Meromixis in Zige Tangco, central Tibetan Plateau

——Discovery and significance

LI Wanchun (李万春), LI Shijie (李世杰), YIN Yu (尹　宇), JI Jiang (季　江) & PU Peimin (濮培民)

Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
Correspondence should be addressed to LI Wanchun (email: wanchun@niglas.ac.cn)

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Abstract Zige Tangco (4560 m a.s.l.), located in central Tibetan Plateau, was first discovered in China to be a meromictic lake. The meromixis was caused possibly by virtual sheltering due to the lake basin's morphometry, and to a less extent by surface inflow of fresh water. As the highest meromictic lake ever discovered in the world, Zige Tangco could provide some insight into world lake systematic classification, and a potential site for present-day lake processes and lacustrine varve studies.

Keywords: meromictic lakes, Tibetan Plateau.

Lakes could be categorized into 3 types, i.e. amictic, holomictic and meromictic lakes according to their hydrodynamic and thermal properties[1,2]. Meromictic lakes—a term that was introduced in 1935 by Findenegg (cf. ref. [1])—have been reported throughout the world despite their comparative rarity[3—5]. In general meromictic lakes have attracted limnological attention in fields of physical limnology[2] and palaeolimnology[6]. More discoveries upon meromictic lakes may offer unique opportunities for limnologists. Up to now, there has been no report concerning meromixis in China's lakes. In June—July, 1998 and July—August, 1999, two limnological expeditions were carried out in the Tibetan Plateau. The investigations revealed that Zige Tangco ("co" means lake) was a meromictic lake, which is the first report herein upon the discovery in China.

1 Backgrounds of Zige Tangco

Located in central Tibetan Plateau, Zige Tangco (32°00′—32°09′N, 90°44′— 90°57′E, 4560 m a.s.l.) lies in the Dongqiao Basin, southern Tanggula Mountains, and belongs to Amdo County, Xizang Autonomous Region. The endorheic lake has an area of 187.0 km^2 with a maximum depth of 38.9 m (fig. 1, field survey in 1999). The hydrological system drains a total watershed of 3 430 km^2 with terrains of gentle slopes. Meteorological records indicate a mean annual air temperature of ~ –1 to –2℃ in the basin. Precipitation (300 — 400 mm/a) falls mainly in summer; in conjunction with melt water provides the major source of inflow to the lake[7]. Zige Tangco is a typical saline lake dominated by Na^+ and HCO_3^- ions (table 1).

2 Chemocline discovery and character

Vertical temperature profiles were observed near the center of Zige Tangco (Site A, 32° 02′48″N, 90° 47′05″E) on August 4—12, 1999 with the WMZ-03 thermometer (precision 0.1℃); dissolved oxygen (DO) variations were determined *in situ* by Winkler method[8] simultaneously (fig. 2). Meanwhile, 20 water samples were collected along the vertical profile and wax-sealed for transportation. In the laboratory, a Dionex 2000i/SP Ion Chromatograph (precision 0.01mg/L) was used to detect ion contents. Densities were calculated according to Hutchinson[1] and Wetzel[2].

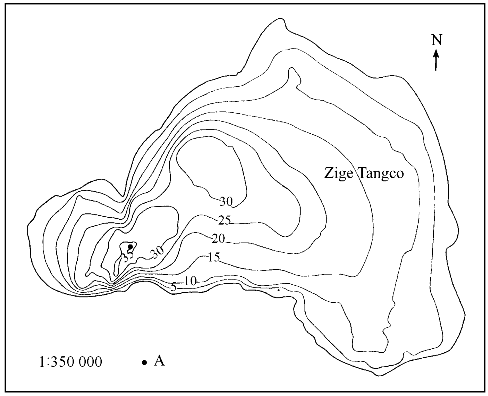

Fig. 1. Bathymetric map and sampling position(A) of Zige Tangco.

Table 1 Hydrochemical character of waters in Zige Tangco (unit: mg • L^{-1} except for pH)

Water	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	CO_3^{2-}	HCO_3^-	Salinity	pH
Lake	756	12 390	9	120	1 520	8 164	3 404	14 794	41 157	10.0
Inflow	3.4	28.4	114.4	48.5	14.7	52.3	5.8	124.3	369.3	8.7

Fig. 2 reveals that Zige Tangco was stratified into three strata: 0 —8 m, 8—22 m, and >22 m. In the upper stratum (0 — 8 m), the extensive mixing resulted in no significant change in DO, salinity, temperature and density except that at the upper 0 —1 m a temperature inversion was noticed. It might be a temporal, partial phenomenon, as surveying in other sites showed no such thermal distribution, which needs further investigations. In the middle stratum (8—22 m), an "S" curve of DO was observed, the oxygen content in 20— 22 m depleted rapidly to 0 at 22 m; salinities and densities increased with depth by degrees; a drastic thermocline was found at 21—22 m with a gradient of 7.7℃/m while temperatures were nearly constant in depths less than 20 m. A complete depletion of DO was formed showing anaerobic

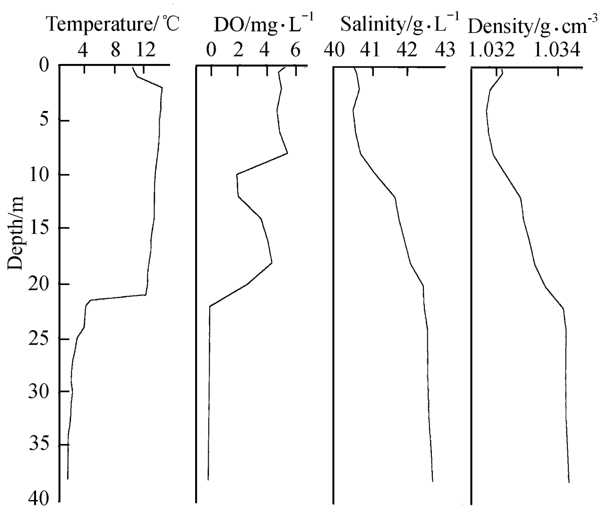

Fig. 2. Profiles of temperature, dissolved oxygen (DO), salinity and density in Zige Tangco.

conditions of the lower stratum (＞22 m), temperatures reduced slowly, and reached 2.3℃ at the lowermost stratum, while no obvious increase in salinities and densities was observed.

3 Discussion

The profiles of salinity, temperature, dissolved oxygen and density for Zige Tangco show characteristics common to most meromictic lakes. These characteristics are (i) a well-mixed, oxygenated, lower salinity, upper water mass (mixolimnion) that periodically circulates, (ii) an intermediate water mass (chemolimnion) in which salinity increases and dissolved oxygen usually decreases rapidly with depth, and (iii) a lower anoxic water mass (monimolimnion) which has a more or less constant temperature and a higher salinity than the mixolimnion[2,3].

The emergence and preservation of meromixis are mainly controlled by local climate, catchment topography and water chemistry[1,6]. Walker et al.[4] concluded that meromictic lakes are formed through two general processes (ectogenic and endogenic meromixis) divided into five types, i.e. (i) surface inflow of (a) fresh water overlying a pre-existing saline layer, or (b) saline water underlying a pre-existing fresh layer, (ii) surface inflow of turbidity currents, (iii) subsurface inflow of fresh or saline water, (iv) effects of shelter afforded by lake basin and/or catchment topography, and biological processes, and (v) deep water accumulation of salts precipitated by freezing out from a surface ice layer.

As to Zige Tangco, we tend to conclude that meromixis was caused by virtue of shelter afforded by the shape and size of the lake basin and by local catchment topography, and to a less extent, by surface freshwater inflow. Genetically, Zige Tangco was one of the 18 lakes that were evolved along the Banggong-Gerze-Nujiang Rift[9]. Moreover, Zige Tangco was located in the intersection of latitudinal tectonic valley and longitudinal rift system[10]. Due to the thrust fault and extrusion effects, a nearly NE-SW stretching deep basin was evolved, as the bathymetric map indicates (fig. 1). Along the N-S profile, the lakebed sloped gently downwards from shore to center, except for two steep slopes at isobaths of 15 m and 25 m, respectively, which was unfavorable for the vertical convective exchange between the upper and lower layers. In addition, any nutrients utilized by organisms in the upper stratum and released in the lower stratum by decay were trapped in the lower stratum and sediments; any exchange of dissolved materials from the upper layer to the lower layer was by slow eddy diffusion. As a result, more saline water in the deeper parts of lake basin became depleted with dissolved oxygen due to anaerobic bacterial decay, and the monimolimnion evolved in the isolated deeper stratum. The upper stratum (mixolimnion) and monimolimnion were separated by a steep density gradient that was called the chemocline. On the other hand, in summer (May—October), plenty of freshwater inflow (table 1) made the water at upper layers mix more entirely and become lighter; whereas in winter, the deep-water accumulation of salts precipitated by freezing out from a surface ice layer every November to next April[7], so that the density gradient between the mixolimnion and monimolimnion would be increased, and the chemical stratification be formed and became more stable in meromictic Zige Tangco.

The preservation of meromixis depends to a greater extent on the density gradient of waters above and below chemocline. In Zige Tangco, it reached 0.0021 g/cm^3 at the chemolimnion. Usually, the salinity gradient across the chemocline can enhance the stability of chemocline; a 1.778 g/L gradient observed in Zige Tangco could make its tendency for meromixis stronger. As pointed out by Wetzel[1], a salt concentration of 1 g/L increases the density of water by approximately 0.0008 g/cm^3. This change in specific gravity is very large in relation to density changes associated with temperature. For example, the density difference between 4℃ and 5℃ is 0.000008 g/cm^3, and it would only require 10 mg/L of salt to give the same effect to resistance to mixing. The existence of thermal stratification is attributable to the magnitude of chemocline, instead of a prevailing factor. In Zige Tangco, as the direct thermal gradient across the chemocline reached 9.1℃, thermal-induced as well as chemical-induced density gradient may augment the stability of lake stratification.

Similar to many meromictic lakes[2,5], the dissolved oxygen profiles in Zige Tangco exhibited an “S” distribution pattern. Major contributors to this phenomenon are incomplete mixing across the chemocline and monimolimnic depletion of any oxygen intrusions[2]. In fact, vertical DO variations could play a key role in the genesis of meromixis[1]. For oligotrophic lakes, a DO depletion in lower stratum may indicate meromixis, whereas in mesotrophic or eutrophic lakes it is no longer the case, as exemplified in some dimictic lakes[2] that do exhibit in summer an anoxic hypolimnion.

4 Significance of meromixis discovery

Meromictic lakes are not common in the world, let alone meromictic saline lakes[3,5]. As the highest meromictic lake (4560 m a.s.l.) ever discovered in the world, we are sure that Zige Tangco could provide some new insight into world lake systematic classification, since it occupies a relative depth (relative depth(%)=$50Z_{\max}A^{-1/2}\pi^{1/2}$, where A= lake surface area(m^2), $Z_{\max}$ = maximum depth(m)) of 0.25%, much smaller than that of most meromictic lakes[4,5]. The existence of lakes in Tibetan Plateau, the world highest plateau, depends on a variety of processes that produce somewhat diversified lake basins. Up to now, 1091 lakes (>1 km^2)[7] have been identified in the Tibetan Plateau after several lake investigations. With regard to limnological studies, the physical environments hinder any further attempts. The meromixis discovery in Zige Tangco will certainly provide an object in view for physical limnologists. Literature available[7,9] attests that Dagze Co, Co Nyi might be meromictic.

Once the clastic, chemical and organic precipitates reach the deeper monimolimnion, they will be easily preserved. The sedimentary deposits could record not only the natural processes such as plant succession, biological geochemistry, soil erosion and morphological evolution history, but also human activity intensities in the catchments, i.e. heavy metal pollution, eutrophication, production and land use[11,12]. Further researches on the lacustrine sediment as well as present-day lake processes of meromictic lakes will bring them to light.

One of the primary issues of climate change studies is to find more reliable proxies with higher resolutions. Preservation of palaeoclimatic information in varved sediments has gained increasing interest for paleolimnologists. It is widely accepted that meromictic lakes are favorite sites for varve formation and preservation[3,13]. We have found a meromictic lake located in the Tibetan Plateau, one of the battlefields for global change studies, and we are sure of its potential for future varve analysis. Further varve analysis in Zige Tangco is in progress. Additionally, the shift of chemocline[14], as well as the emergence and disappearing of meromixis[15] reflects an abrupt climate change or other fundamental alteration in the catchment, which will be genuinely recorded in the waters column and deposits. To study chemistry of meromictic lakes, in conjunction with lacustrine high-resolution records, is one of the trends of palaeolimnological studies[16].

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