Chemical Geology 386 (2014) 80–100

Contents lists available at ScienceDirect

Chemical Geology

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

Trace metal distribution in the Atlantis II Deep (Red Sea) sediments

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ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form 31 July 2014
Accepted 5 August 2014
Available online 15 August 2014

Editor: J. Fein

Keywords:
Atlantis II Deep
Hydrothermal sediments
Metal-rich hot brines
Non-sulfidic metal deposition

ABSTRACT

The Atlantis II Deep is one of the only locations on the modern seafloor where active formation of a brine pool-type stratiform ore deposit can be studied. The presence of the brine pool causes retention of the hydrothermally released metals within the brine covered area, resulting in the accumulation of 90 Mt of low-grade metalliferous sediment (2.06% Zn, 0.46% Cu, 41 g/t Ag, and 0.5 g/t Au; Guney et al., 1988). Almost all metals are derived from hydrothermal input, but some are also derived from seawater (e.g., Mo), pelagic phytoplankton (Ni) and detrital input (Cr). The hydrothermal fluid that is vented into the pool is rich in metals but relatively low in reduced sulfur compared to open ocean black smokers. Metals are deposited as sulfides from the cooling hydrothermal fluid but also by adsorption onto non-sulfidic "surface-active" particles (Si–Fe-OOH) in the brine pool. An unexpected increase in the Cu/Zn ratio of the sediments with distance from the vent source(s) may reflect pulses of higher-temperature venting and increased Cu fluxes to the brine pool, which are recorded as higher Cu/Zn ratios in the distal sediments or, alternatively, more efficient adsorption of Cu to Fe-OOH particles in the distal brine.

During early diagenesis (a few thousand years) metals that are loosely bound to surface-active particles in the sediment apparently react with H_2S to form sulfides. Proximal to the inferred vents, the ambient pore water is highly concentrated in trace metals such as Cd, Ag and Hg that are incorporated in diagenetic sulfides, including chalcopyrite and sphalerite. At greater distance from the vents, trace metals such as Mo, As, and Ga are taken up by framboidal pyrite. High concentrations of Au (up to 3 ppm) are found in both proximal and distal metalliferous sediments, indicating that both primary deposition with sulfides and adsorption by diagenetic pyrite are important depositional processes. Some of the inferred pathways for metal precipitation in the Atlantis II Deep sediments, especially adsorption onto surface-active particles and subsequent incorporation in sulfides during diagenesis, may have been important unrecognized processes for metal accumulation in ancient stratiform ore deposits thought to have formed in brine pools.

1. Introduction

The Atlantis II Deep, situated in the Red Sea rift valley, is one of the first locations where seafloor hydrothermal activity was detected (Miller, 1964; Miller et al., 1966; Degens and Ross, 1969). It also contains by far the largest known hydrothermal mineral deposit on the seafloor (Guney et al., 1988). The metals have accumulated in an ~20 meter-thick sedimentary succession composed of finely laminated beds of oxides, carbonates, sulfides, silicates and other poorly-crystalline phases. The sediments are overlain by about 4 km^3 of hot (~68 °C), anoxic, metal-rich brine, covering an area of about 60 km^2, from which most of the metals have precipitated. This style of metal accumulation is not known anywhere outside the Red Sea but has been widely invoked in the genetic models of many ancient stratiform metal deposits (e.g., Large et al., 1996; Johnson and Skinner, 2003; Solomon et al., 2004; Tornos et al., 2008; Ohmoto et al., 2006; Goodfellow and Lydon, 2007).

The metalliferous sediments of the Atlantis II Deep have been studied extensively since 1969, but comprehensive multi-element analyses by modern ICP-MS techniques have never been published. Fewer than 600 chemical analyses of the sediments are known, most with incomplete trace element data, despite more than 500 sediment cores having been taken. The most recent cores from the 1980s were relocated in a repository in Germany and re-opened for this study. Previous work on these cores mostly analyzed composite samples (~1 m intervals) in attempts to represent the bulk facies or entire stratigraphic units (unpublished data from the MESEDA I–III projects; Bertram et al., 2011). This paper reports the first modern geochemical data on the metalliferous sediments in 20 years (since Anschutz and Blanc, 1995a), including one of the few comprehensive suites of trace elements (67 elements), and is the first to target the fine layering of the sediments at the scale of centimeters. While the spatial distribution of the major metals, Cu and Zn, has been well established from bulk assays of the cores, little has been known about the trace metal distribution in the Atlantis II

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http://dx.doi.org/10.1016/j.chemgeo.2014.08.009

sediments. We present detailed trace element data for the different stratigraphic units and reconstruct the sequence of mineralizing processes that led to the observed trace metal zoning in the basin. It has been known for a long time that the precious metals, for example, have high concentrations in some cores and are a potentially important resource in the Atlantis II Deep (e.g., Oudin et al., 1984), but the major controls on Au and Ag enrichment are unknown. The present study provides some of the first insights into the controls on trace metal distribution, detailing the behavior with respect to the evolution of the basin, the diagenetic history of the sediments, and the zoning with respect to hydrothermal sources. The latter has major implications for understanding brine-pool sedimentation and exploration for mineral deposits thought to have formed in such an environment.

1.1. Geologic setting and depositional environment

The Atlantis II Deep is an axial trough situated in the middle of the slowly spreading Red Sea rift, which is opening at a rate of ~1.1 cm/year at this latitude (Cochran and Martinez, 1988). It has a depth of about 2200 m and is surrounded by bathymetric barriers that confine the sediment and brine to one large basin and 4 sub-basins (Fig. 1). The current composition of the brine reflects contributions from different sources: Red Sea deep water, leaching of surrounding Miocene evaporites, and hydrothermal circulation in the underlying basalts and/or normal Red Sea sediments (Schoell and Faber, 1978; Zierenberg and Shanks, 1986; Dupré et al., 1988; Anschutz et al., 1995; Pierret et al., 2001). The brine pool is interpreted to have developed early in the history of the Deep (Oudin and Cocherie, 1988), prior to the first major hydrothermal activity, which began at least 15,000 years ago (Hackett and Bischoff, 1973; Shanks and Bischoff, 1980).

Hydrothermal fluids at close to black smoker temperatures (~350 °C; Zierenberg and Shanks, 1983; Oudin et al., 1984; Ramboz et al., 1988; Missack et al., 1989) are circulated through the sedimentary succession and underlying mid-ocean ridge basalt (MORB), resulting in exchange of elements with surrounding strata before venting into the brine pool (Shanks and Bischoff, 1977; Pottorf and Barnes, 1983 and ref. therein; Cole, 1988). The exact composition of the hydrothermal fluid is not known (see e.g., Anschutz et al., 1995; Blanc et al., 1995; Anschutz and Blanc, 1995a, 1996) but is clearly influenced by interaction with both Miocene evaporites in the sedimentary strata (Dupré et al., 1988) and the basaltic basement rocks (Pottorf and Barnes, 1983). Salinities up to 32 wt.% NaCl have been measured in fluid inclusions in vein anhydrite (Oudin et al., 1984; Ramboz et al., 1988). These salinities are about 5–10 times higher than in any other modern seafloor hydrothermal system (Von Damm, 1990; Douville et al., 1999).

Fig. 2 shows a schematic cross section through the present-day Atlantis II Deep sediments and brine pool. The deepest part of the brine pool is metal-rich, anoxic, devoid of reduced sulfur, hot (68.3 °C when last measured in 2008; Swift et al., 2012) and extremely saline

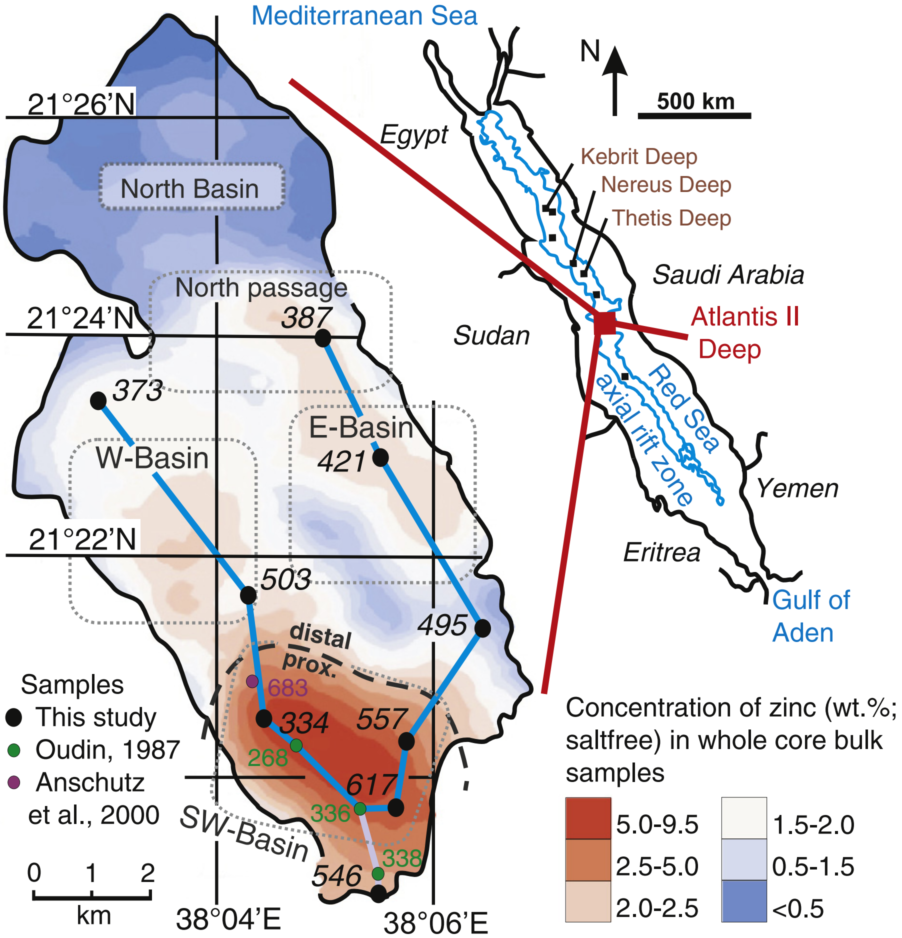

Fig. 1. Location of the Atlantis II Deep in the Red Sea rift axis. On the left, the sub-basins are indicated. Sediment cores are indicated by the numbers; the blue line is a fence of cores used to examine metal zonation within the basin. The location of the inferred present-day hydrothermal vent source(s) (proximal part of the Deep) is delineated by whole-core bulk concentrations of Zn > 2.5 wt.% in all units. Contoured data are averages of all metal assays in each of 497 cores (salt-free, based on washed core samples: unpublished data from the MESEDA I–III projects; Bertram et al., 2011). The cores varied in length from <1 to 20 m and thus represent variable parts of the stratigraphy; the lower stratigraphic units are missing in the SW Basin. Four of the 9 cores selected for this study are within 3 km of the inferred location of the presently active hydrothermal vents and referred to as proximal; cores outside this area (up to 8 km from the current vent source) are referred to as distal.