Earth and Planetary Science Letters 416 (2015) 56–66

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Channelling of hydrothermal fluids during the accretion and evolution of the upper oceanic crust: Sr isotope evidence from ODP Hole 1256D

Michelle Harris *, Rosalind M. Coggon, Christopher E. Smith-Duque, Matthew J. Cooper, James A. Milton, Damon A.H. Teagle

Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, European Way, Southampton, SO14 3ZH, UK

ARTICLE INFO

Article history:
Received 7 July 2014
Received in revised form 27 November 2014
Accepted 29 January 2015
Available online 25 February 2015
Editor: T. Elliott

Keywords:
mid-ocean ridge
IODP
hydrothermal circulation
fluid–rock reaction
Sr isotopes
fluid channelling

ABSTRACT

ODP Hole 1256D in the eastern equatorial Pacific is the first penetration of a complete section of fast spread ocean crust down to the dike–gabbro transition, and only the second borehole to sample in situ sheeted dikes after DSDP Hole 504B. Here a high spatial resolution record of whole rock and mineral strontium isotopic compositions from Site 1256 is combined with core observations and downhole wireline geophysical measurements to determine the extent of basalt–hydrothermal fluid reaction and to identify fluid pathways at different levels in the upper ocean crust.

The volcanic sequence at Site 1256 is dominated by sheet and massive lava flows but the Sr isotope profile shows only limited exchange with seawater. However, the upper margins of two anomalously thick (>25 m) massive flow sequences are strongly hydrothermally altered with elevated Sr isotope ratios and appear to be conduits of lateral low-temperature off-axis fluid flow. Elsewhere in the lavas, high $^{87}Sr/^{86}Sr$ are restricted to breccia horizons. Mineralised hyaloclastic breccias in the Lava–Dike Transition are strongly altered to Mg-saponite, silica and pyrite, indicating alteration by mixed seawater and cooled hydrothermal fluids. In the Sheeted Dike Complex $^{87}Sr/^{86}Sr$ ratios are pervasively shifted towards hydrothermal fluid values (∼0.705). Dike chilled margins display secondary mineral assemblages formed during both axial recharge and discharge and have higher $^{87}Sr/^{86}Sr$ than dike cores, indicating preferential fluid flow along dike margins. Localised increases in $^{87}Sr/^{86}Sr$ in the Dike–Gabbro Transition indicates the channelling of fluids along the sub-horizontal intrusive boundaries of the 25 to 50 m-thick gabbroic intrusions, with only minor increases in $^{87}Sr/^{86}Sr$ within the cores of the gabbro bodies.

When compared to the pillow lava-dominated section from Hole 504B, the Sr isotope measurements from Site 1256 suggest that the extent of hydrothermal circulation in the upper ocean crust may be strongly dependent on the eruption style. Sheet and massive flow dominated lava sequences typical of fast spreading ridges may experience relatively restricted circulation, but there may be much more widespread circulation through pillow lava-dominated sections. In addition, the Hole 1256D sheeted dikes display a much greater extent of Sr-isotopic exchange compared to dikes from Hole 504B. Because seawater-derived hydrothermal fluids must transit the dikes during their evolution to black smoker-type fluids, the different Sr-isotope profiles for Holes 504B and 1256D suggest there are significant variations in mid-ocean ridge hydrothermal systems at fast and intermediate spreading ridges, which may impact geochemical cycles of elements mobilised by fluid–rock exchange at different temperatures.

1. Introduction

Seawater circulation through, and reaction with, the ocean crust is a fundamental Earth process that controls the magmatic accretion of new oceanic crust, modifies the composition of ocean crust and seawater, and through subduction transports surficial geochemical signatures to the mantle. At mid ocean ridges (MOR) hydrothermal circulation is most spectacularly expressed as high temperature (up to 400 °C) vent fluids, but at the ridge axis and ridge flanks, lower temperature (<150 °C) hydrothermal circulation is also important. Because vent fluids provide only limited information on the subsurface, we require improved knowledge on sub-surface fluid flow pathways, and the vigour and longevity of seafloor hydrothermal alteration to further understand magmatic accretion at MOR (e.g., Henstock et al., 1993; Kelemen et al., 1997)

* Corresponding author. Tel.: +44-2380-596539.
E-mail address: michelle.harris@noc.soton.ac.uk (M. Harris).

http://dx.doi.org/10.1016/j.epsl.2015.01.042

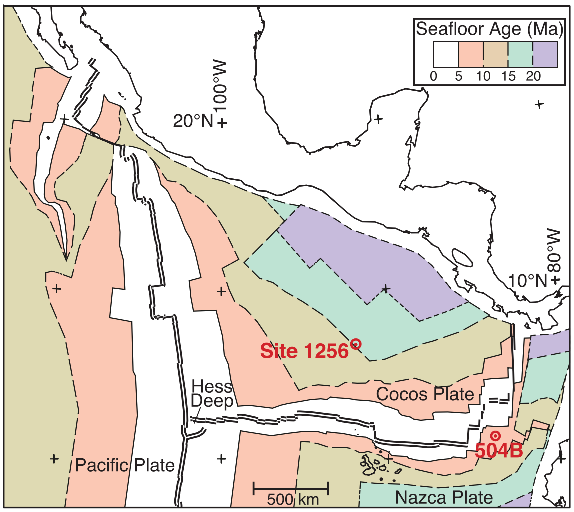

Fig. 1. Map of the locations of Site 1256 and Site 504 with crustal age shown in 5 million year intervals (modified from Wilson et al., 2003).

and better quantify the influence of seawater-basalt exchange on global chemical cycles (e.g., Vance et al., 2009).

To date, much of our knowledge of MOR hydrothermal circulation is reflected by conceptual cartoons developed from active and passive seismic observations (e.g., Kent et al., 1990; Tolstoy et al., 2008), measurements of vent fluid chemistry, thermal models, and core descriptions from ocean crust “reference site” DSDP Hole 504B (Alt, 1995). Unfortunately, observations from ophiolites appear inappropriate for MOR hydrothermal systems (e.g., Alt and Teagle, 2000; Bickle and Teagle, 1992), so key questions remain unresolved principally due to a dearth of direct information from intact ocean crust. For example, many sketches of MOR hydrothermal circulation indicate focused lateral fluid movement along the top of axial magma chambers, but to date there is only limited evidence for such flow. Sheeted sill-type models of ocean crust accretion require deep hydrothermal fluid circulation to remove latent and sensible heat from the lower crust (Maclennan et al., 2004) but the conduits for the downwelling of cool seawater-derived fluid remain elusive. Borehole observations and sampling by scientific ocean drilling is essential to better understand ocean floor hydrothermal systems but the paucity of deep holes into ocean crust limits our knowledge of seafloor basalt-hydrothermal alteration.

Here we present a high spatial resolution whole rock and mineral Sr isotope profile for ODP Site 1256, the first borehole to sample a complete section down to gabbros of intact upper ocean crust formed at a fast spreading rate (Teagle et al., 2006; Wilson et al., 2006). Our interpretations from this profile are tightly integrated with detailed petrography and geochemistry of the drill cores (Alt et al., 2010; Teagle et al., 2006; Wilson et al., 2003) and borehole wireline observations (Tominaga et al., 2009; Tominaga and Umino, 2010). We document sub-horizontal and sub-vertical channelling of seawater-derived hydrothermal fluids at different levels in the ocean crust, and develop a temporal model for the evolving hydrothermal system at Site 1256.

2. ODP Site 1256

ODP Site 1256 is situated in the Guatemala Basin on 15 million year-old ocean crust that formed at the East Pacific Rise (EPR) during an episode of superfast spreading (220 mm/yr, full rate; Fig. 1; Wilson, 1996). This location was selected for deep drilling to reach cumulate gabbros with the minimal depth penetration by testing the inverse relationship between spreading rate and the depths to the axial low velocity zones imaged by multi-channel seismic experiments at MOR (Carbotte et al., 1998; Purdy et al., 1992). Hole 1256D has been deepened down to the dike–gabbro transition during 4 scientific drilling expeditions (ODP Leg 206, IODP Expeditions 309/312, 335) (Teagle et al., 2006, 2012a; Wilson et al., 2003, 2006).

Hole 1256D is only the second borehole to sample sheeted dikes in intact ocean crust following Hole 504B (Alt et al., 1993). Throughout the lavas and dikes, core recovery rates are higher in Hole 1256D than Hole 504B (Hole 1256D 41% and 37%, Hole 504B 30% and 14%, lavas and dikes respectively). Importantly, wireline geophysical logging was undertaken during each stage of the Hole 1256D drilling, and provides an unrivalled suite of continuous physical properties logs and borehole images (Tominaga et al., 2009). These data enable the partial characterisation of material not recovered during coring, the identification of axial and off-axis lava deposition, and the establishment of the sequence of volcanic eruption at Site 1256 (Tominaga et al., 2009; Tominaga and Umino, 2010).

2.1. Lithostratigraphy

The 1271.6 m of drilled basement at Site 1256 is overlain by 250 m of sediments (Wilson et al., 2003) (Fig. 2). The pilot basement Hole 1256C recovered the top 88 m of the volcanic crust not recovered in Hole 1256D because of the installation of casing. The volcanic sequence (250–1004.1 m below seafloor (mbsf)) includes lava flows erupted both on and off axis. The interpretation of off-axis deposition for the uppermost lavas is based on the requirement for significant topography to pond very thick lava flows (Lava Pond) and for the Inflated Flows to have been erupted onto a sub-horizontal surface. On-axis volcanism in Hole 1256D is characterised by sheet flows tens of centimetres to 3 m thick, and massive flows 3 m to 26 m thick. The Lava–Dike Transition (LDT) comprises a 55 m-thick interval of sheet and massive flows punctuated by discrete zones of breccia and mineralisation. The Sheeted Dike Complex (SDC) comprises aphyric basalt with sub-vertical intrusive contacts, with an average dike width of 0.5 m (Tominaga et al., 2009). The lowermost dikes were contact metamorphosed to granoblastic textures and granulite assemblages. The Dike–Gabbro Transition (DGT) is composed of two intrusive gabbro bodies (Gabbro 1, 52.3 m-thick and Gabbro 2, 24.0 m), separated by two granoblastically recrystallised dike screens (Dike Screen 1, 24 m and Dike Screen 2, 23 m). Dike Screen 2 hosts a post-contact metamorphism greenschist facies dike that preserves its igneous texture.

The thickness (>150 m) of strongly recrystallised granoblastic dikes requires greater thermal energy than is available from the two gabbro intrusions (Coggon et al., 2008; Koepke et al., 2008). This requires either a large magma chamber below the bottom of the hole or significant topography on the dike–gabbro boundary at Site 1256. The common occurrence in Dike Screen 2 of cm-scale felsic and gabbroic intrusions suggests that the region of ∼100% plutonic rocks is perhaps within a few tens of metres of the current base of the hole (Teagle et al., 2012a).

The core-based lithostratigraphy is complemented by a wireline logging-based volcanostratigraphy developed from continuous downhole geophysical properties to define 8 electrofacies and quantify their abundance and downhole distribution (Tominaga et al., 2009). Wireline data show that much of the volcanic sequence is dominated by fractured or fragmented flows (∼40%) and that breccias and dike margins are under-represented in the cores recovered.