a drill core, the origin of breccias is often uncertain and ambiguous.

In order to gain an insight on the spatial distribution of breccias through Hole 504B, in relation with different lithologies, and to record all types of breccias recognizable by visual core observations, we carried out a systematic and detailed study on all brecciated intervals occurring in the upper volcanic section, in the transition zone, and in the upper part of the sheeted dikes, in a depth range between 274 mbsf and 1200 mbsf. This investigation was performed by direct core observations by P.T during a visit to the ODP West Coast Repository at La Jolla, CA, and completed with thin section descriptions. The purpose of this paper is first to describe all types of breccias recognized at Hole 504B, and to discuss their origin by integrating results from our core observations with data reported in literature. Second, we focused the attention to a few types of breccias which can be helpful for tracking the past and present fluid circulation patterns of the study hole and interpret their regional and tectonic frame.

GEOLOGICAL SETTING OF SITE 504

DSDP/ODP Hole 504B (1°13.611'N; 83°43.818'W; water depth 3460) is located in the Panama Basin (eastern Pacific Ocean), 200 km south of the Costa Rica Rift (Hey et al., 1977), which is a 171-km long east-west trending segment of the Cocos-Nazca spreading center, bounded by the Panama Fracture Zone to the East and by the Ecuador Fracture Zone to the West (Fig. 1). A well-developed pattern of linear magnetic anomalies trending near east-west south of the Costa Rica Rift, indicates the absence of fracture zones within the segment during the last 10 m.y., and a relatively simple plate spreading history (Klitgord et al., 1975; Lonsdale and Klitgord, 1978). Seismic-reflection data over Hole 504B (Langseth et al., 1988) indicate that the hole is located on a series of half-graben structures, with faults dipping towards the axis, and crustal blocks that tilt gently (< 5°) away from the spreading axis (Fig. 1b).

Hole 504B was spudded in October 1979 during DSDP Leg 69, several hundred meters east of an earlier pilot hole which drilled 73 m into basement during Leg 68 (Hole 501). Hole 504B was subsequently deepened and/or logged during parts of 7 other legs, including Leg 70 (1979), Leg 83 (1982), Leg 92 (1983), Leg 111 (1986), Leg 137 (1991), Leg 140 (1991), Leg 148 (1993).

Hole 504B penetrates 2.1 km into 5.9 m.y. old oceanic crust, providing a significant in-situ reference section for the physical and chemical structure of the upper oceanic litosphere. The lithostratigraphy in the hole includes from top to bottom, a layer of sediments (274.5 m); an upper zone mainly composed of pillow lavas (571.5 m); a transition zone (209 m), and a lower zone consisting of diabase dikes (1056 m). Therefore, the drilled section penetrates oceanic Layers 1, 2A, 2B and 2C to a depth of 2.1 km bsf (Alt et al., 1993). Although a significant increase in the grain size of diabasic rocks has been observed in the cores recovered on Legs 140 and 148, these rocks belong to the sheeted dike complex, and the dike/gabbro boundary is not reached in the hole. However, recent seismic studies conducted around Hole 504B indicate that seismic velocity steadily increases to a

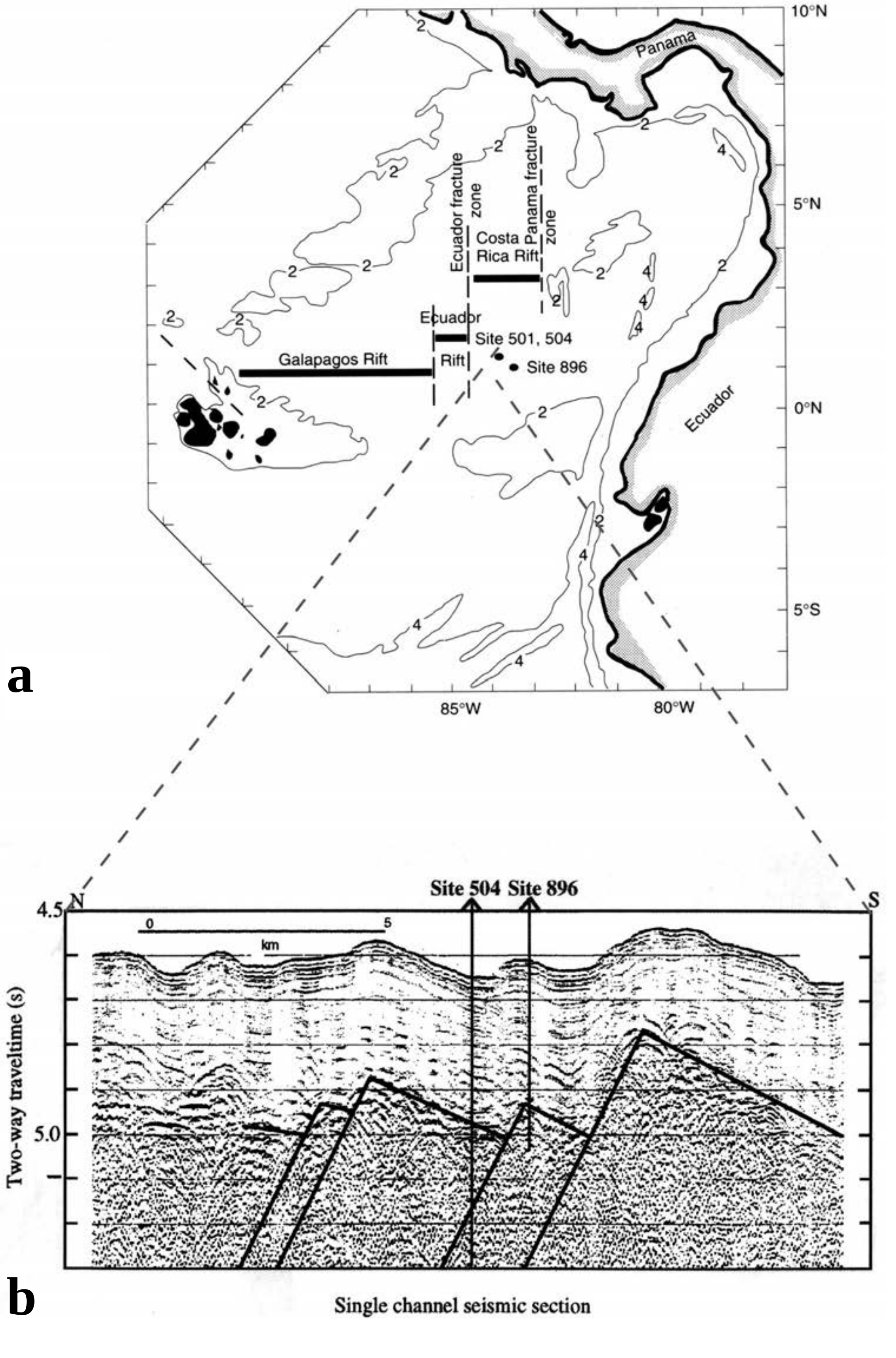

Fig. 1 - (a) Location of DSDP Site 501 and DSDP/ODP Site 504, and ODP Site 896 south of the Costa Rica Rift in the eastern equatorial Pacific (modified after Laverne et al., 1996). (b) Interpretation of the 3.5-kHz seismic-reflection profile over Hole 504B (from Langseth et al., 1988), as a series of gently dipping normal fault block.

value of 6.8 km/s, typical of Layer 3, near 2060 meters below sea floor (Alt et al., 1993; Detrick et al., 1993). These interpretations suggest that the Layer 2/3 boundary may lie within the dike complex, and it may not correspond to a major lithological change from dikes to gabbros (Detrick et al., 1994). During ODP Leg 148, drilling was stopped at 2111.0 m bsf, when the drill string became stuck in the hole in a relatively soft zone with a high penetration rate. Combined with the existence of highly fractured rocks near and at the bottom of the hole, this zone was interpreted as a fault zone at 2104-2111 mbsf (Alt et al., 1993). It is probable that this inferred fault zone is thus close to the Layer 2/3 boundary (Dilek et al., 1996).

BASEMENT LITHOSTRATIGRAPHY

The volcanic section drilled at site 504B (Fig. 2) is 571.5 m-thick and consists of interbedded pillow lava, pillow breccias and hyaloclastites, massive units (flows or sills), thin flows, breccias, and minor dikes (Cann et al., 1983; Adamson, 1985). The 209 m-thick transition zone from the volcanic section to the underlying sheeted dikes and massive units extends from 846 to 1055 meters below seafloor (mbsf), and includes pillows and dikes that are commonly fractured and brecciated and show a pervasive hydrothermal alteration (Alt et al., 1985, 1986a, 1989, Tartarotti et al., 1998). The top of the transition zone is characterized by more abundant pillows and breccias than its bottom, where dikes and massive units are more common. A stockwork-like sulphide mineralization (Honnorez et al., 1985) occurs between 900 and 920 mbsf. This zone consists of highly fractured pillow lavas with abundant breccias and a network of mineralized veins, mainly made of quartz and sulphides.

Underneath the transition zone, a sheeted dike complex extends down to the bottom of the hole. This complex consists of mainly massive, aphyric to phyric diabase including a few chilled margins along intrusive contacts. Although there is not a simple systematic increase in grain size with

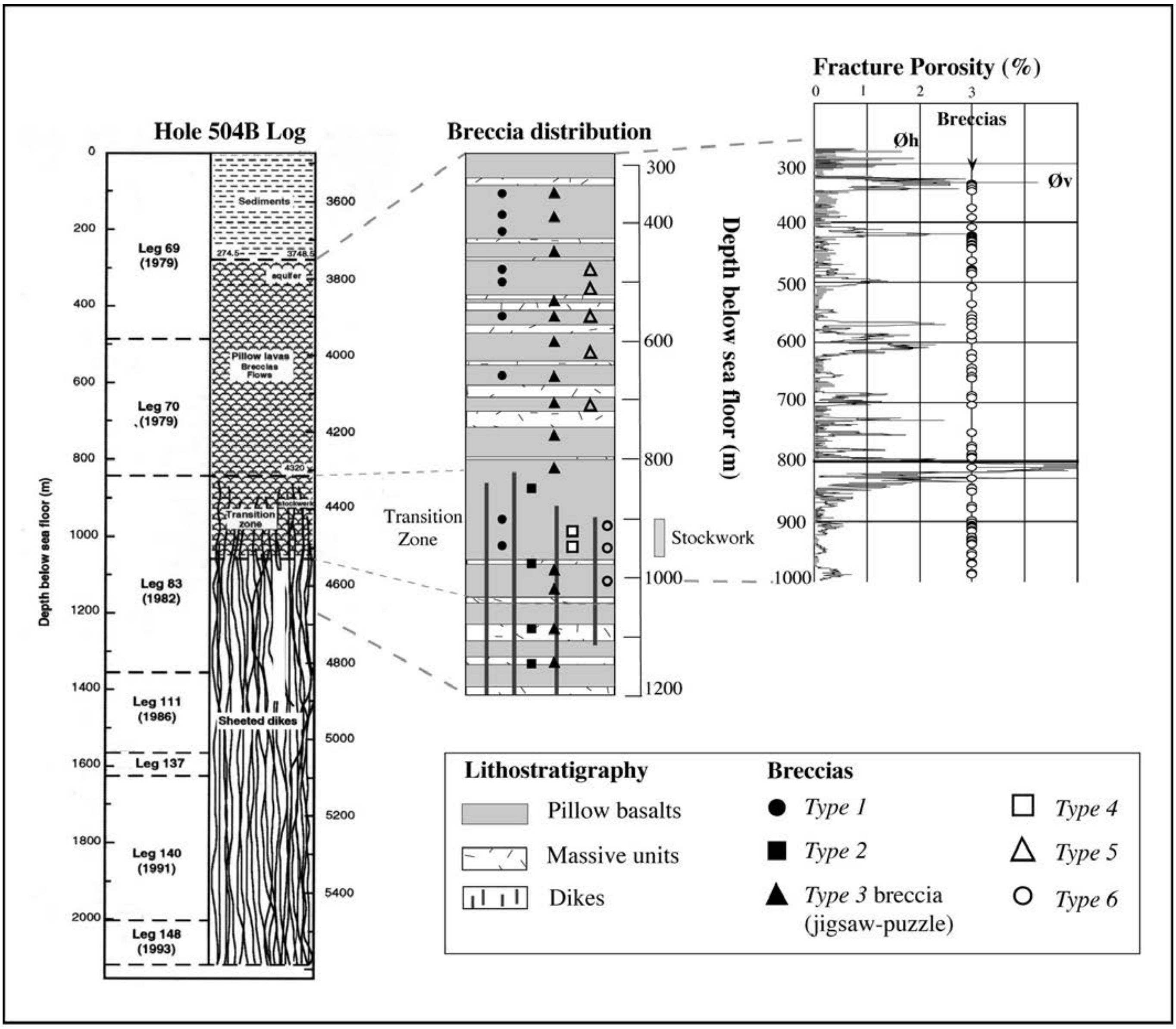

Fig. 2 - Simplified basement lithostratigraphy of the studied crustal section at DSDP/ODP Hole 504B, with location of the breccia *types 1-6*, as described in the text. Comparison between stratigraphy log (as deduced from core observations) and fracture porosity log (modified after Tartarotti et al., 1998) shows that signals mostly correspond to pillow lava units (not massive) and brecciated intervals (see text).

depth, coarser grained diabases actually become more common towards the bottom, whereas glassy chilled margin virtually disappear, an observation that is consistent with generally deeper dike emplacement at higher temperatures (Dick et al., 1992).

The basement rocks can be classified as olivine tholeiites with compositions that are similar to moderately evolved mid-ocean ridge basalts. These characteristics have been observed in 98% of all investigated samples recovered from Hole 504B through 2111 m bsf. There are only minor differences between the compositions of the sheeted dikes and the pillow lavas, and essentially none, when the compositions of aphyric dikes and pillow lavas are compared (Natland et al., 1983; Autio and Rhodes, 1983; Autio et al., 1989; Emmermann, 1985; Kempton et al., 1985).

The lithological stratigraphy of Hole 504B may actually be poorly representative of the drilled crust, especially of the volcanic section, where drilling operations attained an average recovery percentage of 29.8%. For this reason, it must necessarily be integrated with continuous log stratigraphy obtained by downhole geophysical measurements. Core-log integrated studies tested at Hole 504B (e.g. Ayadi et al., 1998; Tartarotti et al., 1998) have contributed to a better understanding of the real stratigraphy of the oceanic crust. These studies have interpreted the upper oceanic crust in Hole 504B as being made of low resistivity-high porosity layers alternating with high resistivity low porosity layers, corresponding to pillow lavas and breccias, and to massive flows, respectively. The most porous units are encountered roughly every 80 m. Two of these units are located between 400 and 575 mbsf and between 800 and 1100 mbsf, respectively. They are characterized by low resistivity, high fracture porosity, high core planes density, and by the occurrence of breccias. Based on the high density of planar features detected by high resolution electrical images of the borehole wall (Formation MicroScanner, FMS), the upper zone is interpreted as a highly fractured zone (Ayadi et al., 1998). The deeper zone corresponds to the main fault inferred by Becker et al. (1988), Kinoshita et al. (1989), Furuta and Levi (1983), Pezard et al. (1997), and Ayadi et al. (1998). In the deeper zone, the mechanical and physical properties change along discrete deformation zones where the rock shows high values of open porosity fraction, especially between 900 and 1050 mbsf (Pezard et al., 1997). In addition, the rock chemical properties are found to be modified, as characteristic of alteration mineralogy (e.g. Cu and Zn; Ayadi et al., 1998). The occurrence, within this zone, of greenschist facies minerals (e.g. actinolite, chlorite, epidote, quatrz) together with zeolites, suggests that the crust underwent successive stages of alteration due to varying circulating fluids (Alt et al. (1986). The intensity of magnetization and the magnetic susceptibility of rocks from the main fault are up to two orders of magnitude lower than those obtained elsewhere in the hole. This fact can be explained in terms of rock alteration due to circulation of hydrothermal fluids at high temperatures (200-400°C; Pariso and Johnson, 1991). The seismic-reflection data over Hole 504B (Langseth et al., 1988; see Fig. 1b) show a series of half-graben structures bounded by faults, supporting the interpretation of such fault zones.

Distribution of breccias

Breccias are a significant component of the studied section. Brecciated intervals have been recorded down to at least 1150 mbsf, in the upper part of the sheeted dike section (Fig. 2). Alt et al. (1996) indicate the presence of 6% breccia in the upper 320 m of the volcanic section, and 19% breccia in the lower volcanic section. Indeed, the actual total proportion of breccias based on visual core observation is likely to be underestimated, because this fragile lithology tends to be lost during drilling. This problem may be partly overcome by integrating core data with wireline logs. Brewer et al. (1995) derived a wireline log stratigraphy for Hole 896A, which is characterized by about 33% pillow lavas, 34% massive units and 47% breccia, in contrast with the lithological stratigraphy that comprises 57% pillow lavas, 38% massive units and only 5% breccia. This result suggests that the distribution of breccias (and rubble material) down in a drill hole may reflect sampling bias due to underestimation.

This conclusion is important since breccias are permeable and porous units which strongly influence the circulation of hydrothermal fluids. By integrating core, donwhole measurements and borehole wall images at Hole 504B, Ayadi et al. (1998) and Tartarotti et al. (1998) found out the high fracture porosity signal (mainly vertical fracture porosity) well correlates with the occurrence of breccias and pillows (Fig. 2). This means that breccias may strongly affect the electrical signal during downhole logs. However, correlation between signals of geophysical logs (including the geochemical log) and the mineral composition of clasts and matrix in breccias has not been tested. This study should be attempted in order to discriminate among different types of breccias.

In this study, the occurrence of breccias was systematically checked during detailed core observations, and located in the cores with respect to the lithostratigraphy between 274 mbsf and 1200 mbsf (Fig. 2). Depth values of breccias were computed with the help of a software program (Agrinier and Agrinier, 1994), based on a model which assumes that the individual probability density of sampling during coring is uniform, and that the relative positions of the rock pieces are preserved in the core. When compared with depth values obtained by the DSDP/ODP conventional system, the "corrected" values differ by an average of 10 cm, which can be considered negligible and beyond the accuracy in determining depth in deep drill holes.

DESCRIPTION OF BRECCIAS

Various types of breccias were identified in the studied section, based on both visual core and petrographic observations. The first type of breccia (*type 1*) is represented by hyaloclastites and pillow breccias. They occur in pillow lavas and aphyric, as well as phyric basalt units, and were mostly observed near chilled pillow rims. These breccias have been already described during DSDP cruises down to core 94R-2, whereas in deeper cores the most common breccias consist of a mixture of hyaloclastites and breccias of probably tectonic origin, cemented by dark and light green clay minerals (Anderson et al., 1985). Clasts in hyaloclastites are made of glass shards and subvariolitic basalt, showing different textures, from glassy to variolitic to sparsely-phyric. Clasts in pillow breccias are moderately-phyric (plagioclase-phyric) basalt and are cemented by altered glass, green clay minerals ± carbonate (Plate 1a).

A second type of breccia (*type 2)* includes clasts consisting of mm- to cm-sized angular to subangular fragments of aphyric or chilled basalt. The matrix consists of submillimetric basaltic fragments cemented by light and dark green clay minerals (smectite?), sometimes with vermicular texture, rare sulphide (pyrite?) and white minerals (carbonate). These breccias mostly occur in the lower transition zone and in the dike section (Fig. 2), and probably represent brecciated chilled dike margins (Plate 1b), although sharp contacts with unbrecciated doleritic basalt are not always visible (not always sampled). In sample 85R1, #6a-c (Plate 1b), the overall contact between breccia and unbrecciated dike is subvertical (i.e., almost parallel to the core edge), but irregular.

This kind of breccia is very similar to a third type of breccia (*type 3)*, the so-called jigsaw-puzzle breccia (Alt et al., 1993; Harper and Tartarotti, 1996), which consists of angular to subangular clasts of highly variable size (from cm to microscopic; Plate 1c), made of aphyric to phyric basalt, cemented by dark-green clay minerals (smectite) and less common light patches of vermicular clay ± carbonate. This breccia is commonly both clast- and cement-supported, depending on the extent of brecciation. The clasts can be often pieced back together; moreover, they show little displacement with respect to each other. Similar breccias have been described in other DSDP/ODP volcanic sections (e.g. Alt, 1993), and in ODP Hole 896A where they have been interpreted as due to hydrofracturing (Alt et al. 1993; Harper and Tartarotti 1996). At Hole 504B, jigsaw-puzzle breccias are often strictly associated with a network of veins filled with dark-green clay minerals. The vein network grades into the breccia through rock fragmentation and incipient brecciation (Plate 1d). Under the microscope, incipient brecciation is also visible inside veins where some basalt clasts float in the clays ± carbonate filling the vein. Jigsaw-puzzle breccia and vein networks were observed in the volcanic section and in the upper part of the sheeted dike complex. These breccias mostly occur (at least until 1050 mbsf) either within pillow lavas, near the contact with less permeable massive flows, or within massive flows (Fig. 2).

Brecciation in the stockwork-like zone (*type4)* has strongly affected the basalts which also show high volume percent of veining and mineral alteration (Anderson et al., 1985; Honnorez et al., 1985). These breccias are characterized by mm- to cm-scale, subangular to subrounded fragments of altered basalt ± glass shards, cemented by dark-green chlorite ± smectite, often including quartz, pyrite, epidote. The breccia is frequently cut by late-stage veins filled with zeolites, showing different orientations and inconsistent cross-cutting relations. Breccias of the stockwork-type were observed down to about 1000 mbsf, i.e. just below the stockwork-like zone (Fig. 2).

Another type of breccia (*type 5)* is of uncertain origin. It consists of angular to subrounded and rounded clasts of glassy to phyric basalt. This breccia is commonly matrix-supported. The matrix is made up of both clay-minerals and small basalt fragments. The matrix contains sub-mm clasts, generally with angular or triangular shape and sharp edges cemented by dark green-clay minerals (Plate 1e). This breccia was observed only within pillow lavas and thin flows (Fig. 2).

Cataclastic zones (*type 6*) were found in the transition zone and within the dike complex; some of them are detectable only under the microscope (e.g., core 78R-1 #3e; Plate 4f). These zones generally consist of submillimetric rounded clasts of unaltered basalt and of plagioclase and clinopyroxene crystals, in a matrix formed by clasts (µm-scale) of plagioclase and clinopyroxene cemented by light-green clay minerals. Local offsets and thin shear zones were observed, mostly along the contact with the unbrecciated rock.

With the exception of the breccia from the stockwork zone, most breccias in Hole 504B have a matrix composed of clay-minerals (saponite averaging 94.5% according to Alt et al., 1996) with lesser zeolite and minor carbonate. In addition, dark-green clay minerals mostly fill veins associated with jigsaw-puzzle breccia. Estimates of alteration temperatures from oxygen isotope ratios for the lower volcanic section range from 0° to 40° for vein carbonates, and to 70°-140°C for vein smectite (Honnorez et al., 1983; Alt et al., 1986).

DISCUSSION

Origin of the breccias

Hyaloclastites and pillow breccias (*type 1*) typically occur within pillow lava units. The former are strictly associated with pillow rims and are interpreted as formed on the sea floor by the fragmentation of the outer parts of pillows (both hyaline outer rim and variolitic inner rim). The latter are made of various parts of the pillow, the texture of clasts ranging from holohyaline to variolitic to intersertal. Thus, this breccia derives from the fragmentation of inner and outer parts of pillows.

Breccia of *type 2* is typically associated with chilled dike margins. It is likely that brecciation occurred during or after intrusion of a dike. However, this interpretation is not always straightforward, especially when the contact with an unbrecciated dike is not sampled.

The most interesting breccias certainly are the jigsaw-puzzle (*type 3)* breccias, because, together with cataclastic zones, they are the only breccias of probable tectonic origin. The rock texture and the clast shape in the jigsaw-puzzle breccias suggest that an increase in volume, although very small, has occurred. Harper and Tartarotti (1996) have evaluated a variable volume increase, ranging from a few percent to more than 25%, in jigsaw-puzzle breccias from ODP Hole 896A. Similar breccias have been observed in samples drilled in geothermal fields and in hydrothermal ore deposits, and they are interpreted as formed by hydrofracturing (i.e., extension fracturing induced by the presence of a pore-fluid pressure; e.g. Phillips, 1972; Hedenquist and Henley, 1985; Sibson, 1987; Gianelli and Bertini, 1993). Sibson (1985; 1986; 1987) suggests that jigsaw-puzzle breccias can form by "implosion" in dilational jogs opened during an earthquake. A comprehensive discussion about the formation and interpretation of jigsaw-puzzle breccias found in the oceanic crust is reported by Harper and Tartarotti (1996). According to these authors, this kind of breccia most likely forms by "longitudinal splitting", a mechanism observed in rock deformation experiments where the vertical effective stress ($\sigma'_1 = \sigma_1 - P_f$, where σ'_1 is the effective vertical stress and P_f is the pore fluid pressure) is low and the effective confining pressure (σ'_3 and σ'_2) is ≤ 0 (i.e., tensional). Such stress conditions are typical of the upper oceanic cust and are due to high hydrostatic pressure resulting from the thick (few km) water column overlying a basaltic crust which is sufficiently permeable and porous. However, hydrostatic pressure will not prevail if a rock mass is sealed by an overlying impermeable cap. In the area of Hole 504B, Anderson and Zoback (1982) measured a pore-fluid pressure slightly lower than hydrostatic, likely due to the sealing effect of the 207m-thick layer of sediments capping the basalts. Low vertical effective stress is a favourable condition for hydrofracturing to occur, even when the basement is sealed by a thick sequence of overlying sediments.

Although overall pore-fluid pressures slightly lower than hydrostatic were measured at Hole 504B, we suggest that jigsaw-puzzle breccias may have been formed under local conditions of suprahydrostatic fluid pressure, favoured by a structural and tectonic setting allowing the action of a fault-valve (Fig. 3). Fault-valve behaviour occurs where a fault cuts across a vertical fluid pressure gradient that exceeds the hydrostatic gradient of ca. 10 Mpa Km^{-1} (Sibson, 1990). Suprahydrostatic gradients may occur in the vicinity of the fault itself, and require the existence of extensive permeability barriers. Suprahydrostatic fluid pressures may develop beneath such barriers from a variety of causes, including permeable connections to a remote high fluid pressure source at greater depth. Valve action initiates with fault rupture due to accumulation of fluid pressure within the overpressured zone, and consequent barrier breaching. The resulting upward discharge of fluids along the fault from the overpressured zone goes on until the hydraulic gradient reverts to hydrostatic or until the fault reseals. Discharge is accompanied by a drop in fluid pressure that allows the deposition of hydrothermal minerals along portions of the fault zone. The stratigraphy log of Hole 504B seems to be suitable for fault-valve behaviour to occur (Figs. 2 and 3), at least in the upper part, being constituted by pillow lavas and breccias (i.e. porous and permeable rocks) alternating with more massive lava flows (impermeable barriers). The existence of highly fractured zones (probable faults zones) identified at depths of ca. 400-550 mbsf and of 800-1100 mbsf,, support the conditions for fault-valve behaviour to occur. These faults likely correspond to faults bounding tilted crustal blocks of the Costa Rica Rift, as also suggested by seismic-reflection data. At Hole 504B, jigsaw-puzzle breccias are mostly localized near the contact between porous/permeable basalts, and impermeable units (see breccia description above). Accordingly, jigsaw-puzzle breccias likely formed during accumulation of water or hydrothermal fluid overpressure, and they were subsequently sealed by secondary or hydrothermal mineral precipitation during discharge in the fault-valve cycle, as suggested by mineral infillings observed in the breccia matrix.

Breccias found in the stockwork-like zone (*Type 4)* show features very similar to those of jigsaw-puzzle breccias, i.e. the shape of clasts, and their association with vein networks, suggesting that pore-fluids could have been overpressured. This zone of basalt crust at Hole 504B has been interpreted as the location of a focused fluid flow associated with a discharge cycle (Alt et al., 1986a; 1986b; Harper et al., 1988; Agar, 1990): it is likely that the fluid flow was under pressure causing the hydraulic disruption of the rock.

Type 5 breccias were defined of “uncertain” origin. The clasts of this breccia are not very different from those of jigsaw-puzzle breccias, because in some cases they can be pieced back together. However, subrounded clasts are also present, and the matrix is more abundant and compositionally different from that of jigsaw-puzzle breccias. Thus, *type 5* breccias could be interpreted either as talus breccias (i.e. sedimentary breccias), or as debris fallen into fractures of massive lava flows (when they occur in thin flow units) and subsequently cemented.

Cataclastic zones (*type 6*) are characterized by grain size reduction and the grains are mostly rounded. It is not easy to infer whether grain size reduction was achieved by dissolution or cataclasis. The fact that local offsets and shear zones are associated with the catacastic zones suggests that they have a tectonic origin.

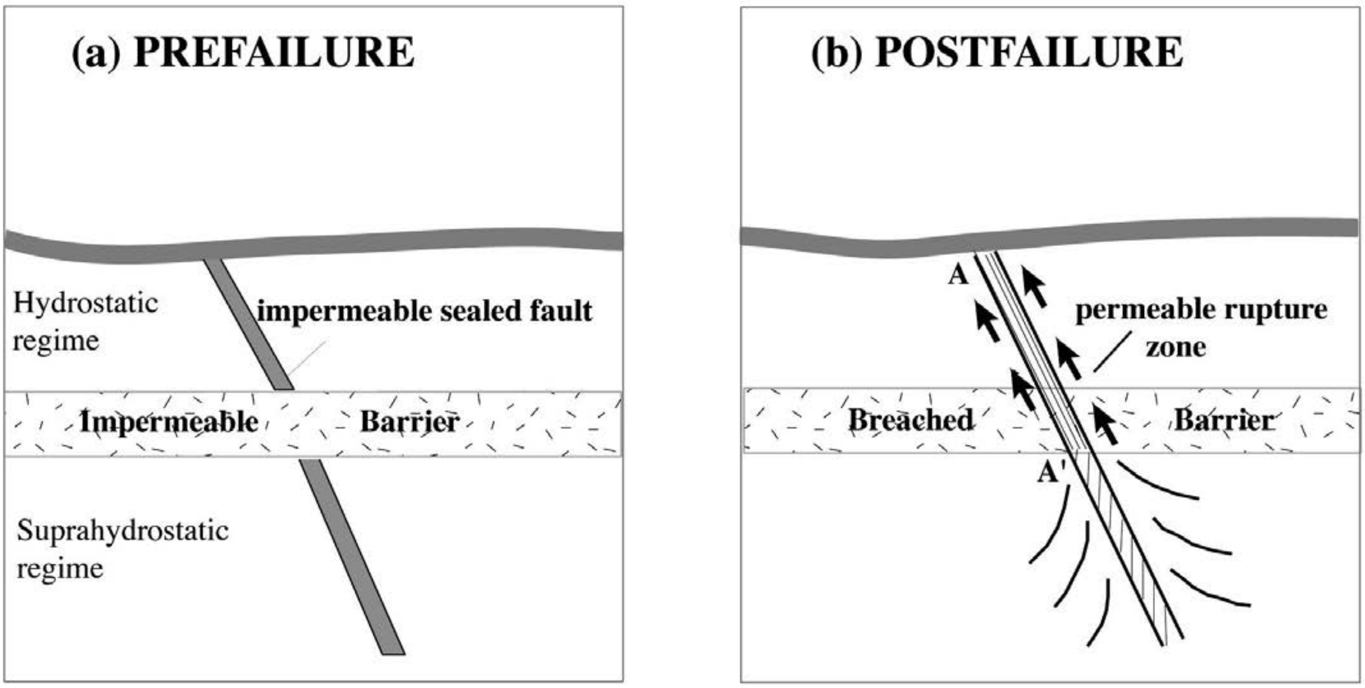

Fig. 3 - Geological conditions favorable for fault-valve behaviour to occur (modified after Sibson, 1990. (a) A fault penetrating permeable rocks alternating with impermeable barriers acts as an impermeable seal before a seismic period. (b) After fault rupture (for example during seismic activity), the impermeable barrier is breached (A-A’); the fault forms a highly permeable channelway for fluid flow.

CONCLUSIVE REMARKS

Basaltic breccias sampled in the volcanic section and at DSDP/ODP Hole 504B, down to the top of the sheeted dike complex can be grouped into six main classes. Among these, only jigsaw-puzzle breccias can be interpreted as being of tectonic origin. Although an overall pore-fluid pressure slightly lower than hydrostatic was measured at Hole 504B, we suggest that jigsaw-puzzle breccias may have been formed under local conditions of suprahydrostatic fluid pressure, mostly beneath impermeable barriers such as massive basaltic flows. High fluid pressure conditions were favoured by a structural and tectonic setting allowing the action of a fault-valve (Sibson, 1990). Highly fractured zones identified at depths of about 400-550 mbsf and of 800-1100 mbsf likely correspond to faults, probably bounding tilted crustal blocks of the Costa Rica Rift, supporting the conditions for fault-valve behaviour to occur.

The development of breccias in the stockwork zone was triggered by focused fluid flow associated with a discharge hydrothermal cycle. All the other breccias recognized in the studied sections are interpreted as deriving from either *in situ* fragmentation of basalts or sedimentation of basaltic debris.

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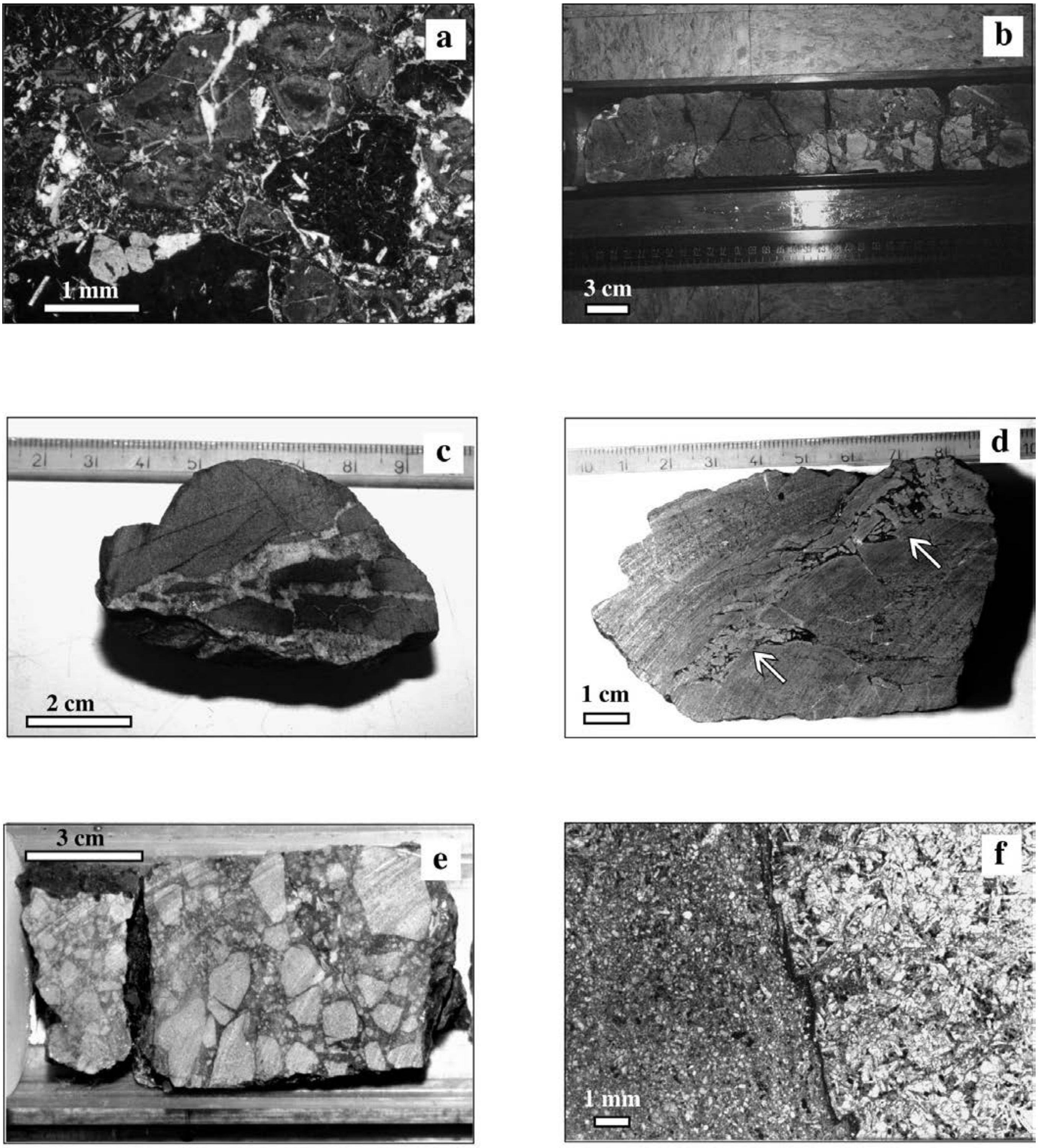

Plate 1 - Photomicrographs and hand-specimen pictures of basaltic breccias at DSDP/ODP Hole 504B. (a) Photomicrograph of pillow breccia (*type 1)* in sample 504B, 83, 80R-3, piece #3. Plane light. (b) Brecciated dike (*type 2*) in sample 504B, 83, 85R-1, pieces # 3a-e. (c) Jigsaw-puzzle breccia (*type 3*) in sample 504B, 83, 91R-2, piece #7. (d) Vein network and incipient brecciation in sample 504B, 83, 101R-1, piece #10f. (e) Breccia of uncertain origin (*type 5)* in sample 504B, 70, 70R-1, piece # 1551. (f) Photomicrograph of cataclastic zone (*type 6)* in sample 504B, 83, 78R-1, piece #3e. Plane light.