

Quantitative assessment of chemical and mineralogical changes due to progressive low-temperature alteration of East Pacific Rise basalts from 0 to 9 Ma

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Abstract

Many studies have focused on low-temperature alteration of the oceanic crust, nevertheless little is known about the initial processes of low-temperature alteration and their influence on the mineralogical and chemical composition of the oceanic crust once it leaves the spreading axis. The lack of such studies is primarily related to the difficulty of recovering samples representative of this initial alteration style. Such information is nevertheless important not only for crust–ocean mass-balances but also to characterize an important input to the subduction zones. We have studied dredged basalts from the eastern flank of the East Pacific Rise at 14°15'S, concentrating on the products of a single spreading segment in a corridor perpendicular to the spreading axis and covering a range of crustal ages from 0 to 9 Ma. Electron microprobe, X-ray fluorescence, X-ray diffraction and ICP-MS analyses have been carried out to examine the mineralogical and chemical changes in the basalts which make up the surface of the upper crust caused by low-temperature alteration.

Fresh rocks were sampled at the ridge axis; off-axis basalts show features of progressive alteration. Celadonite is the main alteration component in 0.12–4.6 Ma old rocks, whereas phillipsite is more abundant in rocks older than 4.6 Ma. Changing compositions of secondary minerals, progressive sealing of fractures and the occurrence of more alteration rinds on older rocks show evidence for a slight change in redox conditions, from an oxidizing, water-dominated to a more reducing, rock-dominated environment with time. Iron oxyhydroxide and celadonite are the first alteration products, partly replaced or covered by saponite under more reducing conditions. The Fe necessary for the formation of these minerals is furnished by the dissolution of glass and the breakdown of olivine. Phillipsite is present in fractures and veins in rocks older than 1 Ma. Analyses also indicate an illite–smectite mixed layered mineral which is believed to be an intermediate between saponite and celadonite and small amounts of a chlorite/smectite mixed layered mineral. All samples are characterized by the lack of minerals formed by hydrothermal processes. We conclude that the alteration took place under seawater-dominated conditions at low temperature.

A comparison of trace element analyses from altered whole rock samples and their appendant fresh glass chips provides a record of element mobility during alteration. Off-axis basalts show significant uptakes of Rb, Cs and Ba which are supplied by

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seawater and incorporated in or on secondary minerals. An enrichment of U is also apparent and appears to be especially strong when alteration conditions are oxidative. K_2O is also gained in all altered off-axis basalts, believed to be linked to the formation of celadonite. However, the volume of rock being altered is so small relative to the volume of the oceans that this scavenging has no noticeable effect on the composition of the oceans. The composition of the oceanic crust, on the other hand, is affected significantly.

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1. Introduction

Seawater circulation through the oceanic crust plays an important role in the interaction between hydrosphere and lithosphere. Passive fluid circulation is driven by the cooling of the lithosphere as the crust moves off-axis. The global geochemical budget is affected by this convection, as both ocean and crustal compositions are buffered by fluid rock interaction. The effects of off-axis heat transfer are important because most of the heat flux through the ocean crust occurs (~70%) in the ocean basins rather than on-axis (Stein and Stein, 1994; Mottl, 2003) and as a consequence most of the fluid flux and much of the geochemical exchange occurs off-axis (Mottl and Wheat, 1994, 2000; Alt et al., 1996b). The crust is also one of the major inputs to subduction zones, its composition following off-axis alteration is therefore relevant for the evolution of mantle, crust and biosphere.

Assessing the characteristic alteration state of the oceanic crust is a complicated task. The upper crust is composed of a variety of rock types (pillows, flows, hyaloclastites, breccias) all of which become modified both chemically and physically (e.g. via cementation) during alteration. There is at present no method available to provide representative samples of this heterogeneous rock assemblage. Both drilling and dredging return a sample suite biased against friable, weak materials.

Alteration takes place as the crust ages, as documented by alteration of primary minerals, glass and the precipitation of secondary minerals. Alteration processes are affected by fluid chemistry, changing fluid–rock ratios and redox conditions. During the low-temperature alteration of the volcanic section, most major elements (Si, Al, Mg, Ca and Na) and many trace elements (Sr, Ba) experience substantial large-scale redistribution (Staudigel et al., 1981,

1996). The crust also takes up large amounts of water and CO_2 , a large fraction of which resides in veins and disseminated alteration minerals, much within the zone of oxidative alteration in the upper part of the oceanic basement. The circulating fluids evolve with time as the crust is buried by sediments and fractures are sealed with secondary minerals. The cementation of fractures acts to increase density and decrease porosity and permeability (Wilkens et al., 1991). Seismic data illustrate that porosity decreases (by a factor of 0.5) within <10 Ma, presumably due to the infilling of voids by secondary minerals (Grevemeyer and Weigel, 1996; Carlson, 1998; Grevemeyer et al., 1999). The convective heat loss from ocean crust is no longer discernible on average at about 65 Ma (Stein and Stein, 1994).

Although the intensity of crustal alteration varies from place to place and no specific alteration state can be related to a specific crustal age, rocks from on or near the ridge axis are generally fresh, whereas off-axis rocks contain features of more intense alteration. The first systematic study to address how crustal alteration varies with age focused on a 57 Ma transect of dredged samples from the Mid-Atlantic Ridge (Ludden and Thompson, 1978). Results from this and other (e.g. Hart, 1973; Hékinian, 1973; Thompson, 1973; Honnorez, 1981) studies show that the upper crust is progressively oxidized and hydrated with age, and that mobile elements such as K, Rb, Cs, Li, B, light rare earth elements (LREE), and ^{18}O are progressively taken up by low-temperature alteration, starting within the first 5 Ma (Ludden and Thompson, 1978; Thompson, 1983). Other investigators have attempted to quantify how alteration varies with age by comparing samples from widely scattered DSDP/ODP sites with known crustal ages. These studies document how alteration proceeds through progressive alteration stages, from oxidizing to reducing

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