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A new bathymetric map based on echo-sounding and morphometrical characterization of the Lake of Banyoles (NE-Spain)

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Abstract

A new bathymetric map of the Lake of Banyoles (NE-Spain) is presented. Echo-sounding transects identified new bathymetric features. The map locates the 13 bottom springs that are presently known and shows a configuration of the lake in six basins. A morphometrical study based on the new bathymetry is also presented.

Introduction

The lake of Banyoles is situated at 172 m above the sea level, on a karstic system, adjacent to the city of Banyoles 17 km from Girona (NE-Spain). According to Margalef (1983) the lake of Banyoles is a flooded polje consisting of independent basins (dolines) which were joined following an elevation of water level. In addition, the Lake of Banyoles has a mixed tectonic-karstic origin, based on the presence of a fault.

Water entry is basically subterranean. A confinated flow enters from an underlying aquifer which is fed by rain deposits in two watersheds located about 20 km to the NW (Sanz, 1981). This feeding through the bottom creates some peculiar meromictic conditions and the existence, characteristic of this lake, of marly and argillaceous materials suspended over the bottom springs (Abella, 1983). The depth where the water-mud interphase occurs fluctuates with changes in flow pressures (Sanz, 1981; Abella, 1983).

These meromictic conditions combined with a high concentration of calcium, and sulfates and carbonates, result in a deficiency of phosphorus and low productivity of the lake (Margalef, 1983).

Smaller ponds and some terrestrial springs occur adjacent to the lake. These are indications of the geological instability of the area. Frequent sinkings (Julia, 1980), some of them recently, result in the formation of ponds such as 'Estanyol nou' (meaning 'new pond' in Catalan) in 1978.

These sinkings can be caused by the dissolving of marly materials intercalated between the underlying gypsum, as discussed by Garcia-Gil *et al.* (1985). This process creates a chamber of water and marl. A subsequent lowering of the water level causes the roof of the cavity to collapse.

Some maps of the 19th and early 20th centuries (referred in Vidal 1908, and Constants 1951) provided very simple approximations to the bathymetry of the Lake of Banyoles (Fig. 1a). But the first detailed bathymetric map (Fig. 1b) resulted from echo-soundings made by Margalef in 1969 (Planas, 1973). This map shows the lake as a polje

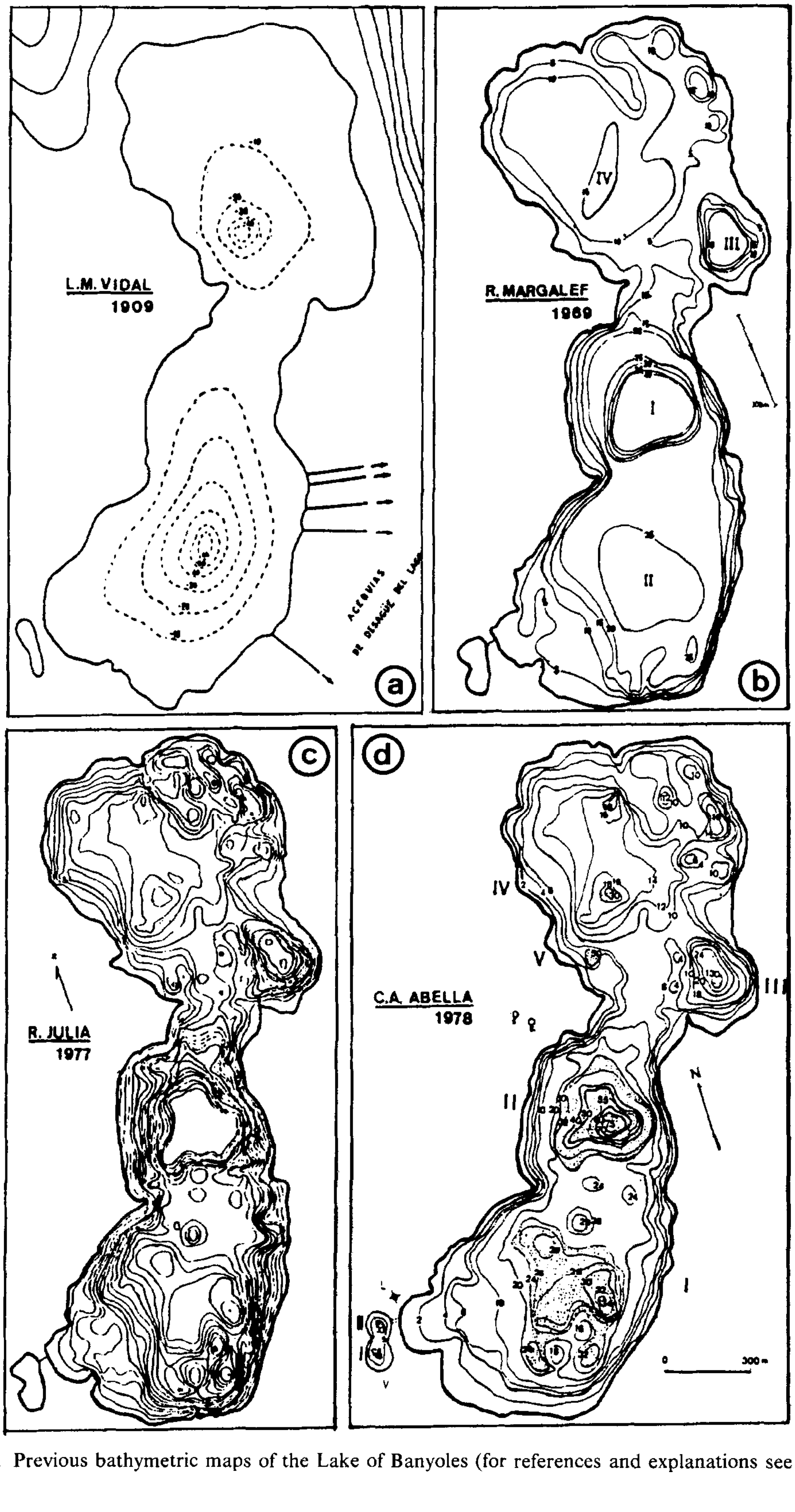

Fig. 1. Previous bathymetric maps of the Lake of Banyoles (for references and explanations see text).

with four distinct basins and indicates suspended mud in deepest zones of basins I and II. This map, with successive modifications, is presently in use. Julia (1980) modified Margalef's map with new information from his own echo-soundings which show a much more complex bathymetry (Fig. 1c). Subsequently Abella (1980), with echo and gravimetric soundings, identified three additional areas with suspended mud (Fig. 1d).

New details including seven new suspended mud areas have recently been reported (Brunet *et al.*, 1985; Moreno-Amich & Garcia-Berthou, 1987). We therefore decided to construct 'de novo' a detailed bathymetric map of the Lake of Banyoles. A new configuration and denomination of basins and springs is also proposed.

Methods

We made 161 transects with a Furuno FE-450M echo-sounder having a transductor of 50 KHz. These observations were made from April, 1986 to April, 1987 from a dinghy with an outboard engine running at the minimum possible speed (mean about 5 Km/h).

A transect's straightness was determined through two reference points. The arrival point in the bank was reached in a straight line of sight from the departure point. We used capes, weirs, piers, etc., clearly localized on the map, as arrival and departure points.

The outline of the lake in which we have reconstructed the echo-sounding profiles was obtained through aereal photograph. We used an enlargement at a scale of 1 : 5000 for an orthophotoscopic model.

The location and configuration of the suspended mud areas was made with several echo-sounding transects. The exact location was verified with multiple triangulation through a compass during calm weather conditions which permitted persistence above these areas, as verified by echo-sounding.

We consider a bottom spring to be the independent area occupied by suspended mud in accordance with Brunet *et al.* (1985). These authors considered the difference of the suspended mud level in relation to adjacent areas to be an independent test for distinct areas.

The term 'suspended sediment' is used by some authors, as synonym of 'suspended mud'. We prefer the latter to avoid the apparent contradiction between the words sediment and suspension, when the suspension is permanent.

In the echo-gram, the suspended mud areas show a rectilinear profile, like a flat bottom. A clear zone occurs just below, and an homogeneous dark zone is seen for the rest of the area.

Measurements of distances and areas were obtained by varying procedures. The depths were determined from echo-sounding. Thus, the maximal depth of the basins which have bottom springs is the mean depth of the water-mud interphase. The bottom spring mean depth is the average between the maximal and minimum depths measured for the water-mud interphase. The areas and lengths were determined by planimetry. For the bottom springs these measurements corresponded to the mean depth. Two measurements were taken for the maximum width of the lake because of its lobed form. The areas of the little bottom spring (the area of the water-mud interphase) were calculated by approximation to an ellipse. The shoreline length is the normalized scale independent value from that estimated with the CTP (i.e. checkered transparent paper) technique.

The map is delineated by 5 m isobates with numerical designations at maximum depths. Some cases are clarified by the use of intemediate isobates.

The basins are identified by 'C' (from the Spanish 'cubeta') followed by a Roman numeral. The bottom springs are indicated by 'S' (from the Spanish 'surgencia') followed by an Arabic numeral. For instance, the bottom springs S-7 and S-8 lie within basin C-I. Both the basin and spring numbers follow the sequence of discovery.

As a measurement of reliability and resolution, we have determined the information value (I) of the map according to the method described by Håkanson (1978, 1981). The intensity of the survey (L_r) is the ratio between the lake area in km squared and the echo-sounding transects total length in km.

The morphometrical study follows the methodology proposed by Håkanson (1981). However, we have also added symbols used by Hutchinson (1957) because of their frequent use in limnological studies.

Results and discussion

The map

In the new bathymetric map (Fig. 2) we propose a lake configurated by 6 basins, with 12 areas occupied by suspended mud corresponding at least to 13 bottom springs.

The bottom spring S-5 is placed in an independent basin C-V. The maximum depth between this basin and basin C-IV is only at 2 m, less than the depth of communication between other basins. Besides this communication, the dinamics of these two basins are independent.

On the north lake zone we have detected basin C-VI that is not on the old map (Figs. 1c and 1d), although his borders were visible in the aereal photographs of 1958. This basin is separated from C-IV by a maximum depth between 3 m and 4.5 m. Unlike the other basins, C-VI has no bottom springs, and its physical-chemical characteristics are quite different with respect to the nearest basins C-III and C-IV, e.g. basin C-VI is holomictic (C-III and C-IV are meromictic).

The new map indicates that basin C-III has its greatest depth of communication with C-IV to the East. Previous maps indicated communications from the North. The eastern communication is evident on the aereal photographs.

Another zone with notable differences is the south of C-I. Its bathymetry is marked by the presence of the bottom springs S-7 and S-9 quite near from the shore. The configuration of the biggest suspended mud area is in two lobes, which suggest the presence of two springs. Recent seismic profiles have detected two inverted cone structures below the mud (Julia, personal communication). For this reason we have named S-1 the biggest lobe and S-13 the smallest lobe.

Sharing suspended mud areas also happens sporadically between S-7 and S-9. These springs are only 5 m distant and are separated at a minimum depth of 22.2 m. When the water flow is small and the water-mud interphase decreases to this depth, only one bigger suspended mud area is detected.

We believe that the observed differences with old map can be imputed to a low intensity of survey. But we cannot exclude, except for some comparisons to old aereal photographs, the possibility that some of these differences have been originated by recent sinkings, after the old map design, proved by the formation of other small lakes during this time (Julia, 1980).

Morphometry

In Table 1 we present the value of the morphometrical parameters derived from the whole lake in accordance with the new bathymetric map. Tables 2 and 3 contain the most important parameters derived from the basins and the bottom springs, respectively.

The parameters whose determination depends on the map scale need special mention (Mandelbrot, 1977). These include shoreling length (l_o) and related measurements such as mean slope ($\bar{\alpha}$) and shoreline development (F). The values of l_o and F differ greatly from older determinations where normalized scale independent values were not derived.

It is apparent in the hypsographic curves that the lake form is slightly convex in the upper half of its cumulative area and convex in its lower half (Scx-Cxmi, using the symbols of Håkanson, 1981). However the significance of this form can be deceiving for a lake structured in basins. For a lake with only one basin, the hypsographic curve would show a preponderance of the shallower zones of the lake and the maximal depths in a very small areas; i.e. the slope would be small at the surface and greater at the depths. But on a structure with several basins, a bigger area is occupied by the lake because of the intercalation of areas between the basins. For this reason, a bigger slope

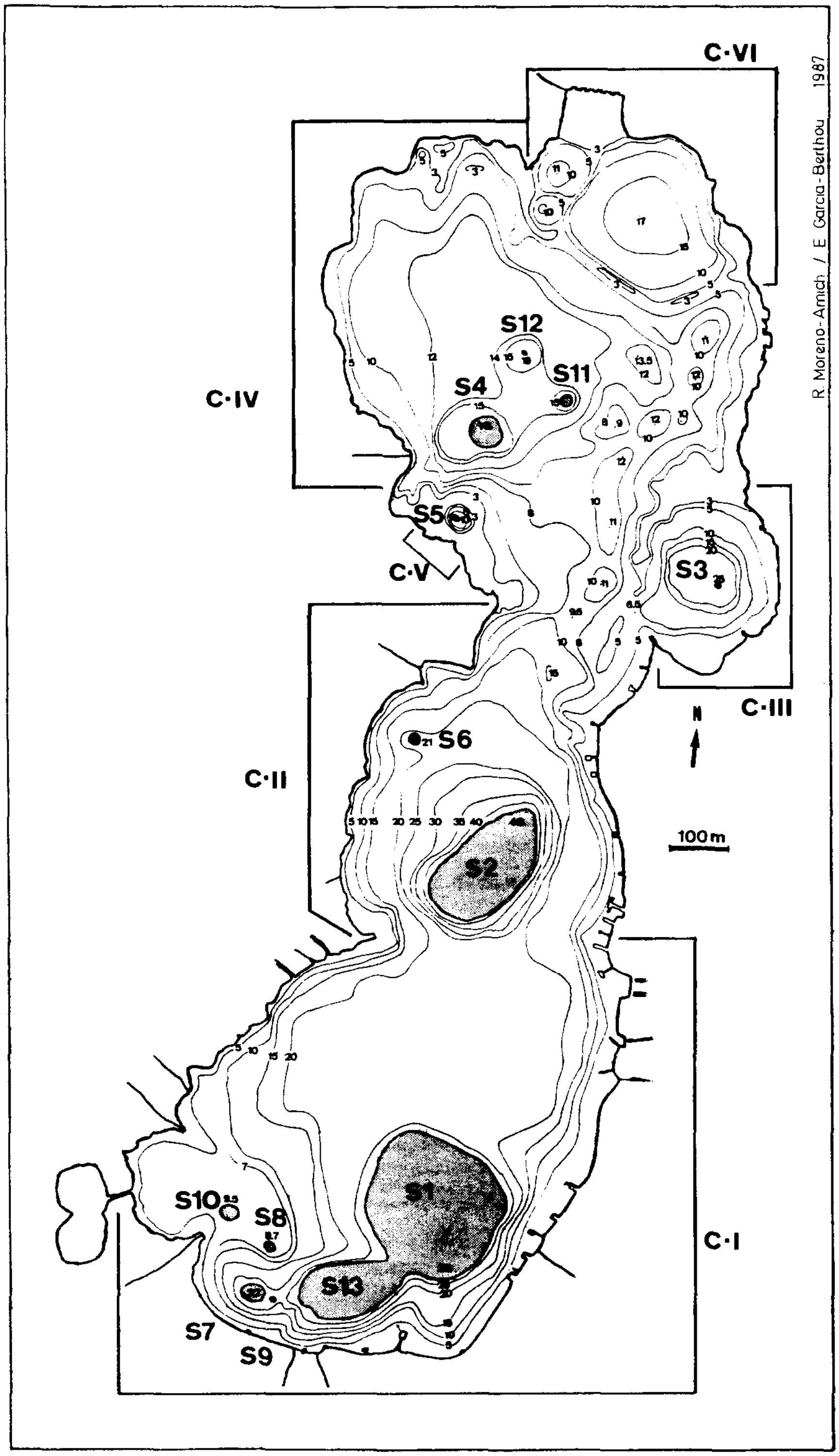

Fig. 2. New bathymetric map of the Lake of Banyoles. Legend: darker zones indicate areas with mud in suspension, 'C-' means basin and 'S-' means bottom springs (see text for details).

Table 1. Morphometrical parameters of the Lake of Banyoles. (Symbols, names and definitions according to Håkanson 1981, parentethical symbols according to Hutchinson 1957)

L_{max}		maximum length		2.150 Km
L_e	(l)	maximum effective length		2.150 Km
B_{max}		maximum width		0.775 Km
B_e	(b)	maximum effective width	(lobe N)	0.775 Km
			(lobe S)	0.725 Km
$\overline{B}$		mean width		0.520 Km
D_{max}	(z_m)	maximum depth		46.4 m
$\overline{D}$	($\overline{z}$)	mean depth		14.8 m
D_{25}		1st quartile depth		20.8 m
D_{50}		median depth		12.3 m
D_{75}		3rd quartile depth		6.7 m
D_r	(z_r)	relative depth		3.89 %
l_o	(L)	shoreline length (CTP-technique)		9.125 Km
a	(A)	area		111.79 Hm2
V_p	(V)	volume		16.12 Hm3
$\overline{\alpha}$		mean slope		20.91 %
F	(D_l)	shore development		2.435
V_d	(D_v)	volume development		0.96
		direction of major axis		SW-NE
		lake form		Cx-SCxmi

Table 2. Morphometrical characteristics of the basins. (Depths are those obtained by echo-sounding)

	C-I	C-II	C-III	C-IV	C-V	C-VI
Area (m^2)	411706	214385	55258	350794	6091	79623
Volume (m^3)	7078521	4286725	535692	3472235	21427	724554
maximum depth (m)	30,8	46,4	32,0	19,2	11,2	17,0
mean depth (m)	17,2	20,0	9,7	9,9	3,5	9,1

Table 3. Morphometrical characteristics of the bottom springs with reference to the areas occupied by suspended mud in 1986.

Bottom spring (by basins)		Depth (m)			Diameter (m)		Area (m^2)
		maximum	minimum	mean	maximum	minimum	
C-I	S-1	30,8	24,6	27,7	255	220	43562
	S-7	23,4	20,8	22,1	45	35	1237
	S-8	8,9	8,7	8,8	15	15	177
	S-9	22,6	20,8	22,9	10	10	78
	S-10	11,2	7,2	9,2	35	28	756
	S-13	30,8	24,6	27,7	175	90	11696
C-II	S-2	46,4	43,2	44,8	225	115	21071
	S-6	22,0	20,5	21,2	15	15	177
C-III	S-3	32,0	25,0	28,5	2	2	12
C-IV	S-4	19,2	17,4	18,3	58	55	2505
	S-11	17,0	16,4	16,7	23	20	361
	S-12	19,0	19,0	19,0	2	2	12
	S-5	11,2	9,6	10,4	17	11	147

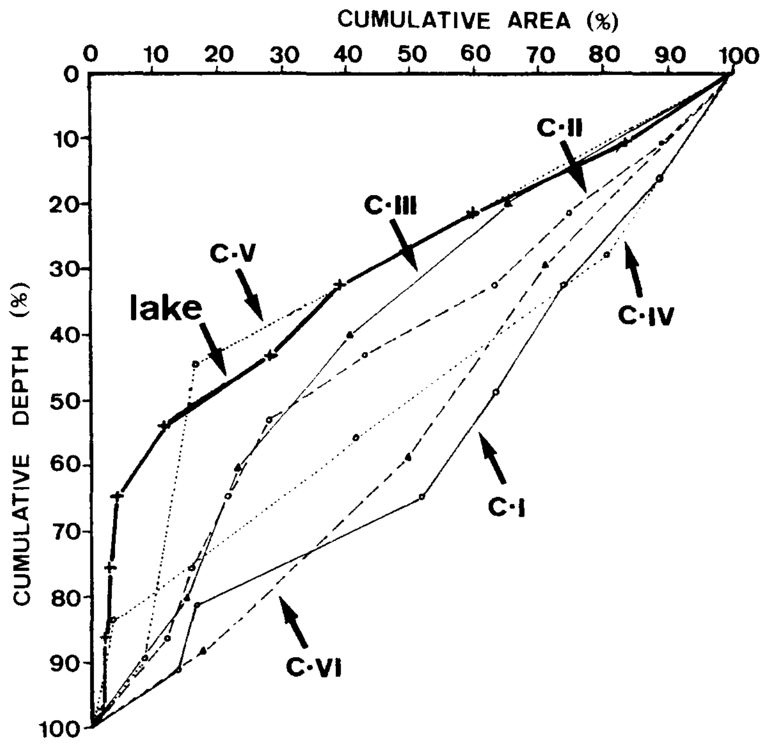

Fig. 3. Relative hypsographic curves for the Lake of Banyoles and its six basins.

and a more linear or concave hypsographic curve is measured for the whole lake. However the hypsographic curves for each basin (Fig. 3) show linear or slightly convex forms (except small C-V with special morphometry).

Finally, because of the high information value (Table 4) of the new map it seems unlikely that the echo-sounding techniques could add substantial knowledge concerning the bathymetry of the Lake of Banyoles. An exception is the location of newly formed bottom springs. In addition, the study of the zones covered by the suspended mud by seismic profiles through multiple receptions will probably give new and important data.

A copy of the map is available free of cost from the authors at scale 1:5000 (in a 48 x 28 cm format).

Table 4. Information parameters of the bathymetric map.

L_r	intensity of the survey	0.014 Km
I′	correctly identified area	0.984
E	area error (1-I′)	0.016
I″	information number	0.972
I	information value (I′.I″)	0.957

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