Fitton, J.G., Mahoney, J.J., Wallace, P.J., and Saunders, A.D. (Eds.)
Proceedings of the Ocean Drilling Program, Scientific Results Volume 192

6. DATA REPORT: LOW-TEMPERATURE ALTERATION OF UPPER OCEANIC CRUST FROM THE ONTONG JAVA PLATEAU, LEG 192: ALTERATION AND VEIN LOGS[1]

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ABSTRACT

This paper presents alteration data for basalts from Ocean Drilling Program (ODP) Sites 1183, 1185, 1186, and 1187 drilled on the Ontong Java Plateau during Leg 192. The entire sequence of recovered basaltic basement has undergone low-temperature water-rock interactions. Alteration and vein logs were compiled for each hole from visual core descriptions made aboard the ship. These logs quantify the alteration types, provide a consistent alteration characterization of the samples, and provide a method for estimation of downhole variations in basalt alteration and vein abundance/mineralogy. The three main alteration types identified include gray basalt, black or dusky green halos, and brown or olive halos. Secondary minerals, in order of decreasing abundance, include phyllosilicates, calcite, pyrite, chalcedony, quartz, Fe oxyhydroxides, and zeolites. Veins commonly contain smectite and/or celadonite, Fe oxyhydroxide or pyrite, and calcite. Alteration of basalts from the Ontong Java Plateau is similar to that observed from other Deep Sea Drilling Program/ODP sites drilled into the upper oceanic crust.

INTRODUCTION

The entire sequence of basaltic basement recovered from Ocean Drilling Program (ODP) Sites 1183, 1185, 1186, and 1187 during Leg 192

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[1] Banerjee, N.R., and Honnorez, J., 2004. Data report: Low-temperature alteration of upper oceanic crust from the Ontong Java Plateau, Leg 192: alteration and vein logs. *In* Fitton, J.G., Mahoney, J.J., Wallace, P.J., and Saunders, A.D. (Eds.), *Proc. ODP, Sci. Results,* 192, 1–8 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/192_SR/VOLUME/CHAPTERS/103.PDF>. [Cited YYYY-MM-DD]

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Initial receipt: 20 March 2003
Acceptance: 14 October 2003
Web publication: 3 March 2004
Ms 192SR-103

has undergone low-temperature water-rock interactions. In order to quantify the alteration types and provide a consistent alteration characterization of the samples, alteration and vein logs were compiled for each hole from visual core descriptions made aboard the ship. These logs are meant to provide a method for estimation of downhole variations in basalt alteration and vein abundance/mineralogy. The logs presented in this paper have been slightly modified from their original formats described in the Explanatory Notes chapter of the Leg 192 *Initial Reports* volume (Shipboard Scientific Party, 2001). These changes reflect the natural evolution of the descriptions during the duration of the cruise. The logs also contain minor additions and omissions that reflect individual variations that could not be accommodated by the log formats. Although every effort to be as quantitative as possible was taken, it is important to note that some aspects of the logs (such as color percentages, thicknesses, and secondary mineral abundances) are estimates based on hand specimen observations.

METHODS

Visual alteration estimates were performed on a piece-by-piece scale by observation of cut wet surfaces of core hand specimens. All descriptions were performed on the archive half, although observations were aided by viewing the working halves where specific features of interest may have been better preserved. Initial observations were conducted by naked eye and with a 10× magnifying lens. Additional observations under the binocular microscope aided in mineral identification. Specific minerals are not generally distinguished (i.e., clay, zeolite, and carbonate minerals) except where unequivocal identification was possible. For example, we commonly noted white veins containing only carbonate in the vein logs, although we observed zeolites in some thin sections. When additional mineralogical evidence was available from either thin section descriptions and/or X-ray diffractograms (XRD), we integrated these identifications into the alteration and vein logs. However, because of the large number of veins described, we did not enter thin section and XRD data into the vein/structure log. Table T1 provides a list of abbreviations used in the alteration and vein/structure logs. Bulk rock and halo colors are from the Munsell Soil Color Charts (1975). A complete description of all methods is provided in Shipboard Scientific Party (2001).

T1. Abbreviations used in alteration and vein logs, p. 8.

VEIN AND ALTERATION LOGS

The alteration logs provide a record of bulk-rock alteration (Shipboard Scientific Party, 2001). Each entry identifies the igneous unit; the core, section, piece, and interval; the length of each piece; and the depth below the seafloor of the top of each piece. Alteration type was classified on the basis of rock color for each piece and calibrated by thin section observations. In addition, alteration of olivine phenocrysts was reported when observed and includes an estimation of the degree of replacement by secondary minerals (in percent) and the type of secondary minerals. Further information on the abundance (in percent) and mineral fillings of vesicles and miarolitic cavities was entered when possible. A column for comments is included in the log for information of interest not easily placed under existing headings.

The vein logs provide a record of all veins observed on the cut surface of the cores (Shipboard Scientific Party, 2001). Each entry identifies the igneous unit; the core, section, and piece; and the depth below the seafloor of the top of the vein. Specific information for each vein includes the apparent orientation, width (in millimeters as measured on cut surfaces), the locations of the top and bottom, vein length (calculated as the difference between the location of top and bottom), and mineral content of the vein (in percent). We also recorded the presence or absence of a related alteration halo and the color, half width (in millimeters), and alteration mineralogy of halos. Once again, a column for comments is included in the log for information of interest not easily placed under existing headings.

PRELIMINARY RESULTS

Although this paper is intended to allow broad dissemination of primary data pertaining to the alteration of basaltic crust drilled during Leg 192, certain preliminary observations have been documented. For a description of alteration on a site-by-site basis, the reader is referred to the Leg 192 *Initial Reports* volume (Mahoney, Fitton, Wallace, et al., 2001).

The entire sequence of basaltic basement rocks recovered during Leg 192 has undergone low-temperature water-rock interactions, resulting in complete replacement of olivine and almost complete replacement of glassy mesostasis. Clay minerals are the most abundant secondary minerals. We have tentatively identified saponite and celadonite based on color in hand specimen, optical properties in thin section, and intermittent XRD analyses. We compared the phyllosilicates observed in rocks from Hole 1183A with well-studied clay minerals identified in other sections of the oceanic crust (Böhlke et al., 1980; Honnorez, 1981; Alt and Honnorez, 1984; Alt et al., 1986). Calcite, pyrite, chalcedony, quartz, and zeolites are less abundant and have more restricted distributions. Throughout this section, we refer to volume percentages of the various alteration types (veins, hyaloclastite, etc.); our assumption is that the area occupied by these features on the sawed surfaces of the cores is equivalent to the volume percentage in the cores. Based on core descriptions and thin section observations, we have identified three major types of low-temperature alteration.

Gray Basalt

The term gray basalt refers to the normal gray color (ranging from dark to light gray) of the least-altered basalts from the inner portions of cooling units, commonly adjacent to the variously colored halos described below. Gray basalt is the most abundant alteration type. This type is characterized by signs of pervasive low-temperature alteration. Clay minerals (predominantly saponite with subordinate celadonite) commonly replace rare interstitial glass and mesostasis in the groundmass. Phyllosilicates (celadonite or saponite) also commonly replace olivine microphenocrysts. Less commonly, Fe oxyhydroxides and calcite or (more rarely) pyrite are found in olivine pseudomorphs and, rarely, plagioclase phenocrysts. Similar secondary mineral assemblages fill miarolitic cavities and rare vesicles. The overall alteration of the gray basalts ranges from 5% to 30% and averages ~20%.

The gray color results from extended interaction between basalt and seawater-derived fluid (evolved seawater) under anoxic to suboxic conditions at low temperature (probably 10°–50°C). These fluids probably reacted previously with basaltic crust (e.g., with the rock of the halo adjacent to the gray basalt [Alt et al., 1986]). The water-rock ratio during such interaction is probably low. This alteration stage ceases once secondary minerals fill fluid pathways, sealing the formation and permeability.

Dusky Green Halos and Black Halos

Centimeter-scale dusky green halos and black halos are observed along surfaces previously exposed to seawater and, less commonly, along the margins of veins. Within these halos, olivine phenocrysts are commonly altered to clay minerals (including celadonite and/or nontronite) and Fe oxyhydroxides. The dusky green halos are very similar to black halos but represent an extreme case of replacement of primary basaltic phases by higher proportions of celadonite, which impart the dusky green color. The overall alteration rarely exceeds 30% in either dusky green or black halos. The boundary beyond the edges of these halos and the adjacent gray rock is commonly marked by fine-grained disseminated pyrite and/or marcasite in the groundmass. Calcite is less common in these halos than in the gray basalt. The contact between black halos and the gray interior is very sharp both in hand specimen and in thin section. This is a result of strong changes in chemical conditions across the alteration front during the formation of the dusky green halos and black halos.

This stage of alteration results from early interaction between basalt and warm (<60°C), seawater-derived fluids (Böhlke et al., 1980; Honnorez, 1981; Laverne, 1987). Such fluids are supplied by diffuse warm springs of shimmering water that have been cooled by mixing with bottom seawater (James and Elderfield, 1996). The formation of black and dusky green halos are characteristic of an early alteration process initiated during cooling of the lava in 1–2 m.y. of basalt emplacement (Böhlke et al., 1980; Honnorez, 1981; Laverne, 1987). Further effusions of lava and/or injection of magma during diking events reactivate this alteration process.

Brown and Olive Halos

Brown halos and olive halos are olive-brown discolorations, in zones <1 to 5 mm thick, of the host rock. They are generally parallel to or concentric with smectite ± celadonite ± calcite veins, Fe oxyhydroxide–bearing veins, or glassy pillow margins, and they surround the least-altered basalt. Their color generally ranges, from the (originally) exposed surface inward, from light yellow brown to dark yellow brown (and, more rarely, dark brown) at the exterior, to olive, and finally grading to gray or dark gray in the inner parts of the cooling unit. In contrast to the sharp contact observed between the dusky green or black halos and the gray basalt, the transition between brown halos and both black (or dusky green) halos and gray interiors is generally gradational. The various brown and olive colors result from variable proportions of Fe oxyhydroxide, tan to brown smectite, and minor calcite staining and partially to totally replacing the primary minerals of the basalt groundmass and filling the interstitial voids in the groundmass. Within these halos, olivine phenocrysts are totally replaced by Fe oxyhydroxide, smectite, and minor calcite. Miarolitic cavities and rare vesicles in the brown and olive halos are filled with similar secondary minerals. Smectite and/or Fe oxyhydroxide replace as much as 90% of the basalt groundmass in the lighter-colored halos. The overall alteration in the brown halos ranges from 30% to almost 100%.

Brown and olive halos result from basalt-seawater reaction referred to as halmyrolysis (or submarine weathering). This form of alteration takes place at bottom seawater temperatures (~2°C), under oxidizing conditions, and generally with large water/rock ratios (Honnorez, 1981, and references therein). This corresponds to passive alteration of basalt by bottom seawater circulating through the crust to depths of several hundred meters. In the most permeable basaltic formations, such as pillow lavas, hyaloclastites, and breccias, halmyrolysis may lead to intense alteration. The halos represent the last low-temperature alteration stage, which ceases when the oceanic crust is sealed off from overlying seawater by a sufficiently thick and comparatively impermeable sediment cover.

Glass Alteration

Alteration of basaltic glass to phyllosilicates ranges from 20% to 100%. Basaltic glass is present either in pillow rims or as shards in hyaloclastites, possibly associated with interpillow cavities. Glassy mesostasis is rare in the pillow interiors. Pillow-rim glass is generally the least altered because of its low permeability. Glass shards in the hyaloclastites, because of their large surface areas, are almost always completely replaced by phyllosilicates, except where cemented by micritic calcite. The association of unaltered glass clasts cemented by calcite is commonly observed in the submarine basalts, regardless of the age of the hyaloclastite or the environment in which it formed (Honnorez, 1967, 1972).

Veins and Pore Space Fillings

Most of the veins result from symmetrical infilling of open cracks with minor or no replacement of the wallrock. Vein widths vary from <1 mm (hairline veins) to tens of millimeters. Most veins contain the following succession of secondary minerals, from vein walls to centers: smectite and/or celadonite, Fe oxyhydroxide or pyrite, and calcite. Disseminated pyrite grains commonly line the walls of smectite and/or celadonite veins cracked open during drilling. Furthermore, where the core is fractured perpendicular to veins containing dusky green halos, bright bands of pyrite (and/or marcasite) are commonly observed at the margins of the halos, indicating the terminus of the reduction front. Evidence for the successive reopening and filling of veins is often clear, particularly in the case of calcite deposition, because of the contrast in color between the carbonate and the other vein-filling secondary minerals. Some veins are filled with micritic pink carbonate that contains Fe oxyhydroxide pellets and foraminifer ghosts, indicating that the veins are sediment-filled open fissures. Rare occurrences of native copper are restricted to smectite-bearing veins in the uppermost basement cores, whereas we only observed chalcedony and quartz in the lower part of the cored basement.

We noticed a clear relationship between vein density and host-rock alteration color. Pervasively altered basalts that display yellow-brown or olive alteration colors are generally associated with portions of cores displaying more horizontal and subhorizontal veins. Not surprisingly, the degree of alteration is highest in the rocks with the highest permeability (e.g., fractured pillow lavas, hyaloclastites, and breccias), in which the rock color is also the lightest.

Summary

Alteration and vein logs compiled for each hole from visual core descriptions made aboard the ship during Leg 192 provide a method for estimation of downhole variations in basalt alteration and vein abundance/mineralogy. Three main alteration types have been identified: gray basalt, black or dusky green halos, and brown or olive halos. These alteration types all result from low-temperature fluid-rock interactions. Phyllosilicates are the most abundant secondary minerals, with lesser amounts of calcite, pyrite, chalcedony, quartz, Fe oxyhydroxides, and zeolites. Veins resulting from symmetrical infilling of open cracks commonly contain smectite and/or celadonite, Fe oxyhydroxide or pyrite, and calcite. Overall, alteration of basalts cored during Leg 192 is similar to that observed from other Deep Sea Drilling Project/ODP sites drilled into the upper oceanic crust.

ACKNOWLEDGMENTS

We are indebted to the captain, crew, and technicians of the drill ship *JOIDES Resolution*, whose hard work made Leg 192 a success. We are also indebted to the many scientists we sailed with for help with the logs and for their many stimulating discussions. Special thanks to Stephanie Laurence, who transferred much of the data in the alteration and vein logs from handwritten form to electronic files. We would also like to thank Jeff Alt for a helpful review and Lorri Peters and Gigi Delgado for editorial handling. This research used samples and data provided by the Ocean Drilling Program (ODP). The ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. Participation in Leg 192 was funded by Canada ODP for N.R.B. and by ODP France for J.H. Funding for this research was provided by the National Sciences and Engineering Research Council of Canada and the Institut National des Sciences de l'Univers of France.

REFERENCES

Alt, J.C., and Honnorez, J., 1984. Alteration of the upper oceanic crust, DSDP Site 417: mineralogy and chemistry. *Contrib. Mineral. Petrol.,* 87:149–169.

Alt, J.C., Honnorez, J., Laverne, C., and Emmermann, R., 1986. Hydrothermal alteration of a 1 km section through the upper oceanic crust, Deep Sea Drilling Project Hole 504B: mineralogy, chemistry, and evolution of seawater-basalt interactions. *J. Geophys. Res.,* 91:10309–10335.

Böhlke, J.K., Honnorez, J., and Honnorez-Guerstein, B.M., 1980. Alteration of basalts from Site 396B, DSDP: petrographic and mineralogical studies. *Contrib. Mineral. Petrol.,* 73:341–364.

Honnorez, J., 1967. La palagonitisation: l'alteration sous-marine du verre volcanique basique de Palagonia (Sicile) [Ph.D. dissert.]. Univ. Libre de Bruxelles.

————, 1972. La Palagonitisation: l'alteration sous-marine du verre volcanique basique de Palagonia (Sicile) [Palagonitization: the submarine alteration of basic volcanic glass in Palagonia, Sicily]. *Publ. Vulkaninst. Immanuel Friedlaender,* 9.

————, 1981. The aging of the oceanic crust at low temperature. *In* Emiliani, C. (Ed.), *The Sea* (Vol. 7): *The Oceanic Lithosphere:* New York (Wiley), 525–587.

James, R.H., and Elderfield, H., 1996. Chemistry of ore-forming fluids and mineral formation rates in an active hydrothermal sulfide deposit on the Mid-Atlantic Ridge. *Geology,* 24:1147–1150.

Laverne, C., 1987. Les altérations des basaltes en domaine océanique: minéralogie, pétrologie et géochimie d'un système hydrothermal: le puits 504B, Pacifique oriental [Thèse Doctorat ès-Science]. Univ. Aix-Marseille III, Aix-en-Provence.

Mahoney, J.J., Fitton, J.G., Wallace, P.J., et al., 2001. *Proc. ODP, Init. Repts.,* 192 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA.

Munsell Color Company, Inc., 1975. *Munsell Soil Color Charts:* Baltimore, MD (Munsell).

Shipboard Scientific Party, 2001. Explanatory notes. *In* Mahoney, J.J., Fitton, J.G., Wallace, P.J., et al., *Proc. ODP, Init. Repts.,* 192 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/192_IR/chap_02/chap_02.htm>. [Cited 2003-03-10]

Table T1. Abbreviations used in the alteration and vein logs.

Common colors*			Primary and secondary minerals*		Apparent vein orientation		Other	
Color Name	Abbreviation	Munsell reference	Minerals	Abbreviation	Orientation	Abbreviation	Term	Explanation
Black	Blk	10YR 2/1	Celadonite	Cel	Inclined	INC	<<	Much less than
White	Wht	2.5Y N8/	Calcium carbonate	CO_3	Curved	CUR	Hf	Hairline fracture
Brown	Brn	10YR 4/3	Iron oxyhydroxides	FeOx	Horizontal	H	–>	Altered to
Yellowish brown	Yel-Brn	10YR 5/8	Olivine	Ol	Vertical	V	Trace	Trace (<1%)
Dark brown	Dk Brn	10YR 3/3	Plagioclase	Pl	Subhorizontal	SH	Sediment	Sediment
Olive	Olv	5Y 4/3	Pyrite	Py	Subvertical	SV	Apparent	Apparent
Green	Grn	10GY 4/4	Saponite	Sap			Identifier	Identifier
Yellowish green	Yel-Grn	10Y 7/6	Smectite	Sm				
Dark green	Dk Grn	10GY 3/2	Zeolite	Zeol				
Dusky green	Grn-Gr	5G 3/2	Manganese oxyhydroxides	MnOx				
Grayish green	Gr-Grn	5G 5/2	Chalcedony	Chal				
Gray	Gr	10Y 5/1	Quartz	Qtz				
Dark gray	Dk Gr	10YR 4/1	Pyroxene	Pyx				
Dark yellowish brown	DYB	10YR 4/6	Copper	Cu				
Light yellowish brown	LYB	10YR 6/4	Manganese	Mn				
Pink	Pink	10R 8/4						

Note: * = other mineral names and colors are spelled out.