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Effects of a turbid hydrothermal plume on the sedimentation rates in a karstic lake

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[1] The formation of a hydrothermal plume has been recently found in the main basin of a karstic lake. The hydrothermal plume carries a concentration of particles in suspension that are transported up to an equilibrium depth. At the equilibrium level, particles are transported horizontally as a turbidity current. The particle volume concentration in the hypolimnion, where the turbidity current occurs, has been found to be homogeneous for points close to the source of the plume. However, there is a decrease in the particle concentration points from close to the source of the plume to the points far from the source, which indicates that the sedimentation of particles from the turbidity current occurs. This sedimentation process has been attributed mainly to double diffusive sedimentation rather than to single particle sedimentation. Here we demonstrate the effect of this turbidity current on the zonal sedimentation rates at the southern lobe of the lake. *INDEX TERMS:* 4239 Oceanography: General: Limnology; 4558 Oceanography: Physical: Sediment transport; 4832 Oceanography: Biological and Chemical: Hydrothermal systems. **Citation:** Serra, T., J. Colomer, E. Gacia, M. Soler, and X. Casamitjana, Effects of a turbid hydrothermal plume on the sedimentation rates in a karstic lake, *Geophys. Res. Lett.*, *29*(0), XXXX, doi:10.1029/2002GL015368, 2002.

[2] A chronic hydrothermal turbid plume has been found to develop in the karstic lake Banyoles, situated in Catalonia, north-eastern Spain (Figure 1) [*Serra et al.*, 2002]. The hydrothermal plume was located in the main basin of the lake, in Basin 1 (B1). The lake is formed by 6 basins (BI-BVI, Figure 1a), with B1 being the largest and deepest (~75 m) from where the water enters and resuspends sediments from the bottom upwards. Sediments are transported up to a sediment interface, the lutocline (at ~30 m depth), which separates the region of clean water above, region A, from the high sediment concentration (100 g l^{-1}) region below, region B (Figure 1b). As a result of the high sediment concentration in region B, the lutocline acts as a false bottom at ~30 m depth as measured by echo-sounding profiles (Figure 1a). The temperature of the water at the lutocline level is warmer (~19°C, constant throughout the year) than the hypolimnetic water immediately above and this difference in temperature generates the convection process that drives the hydrothermal plume [*Colomer et al.*, 2001]. The plume develops upwards carrying a suspension of particles from the lutocline up to an equilibrium depth, i.e. forming a turbid hydrothermal plume. At the equilibrium depth, the water spreads laterally forming a mesopycnal turbidity current, as classified by *Mulder and Alexander* [2001] for a volume sediment concentration <10%. This turbidity current was ~0.02 K warmer than the surrounding water and had a typical thickness of ~1 m [*Colomer et al.*, 2001].

[3] Sedimentation from turbidity currents and density interfaces has been found to be an effective mechanism for the transport of suspended material through the bottom of the water body where it develops. The sedimentation process may occur because of the flocculation of small particles into larger settling aggregates and/or double diffusive sedimentation (DDS). DDS from turbidity currents has been reported in riverine outflows [*Parsons et al.*, 2001; *Koren and Klein*, 2000], volcanic eruptions [*Woods*, 1995] and also in laboratory surface sediment-laden water currents [*Parsons and García*, 2000].

[4] The aim of this study is to demonstrate the effects of the mesopycnal turbidity current in the sedimentation rates of the water column of lake Banyoles. For this purpose, measurements of the particle size distribution (PSD) and particle volume concentration (PVC) were taken with an in situ laser particle size analyser, which measures particles in the size range 1.2–250 μm, at different stations on the lake (SI-SVI, see Figure 1). Three sets of sediment traps consisting of structures containing 5 units of 20 ml glass tubs with an area to volume ratio of 5 [see, details in *Gacia and Duarte*, 2001] were also deployed at three selected stations on the lake (at SIII, SVI and at a point between SIV and SV, see Figure 1a). The sediment trap arrangements (sT1, sT2 and sT3) measured sedimentation rates at four different depths (8, 12, 15 and 19 m deep). Finally, a multiparametric probe (Hydrolab) measured the oxygen concentration at different depths of the water column and it basically performed measurements at the centre of BI (SI).

[5] The field campaign was carried out at the end of July of 2000, when the water column was well stratified. The epilimnion was ~5 m deep at a temperature of ~26°C and the thermocline was ~5 m thick (Figure 2). Below the thermocline, the hypolimnion was completely mixed and remained at a constant temperature of ~16°C, down to a depth of 28.5 m. A phytoplankton population was found within the thermocline layer, together with an increase in the oxygen concentration up to 8 mg l^{-1}, as could also be observed from microscopic observations of the water samples. The PVC at SI was found to be constant at ~4.5 μl l^{-1} from the lutocline level up to a depth of 15 m, and decreased upwards to the base of the thermocline, reaching values of 3.5 μl l^{-1}. The PVC increased again (up to ~4.5 μl l^{-1})

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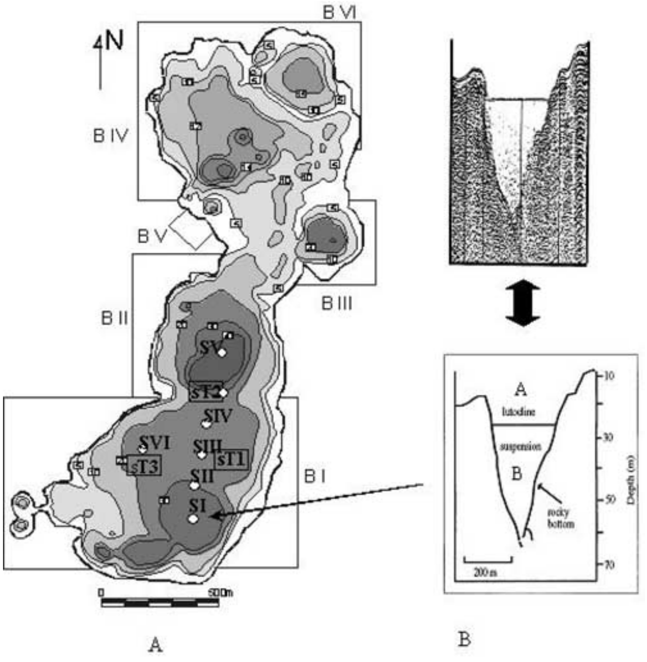

Figure 1. (a) Bathymetric map of lake Banyoles obtained from echosounding profiles [*Moreno-Amich and Garcia-Berthou*, 1989]. Depth contours are in meters. White dots represent measuring stations. sT represents the stations where sediment traps were deployed (b) Seismic profiles of BI according to Canals et al. [1990].

slightly above the base of the thermocline, maybe due to the presence of the algal population, and decreased thereafter up to the surface of the lake. All the PSD obtained below the thermocline presented a bimodal shape (Figure 3a), with peaks centred at 10 and 50 μm-diameter and with constant PVC values with depth. On the epilimnion layer, the PSD shows a trimodal shape (Figure 3b), with particles centred at 5, 20 and 50 μm-diameter. At the thermocline layer, the PSD is midway between the PSD of the hypolimnion and that of the epilimnion. Rising tales at the end of the PSD (<2 μm-diameter) have been discarded due to the way the software handles the scattering pattern [*Mikkelsen and Pejrup*, 2000]. Scanning electron microscope photographs (Figures 3c and 3d) of the samples harvested from the hypolimnion and from below the lutocline level, respectively, with a double-conus end shaped device [*Jørgensen et al.*, 1979], show similar appearances. Clays and silts are dominant in these samples and some aggregates of them have been also found, as can be observed from the photographs. This fact provides strong evidence that sediment particles from the hypolimnion are transported from the lutocline level through the lake hypolimnion. The thermocline acts as a barrier for the plume and the PSD at the epilimnion presents a different spectra of sizes, due to the presence of an algal population, concomitant with the peak of oxygen at ~6 m depth (Figure 2). In addition, the Richardson number Ri = $g' h_o/(B_o R)^{2/3}$ – where g' is the reduced gravity across the density interface, h_o is the depth of the convective layer, Bi is the buoyancy flux per unit area [*Colomer et al.*, 2001] and R is the radius of the source –can be used to determine whether the plume penetrates through the density interface. *Narimousa* [1996] showed that for Ri > 11, convective flows do not penetrate through the density interface. In this study, for $h_o = 20$ m, $B_o = 4.4\ 10^{-8}$ m^2 s^{-3} and R = 150 m, the value of Ri is 591, which is larger than 11, i.e. the plume does not penetrate the interface.

[6] PVC profiles for stations SII, SIII, SIV and SVI (all located around the plume source) show similar values to those found at station SI (Figure 4). Station SV, which is situated far from the hydrothermal plume source, at the centre of BI, presents lower mean PVC values (~2–3 μl l^{-1}) than those found at stations closer to the plume (Figure 4). Sediment trap data also showed that traps located closer to the source (sT1 and sT3) receive higher particle sedimentation amounts (10–25 g m^{-2} d^{-1}) compared to the low amount received at sT2 (<5 g m^{-2} d^{-1}), situated far from the plume source (see Figure 1b for the sT situation and Figure 4 for sedimentation rates). The sedimentation rates found in sT1 and sT3 are comparable to those obtained at the entrance of lake Kinneret (10–35 g m^{-2} d^{-1}) as a result of the discharge of the river Jordan [*Koren and Klein*, 2000].

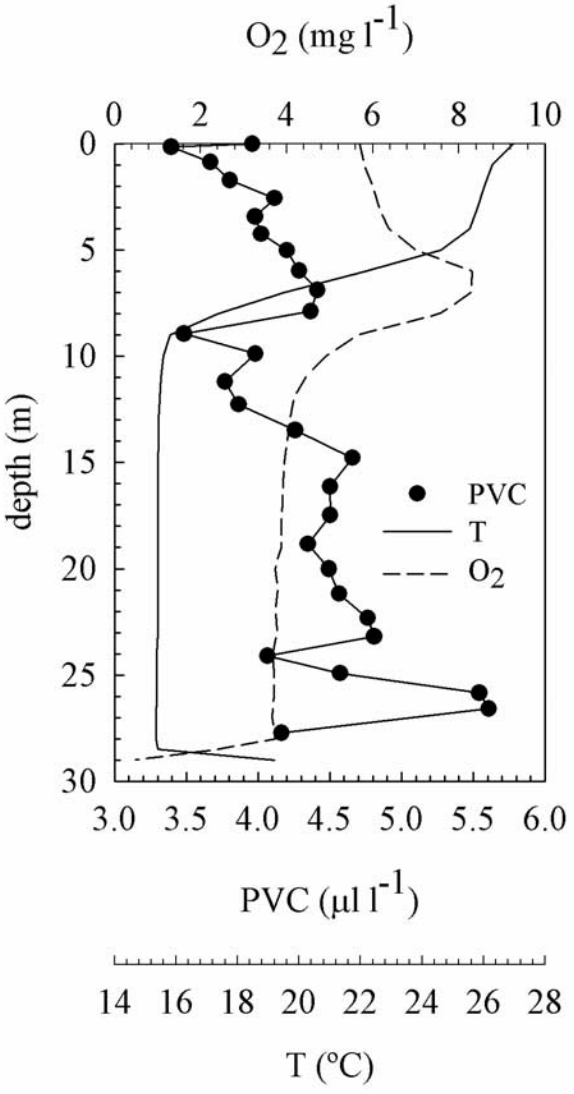

Figure 2. PVC obtained with LISST-100 and oxygen concentration and temperature profiles measured with the multiparametric probe at station SI.

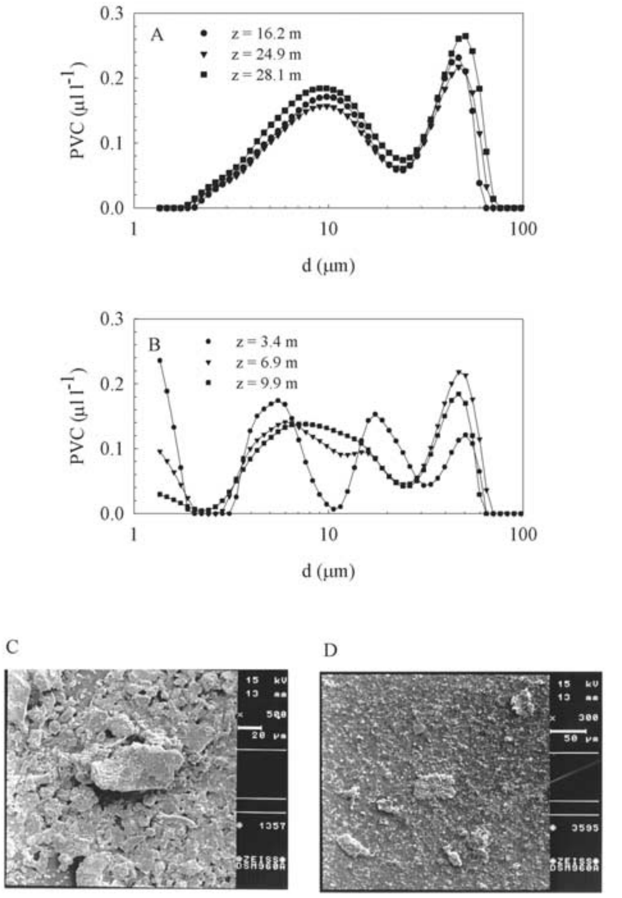

Figure 3. (a) PSD of particles obtained at different depths of the hypolimnion at SI and (b) at different depths of the epilimnion and thermocline at SI. (c) Scanning electron microscope photographs of particles extracted from layers below the lutocline level at ~35 m depth, in zone B (see Figure 1b) and (d) particles harvested from the hypolimnion (at 15 m depth) of SI.

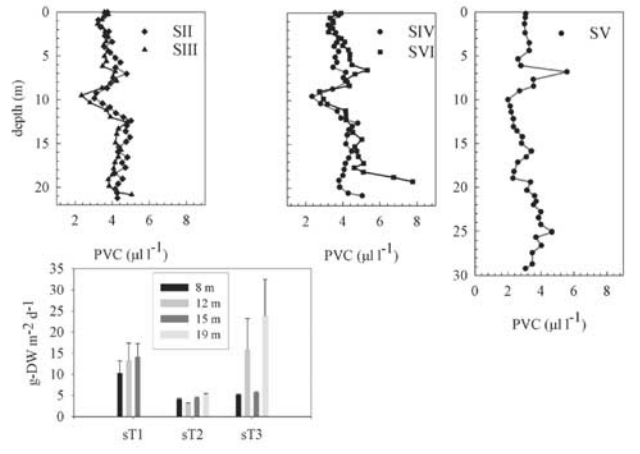

Figure 4. PVC obtained at different stations of the lake (SII-SVI) and sediment trap results in grams of dry weight per cm^2 and day of the sedimented matter measured at sT1, sT2 and sT3. Error bars represent the standard deviation of the data.

[7] Finally, the PSD at the hypolimnion for different stations has always been found to have the same bimodal shape (Figure 5), characteristic for particles transported by the mesopycnal turbidity current, as can be observed when compared with the PSD found in the hypolimnion at SI (Figure 3a). The PSD at SV presents lower PVC values than those for the other stations closer to the hydrothermal plume source. This result is again in accordance with the results from the sedimentation traps and indicates that particles from the turbidity current settle. The PVC in the turbidity current therefore decreases as it travels from BI to BII.

[8] Although further work should be done in order to assess what mechanism drives the transport of particles to the bottom of the lake; here we suggest some possible mechanisms. *Parsons et al.* [2001] demonstrated the presence of fingers and leaking of sediments from turbidity currents with low concentrations: ~0.1 Kg m^{-3}. In this study, assuming a typical dry sediment density of 2.5 Kg l^{-1} and a PVC of ~5 µl l^{-1}, the mass concentration of the turbidity current results in 0.01 Kg m^{-3}, which is one order of magnitude lower than that used by *Parsons et al.* [2001]. Although no laboratory experiments have been undertaken to establish if DDS also occurs at these low concentrations, the fact that the turbidity current is ~7 m thick, whereas temperature measurements showed that the current is ~1 m thick, shows that a DDS process might be present in the turbidity current under study. DDS has been found to occur if $R(=\alpha\Delta T/\beta\Delta C_m) \leq K(=\kappa_t/\kappa_p)^{3/2}$ [*Hoyal et al.*, 1999], where α is the volumetric expansion coefficient of heat, ΔT is the temperature difference between the upper and lower layers, C_m is the particle concentration of the suspension in mass/mass, β is the volumetric expansion coefficient for a particle suspension, κ_t is the heat diffusion coefficient and κ_p is the sediment diffusion coefficient. For T = 16°C, $\alpha \sim 1.5\ 10^{-4}$ K^{-1}, $\Delta T \sim 0.02$ K, $\beta = 0.6$, $\Delta C_m \sim 1\ 10^{-5}$, $\kappa_t = 10^{-3}$ cm^2 s^{-1} and $\kappa_p = 4.2\ 10^{-10}$ cm^2 s^{-1}, therefore R is of the order of 1, which is much smaller than K ~ 10^9, suggesting that DDS might occur. On the other hand, flocculation has been also found to play an important role in the removal of particles from turbidity currents, as has been claimed by authors such as *Hill et al.* [1998]. However, this process has been ruled out, because the PSD were exactly the same along the turbidity current (from SI to SV, Figures 3a and 5). Here we demonstrate that

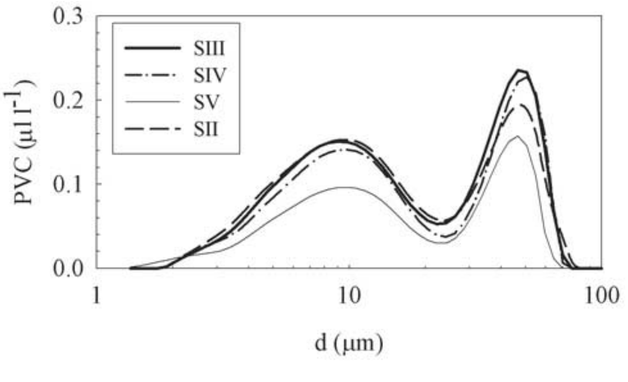

Figure 5. PSD obtained at 15 m depth for different stations (SII-SV).

turbidity currents are important sources of sediments and that they enhance the typical sedimentation rates of particles from the water column where they are present, thereby determining the bottom sedimentary records.

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