ELSEVIER

Marine Geology 225 (2006) 191–208

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Pore water geochemistry of eastern Mediterranean mud volcanoes: Implications for fluid transport and fluid origin

Ralf R. Haese [a,*], Christian Hensen [b], Gert J. de Lange [a]

[a] *Department of Geochemistry, Faculty of Earth Sciences, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, The Netherlands*
[b] *Leibniz-Institute of Marine Sciences (IFM-GEOMAR) and SFB 574, Marine Biogeochemistry, Wischhofstr. 1-3, D-24148 Kiel, Germany*

Received 6 August 2004; received in revised form 4 August 2005; accepted 2 September 2005

Abstract

The pore water chemistry of mud volcanoes from the Olimpi Mud Volcano Field and the Anaximander Mountains in the eastern Mediterranean Sea have been studied for three major purposes: (1) modes and velocities of fluid transport were derived to assess the role of (upward) advection, and bioirrigation for benthic fluxes. (2) Differences in the fluid chemistry at sites of Milano mud volcano (Olimpi area) were compiled in a map to illustrate the spatial heterogeneity reflecting differences in fluid origin and transport in discrete conduits in near proximity. (3) Formation water temperatures of seeping fluids were calculated from theoretical geothermometers to predict the depth of fluid origin and geochemical reactions in the deeper subsurface.

No indications for downward advection as required for convection cells have been found. Instead, measured pore water profiles have been simulated successfully by accounting for upward advection and bioirrigation. Advective flow velocities are found to be generally moderate (3–50 cm y^{-1}) compared to other cold seep areas. Depth-integrated rates of bioirrigation are 1–2 orders of magnitude higher than advective flow velocities documenting the importance of bioirrigation for flux considerations in surface sediments. Calculated formation water temperatures from the Anaximander Mountains are in the range of 80 to 145 °C suggesting a fluid origin from a depth zone associated with the seismic decollement. It is proposed that at that depth clay mineral dehydration leads to the formation and advection of fluids reduced in salinity relative to sea water. This explains the ubiquitous pore water freshening observed in surface sediments of the Anaximander Mountain area. Multiple fluid sources and formation water temperatures of 55 to 80 °C were derived for expelled fluids of the Olimpi area.

Keywords: mud volcano; cold seep; advection; bioirrigation; subsurface

1. Introduction

Submarine fluid flow and associated cold seeps have been found at various tectonically active and passive continental margins: well-studied active margin settings are the Cascadian (Kulm et al., 1986; Suess et al., 1999), the Aleutian (Suess et al., 1998), the Sagami (Masuzawa et al., 1992), the Nankai (Le Pichon et al., 1992; Henry et al., 1992), the Barbados (Henry et al., 1996), and the Costa Rica (Zuleger et al., 1996) subduction zones. Seepage along major fault zones is found off Monterey (U.S.A.) (Barry et al., 1996). Cold seeps at passive margins are mostly associated with rapidly accumulating sediments such as in the Gulf of Mexico (MacDonald et al., 1994), in the North Sea (Hovland et al.,

* Corresponding author. Present address: Geoscience Australia, P.O. Box 378, Canberra, ACT 2601, Australia.
E-mail addresses: ralf.haese@ga.gov.au (R.R. Haese), chensen@ifm-geomar.de (C. Hensen), gdelange@geo.uu.nl (G.J. de Lange).

0025-3227/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2005.09.001

1987) and on the Norwegian shelf (Ginsburg et al., 1999). If subsurface fluids become over-pressured, sediment is mobilized and subjected to expulsion at the sediment surface inducing mud flows and the build-up of mud volcanoes (Brown, 1990). The chemical composition of the expelled fluids can be used to deduce their origin with respect to the temperature conditions and the geologic regime (Dia et al., 1999). The depth distribution of pore water constituents allows to derive estimates of the advective flow velocity (Han and Suess, 1989; Wallmann et al., 1997). Advective flow rates at submarine seeps have been found to vary by four orders of magnitude (Moore and Vrolijk, 1992) which points to significant differences in the hydrodynamic conditions. Consequently, a distinction between diffuse and focused flow has been suggested.

Fluid seepage may be spatially and temporally highly variable on a local and regional scale. Consequently, estimates on the importance of cold seeps for global biogeochemical cycles are ambiguous. The volume of global annual fluid expulsion at cold seeps has been cautiously estimated to be 1 km^3 (Von Huene and Scholl, 1991). Boron (B) has been found to be significantly enriched in cold seep fluids and has consequently been included in an oceanic B budget (Lemarchand et al., 2000).

Ascending fluids are typically rich in methane, which is the basis for abundant and highly specialized micro-, macro- and megafauna effectively altering the chemistry of the fluids. In methane-rich sediments, microbial consortia consisting of archaea and sulfate reducing bacteria carry out anaerobic oxidation of methane (Hinrichs et al., 1999; Boetius et al., 2000; Pancost et al., 2000), which results in the production of dissolved inorganic carbon and sulfide (Kulm et al., 1986; Masuzawa et al., 1992; Boetius et al., 2000). Aerobic methane and sulfide oxidation serve as energy sources for free living and symbiotic microorganisms hosted within macro- and megasized benthic organisms. The macro- and megafauna exchange their burrow water with oxygen-rich bottom water by bioirrigation, which has significant impact on solute transport and biogeochemical reaction rates (Haese, 2002). The depth-integrated rate of bioirrigation can be compared to the advective flow velocity, illustrating the relative importance of each fluid transport mode at cold seeps (Wallmann et al., 1997). Apart from microbiologically mediated methane oxidation, methane may become stored in gas hydrate under certain temperature and pressure conditions and provides supersaturated concentrations of methane (Brooks et al., 1984; Haese et al., 2003).

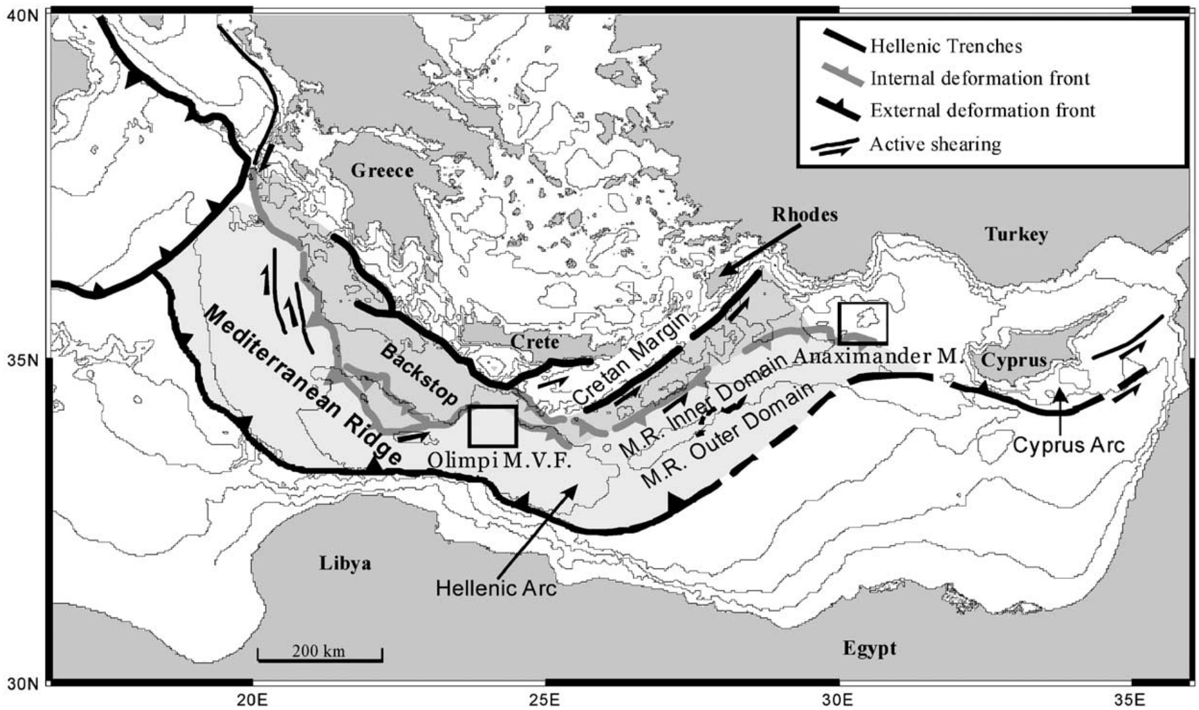

Fig. 1. Map of the eastern Mediterranean Sea with major tectonic units and the sampling areas (in boxes), the Olimpi Mud Volcano Field and the Anaximander Mountains (modified after MEDINAUT/MEDINETH Shipboard Scientific Parties 2000).