Hydrothermal plumes trapped by thermal stratification

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[1] Hydrothermal plume penetration through density interfaces has been widely studied in laboratory experiments. It has been found that competition between plume buoyancy and background stratification (parameterised as the Richardson number) is crucial in determining whether or not the plume will penetrate through a density interface. In this paper, we present the analysis of field data concerning two hydrothermal sediment-laden plumes in a stratified lake. Measurements of the particle concentration within these plumes have been used to determine their vertical, spatial and temporal development in the water column. The results show that neither of the plumes penetrate the lake thermoclines for large Richardson numbers, which is in accordance with the results found in laboratory experiments. *INDEX TERMS:* 1719 History of Geophysics: Hydrology; 1845 Hydrology: Limnology; 1854 Hydrology: Precipitation (3354); 1884 Hydrology: Water supply; 4558 Oceanography: Physical: Sediment transport; *KEYWORDS:* plume, stratification, sediment, karst basin, Richardson number. **Citation:** Colomer, J., T. Serra, M. Soler, and X. Casamitjana, Hydrothermal plumes trapped by thermal stratification, *Geophys. Res. Lett.*, *30*(21), 2092, doi:10.1029/2003GL018131, 2003.

1. Introduction

[2] Lake Banyoles (42°07′N, 2°45′E), in the eastern Catalan pre-Pyrenees, is a small multibasin lake (surface area of 1.12 km^2) of mixed tectonic-karstic origin, composed of six main basins (B1–B6, see Figure 1). B1 is the largest basin and supplies around 85% of the total incoming water and the rest is supplied by river inflows. Eventually, B2 supplies water to the lake at a rate comparable to B1. An underlying fault (to the east of the lake), which acts as a barrier to ground water movement in a complex series of confined aquifers, forces the vertical discharge of the ground water flow through the bottom of the basins. The subterranean springs mix the sediments above up to a fairly sharp interface known hereafter as the lutocline. The difference in temperature between the suspension zone below the lutocline and the water above induces the development of a hydrothermal plume, in the same way that convective plumes develop from localized sources [*Maxworthy*, 1997] in oceanic and atmospheric deep convection [*Schott et al.*, 1993; *Schott et al.*, 1996; *Fernando and Smith*, 2001], microbursts [*Lundgren et al.*, 1992], urban heat islands [*Lu et al.*, 1997] and polynyas [*Chapman and Gawarkiewicz*, 1997]. The lutocline is well detected by seismic profiling and is located at a depth Z_L from surface (Figure 2a). In the last seventeen years (1986–2002), while the sediments in B1 were found to be in suspension, the sediments in B2 usually remained compacted at the bottom of the basin (Figure 2a), except for periods of high precipitation (Figure 2b), when sediment resuspended and migrated upward, producing the fluidization of the sediment. These fluidization events (F1, F2, etc.) were detected when measuring the depth of the lutocline (Z_L) in B2 (Figure 2c). The shallower depth of the lutocline in B2 was found to be at about 24 m during the F7 event in 1996 (Figure 2b). The last fluidization event, F9, was detected between May and September 2002 (Figure 2c) with the lutocline undergoing a vertical displacement of around 8 m.

[3] We chose to examine the dynamics of the hydrothermal plumes in Lake Banyoles for three main reasons. First, the history of sediment fluidizations in basins B1 and B2 has been studied over the past 17 years. These studies [*Casamitjana and Roget*, 1993; *Colomer et al.*, 2001; *Colomer et al.*, 2002] reveal that the plume developing in B1 is permanent (chronic plume) and that the plume in B2 develops episodically (episodic plume). The plume in B1 was reported for the first time in 1998 whereas this paper is the first to describe the plume in B2. Second, these hydrothermal plumes carry particles in suspension (turbid plumes), which affect both fish distribution [*Serra et al.*, 2002a] and sedimentary records between basins B1 and B2 [*Serra et al.*, 2002b]. Third, the development of localized convection in rotating stratified fluids have been largely studied using both laboratory and field oceanic experiments, especially for the case of deep and intermediate water masses of the world's oceans [*Schott et al.*, 1993; *Maxworthy*, 1997], but it has not yet been described in a lake.

[4] The sampling was conducted over a period of 109 days from May 18th to September 3rd, 2002, in the small lake of Banyoles (Figure 1). Fourteen surveys were made during this period. The stations along each transect were separated from each other by ~150 m, between B1 and B2 (Figure 2a). At each station, conductivity, temperature and depth were measured with a CTD profiler (Seabird SBE19, Seacat). Particle size distribution and concentration were also measured with an *in situ* laser particle size analyser (Lisst100, Sequoia Instruments), which measures particles in the size range 1.2–250 μm.

[5] Hydrothermal plumes are best thought of as efficient mixing agents, responsible solely for 'churning' the column where they develop [*Visbeck et al.*, 1996]. Assuming that the input of unstable buoyancy flux at a surface of radius R is balanced by the lateral removal of flux by eddies ejected out of the convective region, *Whitehead et al.* [1996] and *Visbeck et al.* [1996] were able to determine the depth of the convection. Similar results were found by *Colomer et al.* [1998] when considering that the depth of convection is determined by the inhibition of vertical growth due to the stratification of the water column. For both hypotheses, the maximum height to which a plume migrates has been found

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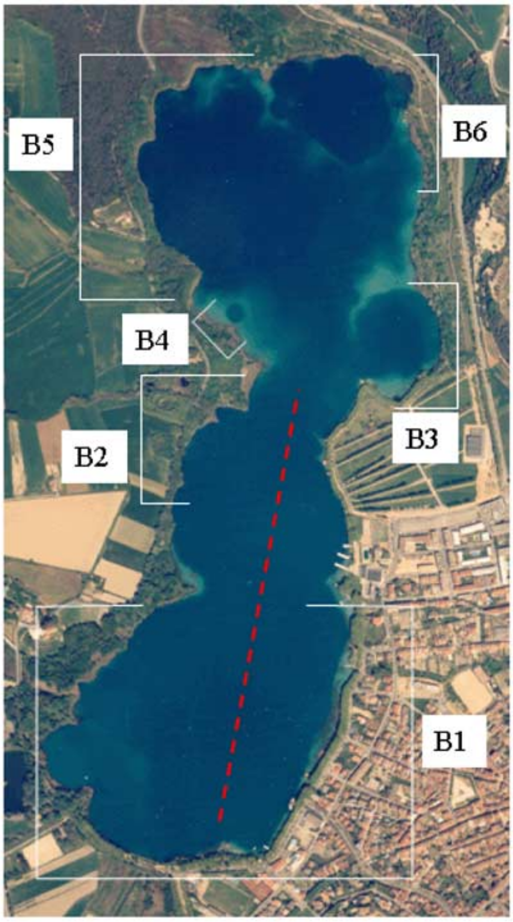

Figure 1. Aerial photograph of Lake Banyoles with marked transect of measurements. The lake is divided into six basins. Basin B1 is located in the southern lobe, basin B2 in the central lobe and B3, B4, B5 and B6 in the northern lobe, some of them clearly seen in the photograph. This photograph was kindly provided by the *Institut Cartogràfic de Catalunya*.

to be a function of the source radius, R, the buoyancy flux per unit area, B_o, the stratification of the water column, N, and independent of the rotation rate, f [*Whitehead et al.*, 1996]:

$$h_{max} = 4.6(B_o R)^{1/3} N. \tag{1}$$

In Lake Banyoles, above the lutocline in basin B1, the hydrothermal plume transports particles with diameter peaks centred at 2.8, 10.5 and 46.5 μm from the lutocline level upwards. *Colomer et al.* [2001], found that particles above and below the lutocline presented the same particle size distribution, therefore, showing that the particles in the plume originated from the lutocline. The lake hypolimnion in B1 is also characterized by a vertical homogeneous distribution of both temperature (Figure 3a) and PVC of ~ 3–4 μl L^{-1} (Figure 3b), with only a few variations with time. This homogeneity may be attributed to the mixing caused by the continuous vertical movements within the plume [*Muñiz*, 2000]. Temperature measurements, in line with the results of the observed deep and intermediate ocean plumes [*Visbeck et al.*, 1996; *Buongiorno Nardelli and Salusti*, 2000], yielded a vertical stratification in the hypolimnion of N ~ 2.2–5.2 10^{-3} s^{-1}. The buoyancy flux at the lutocline varied between B_o = 3.1 10^{-8} and 7.6 10^{-8} m^2 s^{-3}, which is comparable to those forcing the convection in polynyas which are 3 10^{-7} m^2 s^{-3} [*Chapman and Gawarkiewicz*, 1997; *Fernando and Smith*, 2001], 3 10^{-7} m^2 s^{-3} in Central Artic ocean chimney [*Narimousa*, 1996], 6 10^{-8} m^2 s^{-3} in Central Greenland Sea chimney [*Narimousa*, 1996], and 1.5–4 10^{-8} m^2 s^{-3} in the Mediterranean Sea [*Buongiorno Nardelli and Salusti*, 2000]. Equation (1) predicts maximum heights of the hydrothermal plume as varying from 19.5 to 46.2 m, therefore the plume should, in theory, migrate to positions further up than those indicated by the PVC contours in Figure 3b. It is likely the rise of the plume is constrained by the hypolimnion of the lake. As shown in Figure 3a, the water column in B1 presents a summer stratified pattern with a well developed epilimnion and a seasonal thermocline with a vertical thickness of ~5 m. The bottom of the

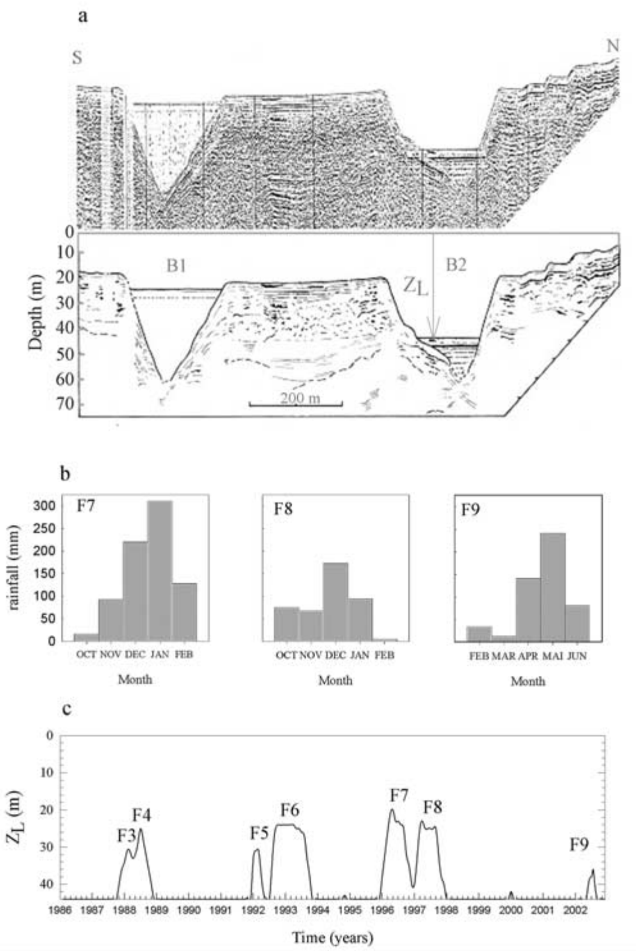

Figure 2. (a) South-North seismic transect and schematic interpretation of the section from B1 to B2 [*Canals et al.*, 1990]; the lutocline is well detected by the seismic profile and is located at a depth Z_L from the surface, (b) monthly precipitation in the area of the aquifer recharge during the fluidization events (F7, F8 and F9) and (c) lutocline depth, Z_L, at B2 (as shown in b) during the period 1986–2002, where fluidization events are identified (from F3 to F9).

thermocline is found to be at depths varying from 9.2 m on day 137 to 10.6 m on day 246 (Figures 3a and 3b). The top of the hydrothermal plume is well delineated by the PVC contour of $\sim$1 μl L^{-1}. At the lutocline level, where the plume originates, the temperature is found to be constant at 19.2°C; at this level, the PVC is of $\sim$50000 μl L^{-1}. In other words, there is an increase of about four orders of magnitude (the corresponding sediment mass is $\sim$130 g L^{-1}).

[6] In basin B2, there is thermal stratification of the hypolimnion (Figure 4a) with a PVC of $\sim$2 μl L^{-1} (Figure 4b) as a result of the intrusion of the gravity current associated with the impingement of the hydrothermal plume at the thermocline in B1 (Figure 4b). Of great interest is the increase in PVC, with maximum values $\sim$20 μl L^{-1} on the Julian day 163 (Figure 4b), inside the depression of B2 as a result of the confinement of particles below the secondary thermocline (Figure 4a) found at the entrance of the cone-like depression (Figure 2a). The sediment plume in B2 contains small and large grains with two peaks centred at diameters of 8.9 and 42.9 μm. Maximum PVC values were found between Julian days 150 and 190 correlating with the maximum activity of the sediment fluidization. The buoyancy flux at the lutocline varied between 4.7 10^{-8} to 5.9 10^{-8} m^2 s^{-3} giving values of h_{max} $\sim$27.0 and 30.0 m, calculated with equation 1, which are larger than the distance between the lutocline and the secondary thermocline in B2. Values of the maximum height of the hydrothermal plume, measured with the particle analyser in the B2 depression, were found to be smaller than those calculated from equation 1, therefore we infer that the secondary thermocline at the entrance of the depression acts as a barrier to the propagation of the plume. Once the fluidization event in B2 finishes, the activity of the hydrothermal plume decreases too, with the PVC diminishing as a result of particle sedimentation (lasting until day $\sim$205).

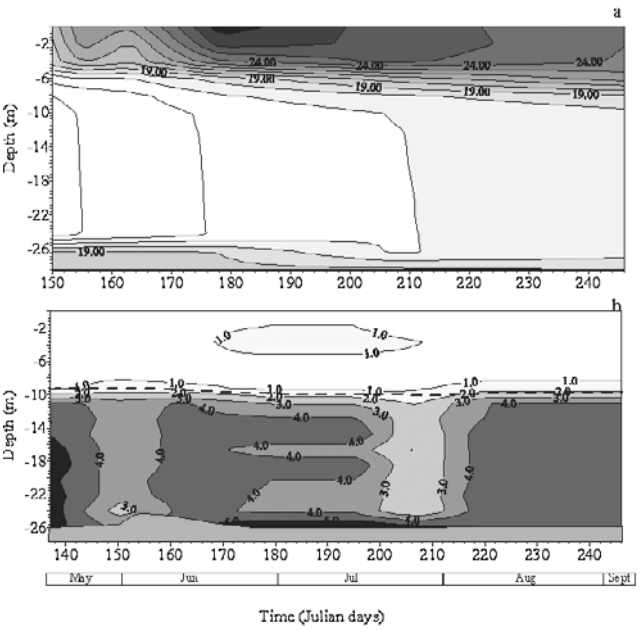

Figure 3. Temporal distribution of isotherms, in °C (a) and isolines of PVC, in μl L^{-1} (b) in basin B1 during the period of study. The dashed line indicates the depth of the base of the thermocline. The grey area at the bottom of the figure denotes the zone below the lutocline.

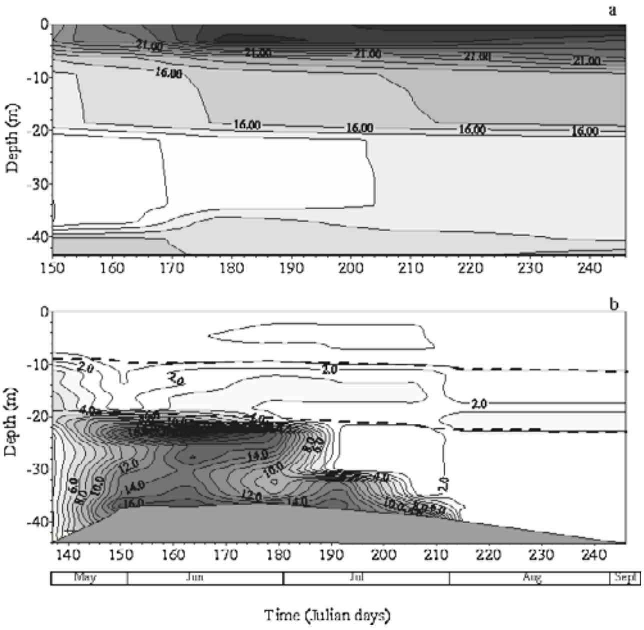

Figure 4. Same as Figure 3 for basin B2. The dashed line at depths of $\sim$20 m indicates the base of the secondary thermocline at the entrance of the basin.

[7] Also to be considered is the Richardson number, which evaluates whether or not the plume penetrates through a density interface [*Narimousa*, 1996]. It is defined as

$$Ri = g'h_o/(B_oR)^{2/3}, \quad (2)$$

where g' is the reduced gravity across a density interface and h_o is the depth of the convective layer (i.e., the vertical thickness of the plume). *Narimousa* [1996] clearly showed when Ri > 11, convective flows do not penetrate through the density interface.

[8] The Richardson number calculated from equation (2) varied between 274 and 950 in basin B1 with the maximum values attained when the summer stratification is greater (between days 180 and 220) as a result of summer heating. For the hydrothermal plume confined at the B2 depression, Ri varied between 162 and 221. Clearly, the Ri values calculated using equation 2 are greater than the critical Ri of 11, above which plumes do not penetrate through thermal stratification. The Ri values attained for the plumes in Lake Banyoles are greater than the Ri = 50 values calculated from field measurements of density stratification in the upper layers of the Central Artic region [*Newton et al.*, 1974] and the Ri = 7.8 values calculated from field measurements of deep convection in the Central Greenland Sea during the winter 1998–1999 [*Schott et al.*, 1993], in which case, the convective layer penetrated through the thermal ocean interface and likewise, in the deep waters of the Atlantic Ocean [*Narimousa*, 1996]. Therefore, the set of data here presented is also in accordance with laboratory experiments in relation to penetration of plumes through density interfaces.

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