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High sedimentation rates in a karstic lake associated with hydrothermal turbid plumes (Lake Banyoles, Catalonia, NE Spain)

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ABSTRACT

In Lake Banyoles (northeastern Spain), warm water enters through lake bottom seeps and generates two hydrothermal turbid plumes. One of them is perennial in character and the other is active only after fluidisation events of the bottom sediment caused by reactivation of the bottom seeps after rainfall in the aquifer recharge area. The vertical development of both hydrothermal plumes is very sensitive to the thermal stratification of the water column. When a plume reaches a level of neutral buoyancy, a turbidity current spreads laterally and transports sediment particles across the lake. Silt particles transported by the plume are used in ADCP backscatter images to determine its maximum and equilibrium heights. Field results are compared and found to be in accordance with models for thermal convection from finite isolated sources. When the lake is stratified, the vertical transport of sediment is confined to the hypolimnion; when the lake water column is mixed, the plume reaches the surface of the lake. The turbidity current is usually confined to the southern sub-basin of the lake during stratification, resulting in higher sedimentation rates. During fluidisation events the sedimentation rates are one order of magnitude greater than in periods without fluidisation. For the fluidisation periods, turbidity has been estimated to be ~10 FTU.

1. Introduction

Convection from isolated sources has received much attention because of its application to geophysical and engineering flows. Relevant examples include plumes (continuous sources of buoyancy) and thermals (fixed volumes of buoyant fluid). Man-made plumes include waste in oceans and chimney stacks in the atmosphere (Turner, 1973; List, 1982). In devices that eject buoyant fluid with some momentum, the buoyancy becomes the dominant driving force as the flow evolves and can be defined as buoyant jets. Oceanic hydrothermal vents are an example of a natural flow driven by isolated buoyancy sources. They are formed in regions where upwelling magma from the Earth's interior solidifies on mid-ocean ridges to form new crust, thus transferring heat from the magma to the surrounding waters to create turbulent plumes (Lupton et al., 1985; Speer and Rona, 1989). Another phenomenon of geophysical interest is deep ocean convection, where predisposed regions of high-latitude oceans (known as "chimneys") become unstable due to intense surface cooling and generate turbulent convection that can penetrate to depths of between 2 and 4 km (Fernando et al., 1998).

Whether and when deep convection occurs depends on the seasonal development of the surface buoyancy flux with respect to the initial stratification at the beginning of the winter period, and on the role of lateral advection (Marshall and Schott, 1999). In the open ocean the convective plumes entrain ambient fluid and, if deep enough, become affected by rotational effects and any pre-existing stratification. In shelf regions the convective plumes reach the sloping bottom, spread along it toward deeper locations, and are diverted by the Coriolis force where this applies.

Convection dynamics and flow features have also been studied in many laboratory and numerical experiments. Localised turbulent convection has been generated in laboratory tanks, for both laterally confined and unconfined domains issuing into a homogeneous, non-rotating environment (Kaimal et al., 1976; Boubnov and Van Heijst, 1994; Colomer et al., 1998a; Colomer et al., 1999) and into a homogeneous, rotating fluid (Maxworthy and Narimousa, 1994; Boubnov and Van Heijst, 1994; Dai et al., 1994; Narimousa, 1996; Whitehead et al., 1996, Narimousa, 1997; Jacobs and Ivey, 1998). These experiments have led to the prediction of a physical scaling of the convective chimney's length and velocity under gravity and rotation, with a resulting dependency on buoyancy, B_o, the Coriolis parameter, f, and the chimney length scale, h. As an alternative to laboratory experiments, localised open-ocean convection has been examined by high-resolution numerical models (Morton et al., 1956; Legg et al., 1996; Julien et al., 1999; Fannelop and Webber, 2003) to investigate the relationship between the convection process and the external

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parameters (Phillips, 1966; Okada et al., 2004). In addition, numerical experiments have allowed studies of the growth as well as the scaling laws of buoyant plumes (Speer and Marshall, 1995) and megaplumes (Lowell and Germanovich, 1995; Palmer and Ernst, 1998), and analysis of the rotation effect of the heat source (Leaman and Schott, 1991; Pham et al., 2006).

The convection process — the thermal plume — is generated by an underlying heat source. If the heating is confined to a finite area, a vertical thermal plume and associated circulation will develop as a result of the temperature (density) difference between the plume and its environment. The plume stops rising as the temperature difference between the plume and its surroundings decreases due to entrainment

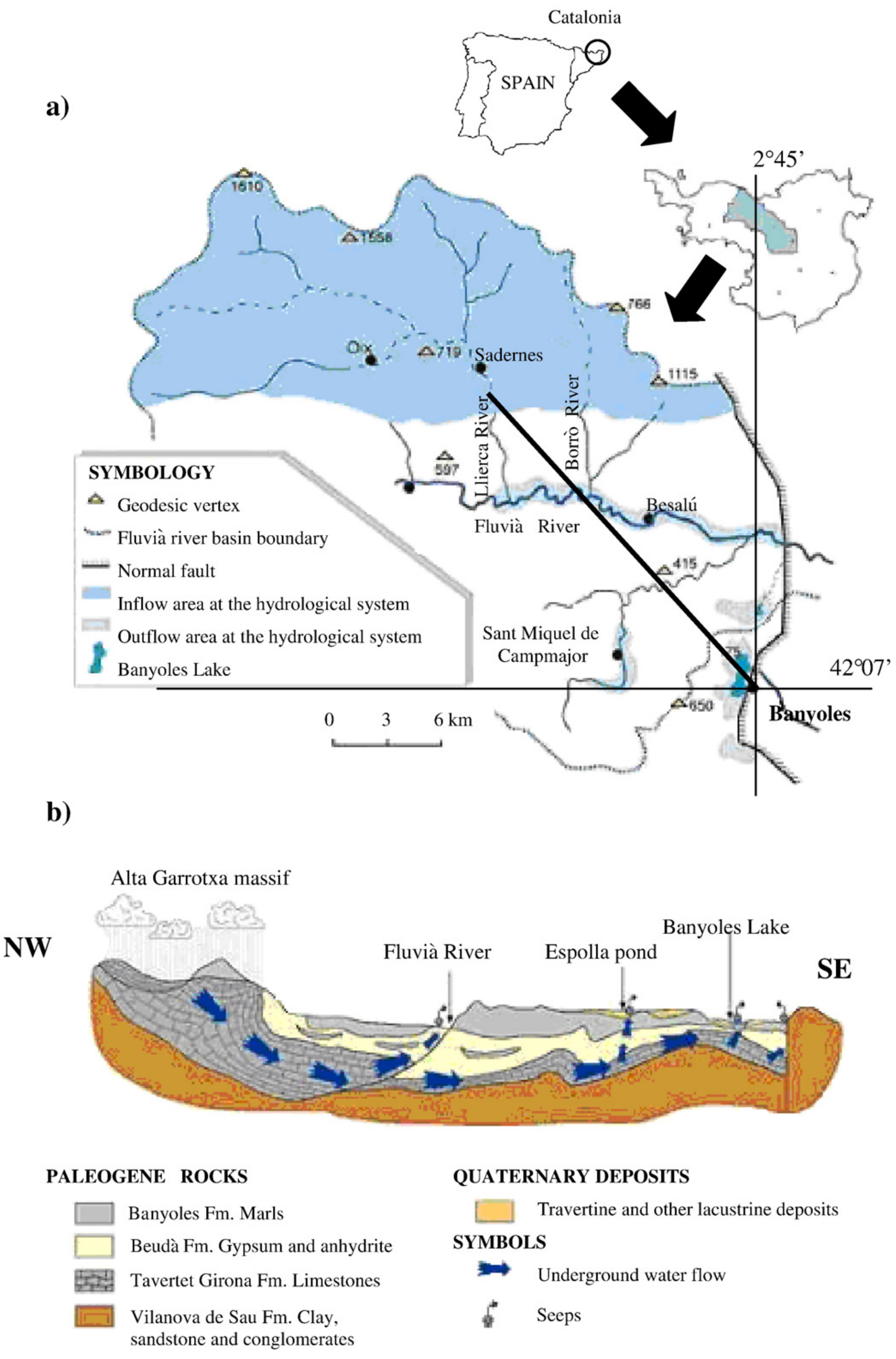

Fig. 1. a) Location of Lake Banyoles (Catalonia, northeastern Spain) and representation of the hydrological system in the Lake Banyoles region. The solid line shows the location of the cross section below. b) Path of the groundwater flow along the cross section marked at (a) (Sanz, 1985 redrawn by Brusi et al., 1992).