Chemical Geology 254 (2008) 19–35

Contents lists available at ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

Sr- and Nd-isotope geochemistry of the Atlantis Massif (30°N, MAR): Implications for fluid fluxes and lithospheric heterogeneity

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ARTICLE INFO

Article history:
Received 19 July 2007
Received in revised form 14 February 2008
Accepted 26 May 2008

Editor: R.L. Rudnick

Keywords:
Fluid fluxes
Water–rock ratios
Radiogenic isotopes
Serpentinites
Atlantis Massif
Lost City

ABSTRACT

The Atlantis Massif (Mid-Atlantic Ridge, 30°N) is an oceanic core complex marked by distinct variations in crustal architecture, deformation and metamorphism over distances of at least 5 km. We report Sr and Nd isotope data and Rare Earth Element (REE) concentrations of gabbroic and ultramafic rocks drilled at the central dome (IODP Hole 1309D) and recovered by submersible from the southern ridge of the massif that underlie the peridotite-hosted Lost City Hydrothermal Field. Systematic variations between the two areas document variations in seawater penetration and degree of fluid–rock interaction during uplift and emplacement of the massif and hydrothermal activity associated with the formation of Lost City. Homogeneous Sr and Nd isotope compositions of the gabbroic rocks from the two areas ($^{87}Sr/^{86}Sr$: 0.70261–0.70429 and ε_{Nd}: +9.1 to +12.1) indicate an origin from a depleted mantle. At the central dome, serpentinized peridotites are rare and show elevated seawater-like Sr isotope compositions related to serpentinization at shallow crustal levels, whereas unaltered mantle isotopic compositions preserved in the gabbroic rocks attest to limited seawater interaction at depth. This portion of the massif remained relatively unaffected by Lost City hydrothermal activity. In contrast, pervasive alteration and seawater-like Sr and Nd isotope compositions of serpentinites at the southern wall ($^{87}Sr/^{86}Sr$: 0.70885–0.70918; ε_{Nd}: −4.7 to +11.3) indicate very high fluid–rock ratios (~20 and up to 10^6) and enhanced fluid fluxes during hydrothermal circulation. Our studies show that Nd isotopes are most sensitive to high fluid fluxes and are thus an important geochemical tracer for quantification of water–rock ratios in hydrothermal systems. Our results suggest that high fluxes and long-lived serpentinization processes may be critical to the formation of Lost City-type systems and that normal faulting and mass wasting in the south facilitate seawater penetration necessary to sustain hydrothermal activity.

1. Introduction

The penetration, circulation and interaction of seawater with basalts, gabbros and/or peridotites in mid-ocean ridge environments is a first order process that leads to the release and/or uptake of elements (e.g., Si, Mg, Na, S, B, volatiles) and determines mass transfer between geochemical reservoirs. Fluid–rock interaction has important consequences for geochemical cycles in the oceans as well as for elemental fluxes during dehydration of altered oceanic crust in subduction zones, and in turn influences the chemical variability of the overlying mantle wedge. Numerous studies have documented chemical exchange and mineralogical changes during seawater interaction with the volcanic section, sheeted dykes and plutonic section of the oceanic crust (e.g., Hart, 1970; Humphris and Thompson, 1978a,b; Ludden and Thompson, 1979; Kempton et al., 1991; Stakes et al., 1991; Alt, 1995; Hart et al., 1999; Bach et al., 2001; Alt, 2003, 2004; Alt and Bach, 2006; Gao et al., 2006) and in obducted ophiolite complexes (e.g., Troodos; Spooner et al., 1977; Kawahata and Scott, 1990; Gillis et al., 1992). Sr isotope compositions have proven an important geochemical tool to quantify fluid–rock interaction in these environments (Dasch et al., 1973; Hart et al., 1974; Spooner et al., 1977; Jacobsen and Wasserburg, 1979; Menzies and Seyfried, 1979; McCulloch et al., 1980; Hess et al., 1991; Kempton et al., 1991; Bickle and Teagle, 1992; Hart et al., 1999; Gillis et al., 2005); however, fewer studies address chemical and mineralogical changes during seawater–peridotite interaction in present-day oceanic environments (Bonatti et al., 1970; Kempton and Stephens, 1997; Mével, 2003; Bach et al., 2004; Früh-Green et al., 2004; Bach et al., 2006; Boschi et al., 2006; Paulick et al., 2006). Studies that quantify fluid fluxes with Sr isotope data from serpentinites are limited to ophiolite complexes and Nd isotope data on serpentinized peridotites are particularly rare (Snow et al., 1994; Salters and Dick, 2002; Cipriani et al., 2004).

The Atlantis Massif (AM; Fig. 1) is an ideal site to study the influence of seawater–peridotite and seawater–gabbro interaction linked to the

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0009-2541/$ – see front matter
doi:10.1016/j.chemgeo.2008.05.018

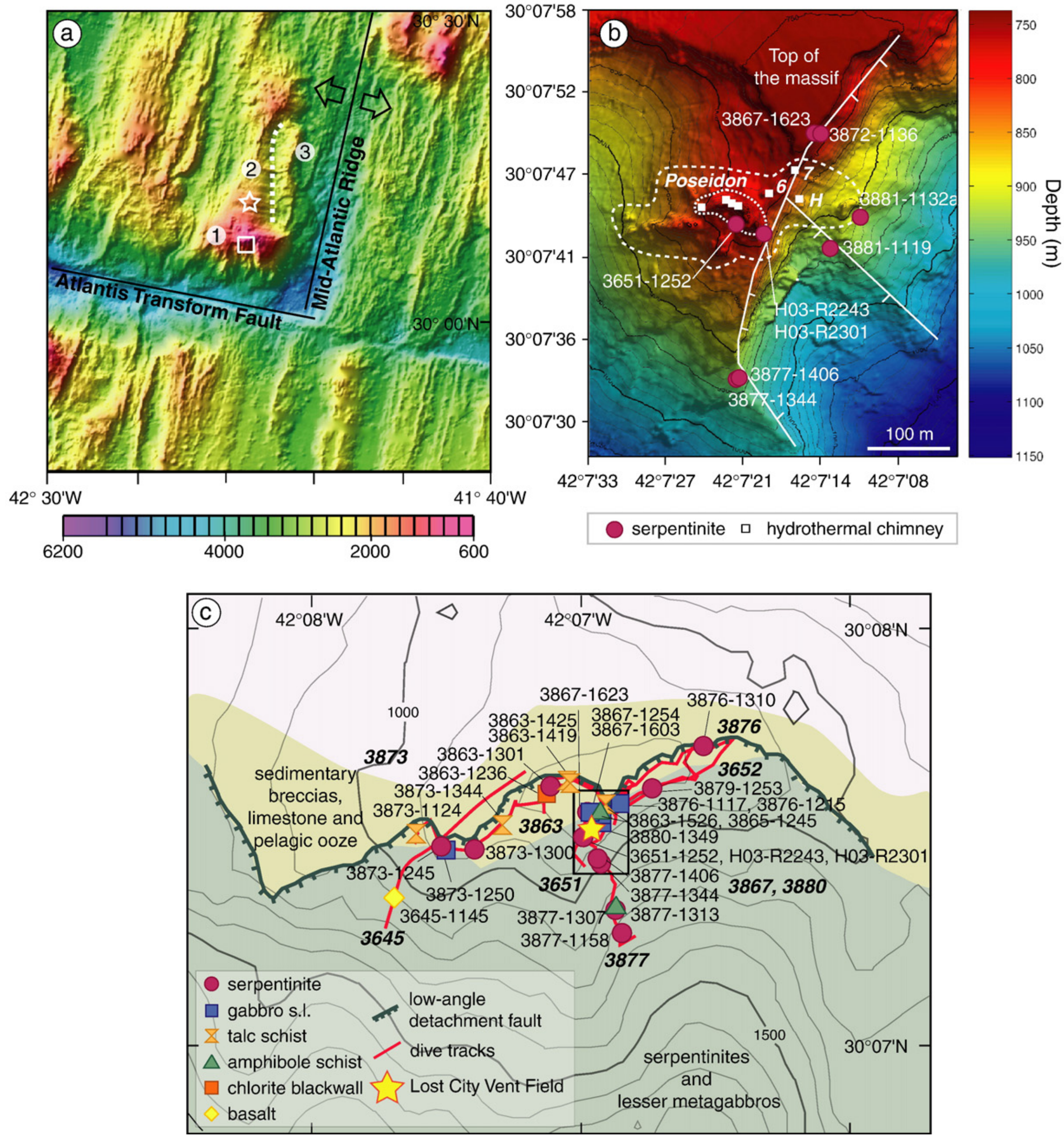

Fig. 1. a. Location map and morphology of the Atlantis Massif (AM) at the inside corner of the intersection between the slow-spreading Mid-Atlantic Ridge and the Atlantis Transform Fault. Based on morphologic and lithologic criteria, the AM is divided into three domains: (1) the peridotite-dominated southern ridge; (2) the gabbroic central dome; and (3) the volcanic eastern block. The white box shows the study area of the southern ridge of the massif and the Lost City Hydrothermal Field (LCHF), enlarged in Fig. 1b and c. White star: Site U1309 investigated during IODP Expeditions 304 and 305. b. High resolution map of LCHF obtained by the autonomous vehicle ABE and gridded at 2 m (Kelley et al., 2005). The external dashed line shows the spatial extent of the active field and major carbonate structures, whereas the internal finely dashed line indicates the base of the largest, 60 m high, hydrothermal structure, Poseidon. The location of the samples investigated in this study are shown relative to the positions of other active structures, identified by field markers 6, H and 7 (shown as solid squares). Locations of normal faults identified by Karson et al. (2006) are shown by the white-hatched lines. c. Simplified geologic map of the top of the southern wall of the Atlantis Massif showing location and lithologies of the samples analyzed in this study and dive tracks (red lines) from the 2000 and 2003 cruises. Green hatched line: trace of the detachment shear zone (DSZ) at the top of the massif (Karson et al., 2006); yellow star: location of the LCHF.

formation of an oceanic core complex (OCC) and to an active peridotite-hosted hydrothermal system. The southern ridge of the massif hosts the Lost City Hydrothermal Field (LCHF), which is driven by serpentinization processes and cooling of underlying mantle peridotites (Kelley et al., 2001, 2005). Interaction of infiltrating seawater with the mantle peridotites influences the chemical compositions of the venting fluids and the newly formed serpentinites and leads to up to 60 m-high towers of hydrothermal carbonate precipitates. Elements such as U, B, and Rare Earth Elements (REE) are enriched in the serpentinites relative to estimated primary compositions, whereas Ca is lost during serpentinization (Früh-Green et al., 2005).

Recent drilling of the Integrated Ocean Drilling Program (IODP) at the central dome of the Atlantis Massif (Fig. 1a) recovered predominantly gabbroic rocks with minor intercalated ultramafic rocks (Expedition Scientific Party, 2005a,b; Blackman et al., 2006) and revealed the heterogeneous nature of the massif over a distance of at least 5 km. Preliminary shipboard results indicate that seawater circulation and high temperature alteration was limited in the central dome and that this portion of the massif remained relatively unaffected by hydrothermal circulation related to the LCHF (Expedition Scientific Party, 2005a,b; Blackman et al., 2006). The gabbroic and ultramafic rocks of the central dome can therefore be regarded as providing "background" compositions