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Short note

Karst drainage of lake Chakanbacán and its relation to Icaiche Formation

Drenaje kárstico del lago Chakanbacán y su relación con la Formación Icaiche

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ABSTRACT

Sudden drainage of Lake Chakanbacán (also known as Om or Chakambacab) occurred naturally and without warning between 19 and 21 August, 2018. Lake Chakanbacán, located in southern Quintana Roo, 16.5 Km WNW of Nicolás Bravo, Quintana Roo is part of the western edge of the composite Morocoy-Nuevo Becak polje. Slumping associated with lake drainage has opened up fractures on the west bank of the lake, exposing gypsum of the Icaiche Formation. This occurrence establishes the western lake bank as the easternmost known outcrop of Icaiche gypsum in the area. Drainage of Lake Chakanbacán appears to be part of a karst process that proceeds by rapid dissolution and selective removal of layers of gypsum of the Icaiche Formation beneath the lake bed. Thus, the August 2018 lake drainage may demonstrate, in real-time, an ongoing weathering process responsible for a major regional geomorphic feature: the numerous internally drained karst depressions (poljes) up to >100km long in Campeche and southern Quintana Roo. It has been proposed that these poljes are collapse features resulting from removal in solution of gypsum of the Icaiche Formation. They occur both within and adjacent to a large area where the Icaiche Formation crops out, and, notably, over an estimated 10000 km² or more within that formation where massive beds of gypsum are present on the surface or beneath a thin protective cap of rock resistant to chemical weathering.

Keywords: karst collapse, lake drainage, Yucatán Peninsula, Gypsum.

RESUMEN

El repentino colapso del lago Chakanbacán (también conocido como Om o Chakambacab) ocurrió de forma natural y sin previo aviso entre el 19 y el 21 de agosto de 2018. El Lago Chakanbacán, situado al sur de Quintana Roo, 16.5 Km WNW de Nicolás Bravo, Quintana Roo es parte del borde occidental del polje Morocoy-Nuevo Becak. El desplome asociado con el drenaje del lago ha abierto fracturas en la orilla oeste del lago, exponiendo el yeso de la Formación Icaiche. Esta ocurrencia establece la orilla occidental del lago como el afloramiento más oriental conocido del yeso de Icaiche en la zona. El drenaje del lago Chakanbacán parece ser parte de un proceso kárstico que ocurre por rápida disolución y eliminación selectiva de capas de yeso de la Formación Icaiche bajo el lecho del lago. Por lo tanto, el colapso del lago en agosto de 2018 puede demostrar, en tiempo real, un importante proceso de karstificación continuo responsable de una característica geomorfológica regional: las numerosas depresiones kársticas drenadas internamente (poljes) de hasta >100 km de largo en Campeche y el sur de Quintana Roo. Se ha propuesto que estos poljes son característicos de colapso resultantes de la eliminación en la solución de yeso de la Formación Icaiche. Estos se producen tanto dentro como adyacentes a una gran área donde la Formación Icaiche se extiende, y, en particular, sobre un estimado de 10000 km² o más dentro de esa formación donde hay enormes lechos de yeso en la superficie o debajo de una fina capa protectora de roca resistente a la intemperie química.

Palabras clave: colapso kárstico, laguna drenada, Yucatán Península, yeso.

1. Introduction

The objective of this short communication is to document the sudden drainage event of Lake Chakanbacán of southern Quintana Roo. We suggest that the occurrence of the lake in highly soluble gypsum beds located above a probable fault indicates that what we have observed is a regional aquifer recharge event. The lake location at the western edge of the Nuevo Becak-Morocoy polje, furthermore indicates that the lake drainage may be part of a regional mechanism by which the numerous poljes that are present, at both the eastern and western margins of the Icaiche Formation have developed and, in some or all cases, may be expanding as collapse features above subsurface gypsum layers.

If the Morocoy-Nuevo Becak polje did form, as proposed, by collapse of rocks overlying gypsum of the Icaiche Formation, then the August, 2018 rapid drainage of Lake Chakanbacán offers a possible specific answer to the question: Where did the gypsum go? Lake Chakanbacán and adjacent surface water bodies lie in a NNW-SSE depression that is up to about 30m deep. It has been proposed that Lake Chakanbacán, with known exposures of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) on its banks, is part of a recharge system for groundwater of high sulfate content that discharges into the Rio Hondo Fault System. The August, 2018 discharge event indicates that the karst system draining Lake Chakanbacán has exceptionally high flow capacity. Thus, the 30m depression that contains the lake appears to have formed by dissolution and removal of gypsum of the Icaiche Formation through a high-flow system capable of producing extensive subsidence.

Assuming that the 30m of the Lake Chakanbacán depression represents the thickness of the gypsum layer removed to form the Morocoy-Nuevo

Becak polje (Perry *et al.*, 2019) we calculate that in the present-day climate, in about 20,000 years or less, water of the Rio Hondo, at its present flow rate and ionic concentration of sulfate, could carry off enough gypsum to cause collapse of an area comparable in size to the Morocoy part of the Morocoy-Nuevo Becak Polje. We think this estimate offers support both to the proposed mechanism for polje formation in Campeche and southern Quintana Roo and to the suggestion that the highland area bounded on the east by Lake Chakanbacán is the recharge area for high-sulfate groundwater entering the Rio Hondo Fault Zone¹.

1.1. THE EVENT IN CONTEXT

The unexpected natural drainage of Lake Chakanbacán (also known as Lake Om or Lake Chakambacab), was first observed directly on August 21, 2018. Lake Chakanbacán (18.49°N, 89.08°W) is 16.5 km WNW of Nicolas Bravo, Quintana Roo. It is one of a chain of *aguadas* and shallow lakes extending for about 8.9 km in a NNE-SSW direction, a linear alignment that suggests fault control. These water bodies occupy a depression (gray dashed line in Figure 1) that begins in the south at lake Om in the town of Caobas, Quintana Roo and extends northward to an unnamed lake several kilometers beyond Lake Chakanbacán, where the depression broadens out and joins the floor of the contiguous Morocoy-Nuevo Becak poljes (henceforth referred to as Polje MNB) (Figure 1). In that distance the depression descends from an elevation of 130 masl at Lake Om to an elevation of about 100m in the north at the junction with Polje MNB. Elevation at Lake Chakanbacán is intermediate, about 110m (INEGI map E16A73, Google Earth). The August 2018 drainage of Lake Chakanbacán is an event that is important for understanding the

¹**Authors note:** There is unfortunate confusion about naming of local lakes. On the Caobas 1:50,000 map of the area (INEGI map E16A73) the lake adjacent to the town of Caobas (at 18.45°N, 89.10°W) is labelled Laguna Om and the disappearing lake that we are reporting on at 18.49°N, 89.08°W is labelled Laguna Chacambacab. Some press reports have referred to the disappearing lake as Laguna Om, perhaps because the region is part of Ejido Om. Here we use Lake Om for the well-known and accessible lake at Caobas, and we follow usage of Ing. Jose Luis Blanco of CONAGUA in calling the disappearing lake under study Lake Chakanbacán.

hydrogeology and geomorphology of the Yucatán Peninsula because it demonstrates that the lake and other water bodies in the chain are parts of a karst groundwater system with a large discharge capacity in an important groundwater recharge area. Onsite investigation revealed fractures along the western lake bank that exposed bedded gypsum protected from exposure to rain by soil cover. These observations make it probable that the Lake Chakanbacán drainage event is directly related to processes that result in subsurface dissolution of massive beds of gypsum of the Icaiche Formation in Campeche and southern Quintana Roo.

Although gypsum is very abundant in near-surface rocks in many parts of the earth (Klimchouk, 1996) its solubility is so high that, in humid climates, when gypsum is exposed at the surface it is often removed by weathering too rapidly and

completely to develop karst features. However, it is common for gypsum present beneath a protective rock cap to dissolve in flowing groundwater and produce cavities that subsequently collapse. Johnson (2008) has given numerous examples of this process; and Perry *et al.*, 2019, and Perry *et al.*, 2021, have presented evidence that dissolution of massive beds of gypsum in the Icaiche Formation of Campeche and southern Quintana Roo have dramatically affected landforms and hydrogeology of a large area in this southern part of the Mexican Yucatán Peninsula.

The beds of gypsum along the west bank of Lake Chakanbacán, which were exposed by subsidence from the lake draining event, constitute the easternmost outcrops of massive bedded gypsum of the Icaiche Formation. That formation is present at or near the surface west of Lake Chakanbacán

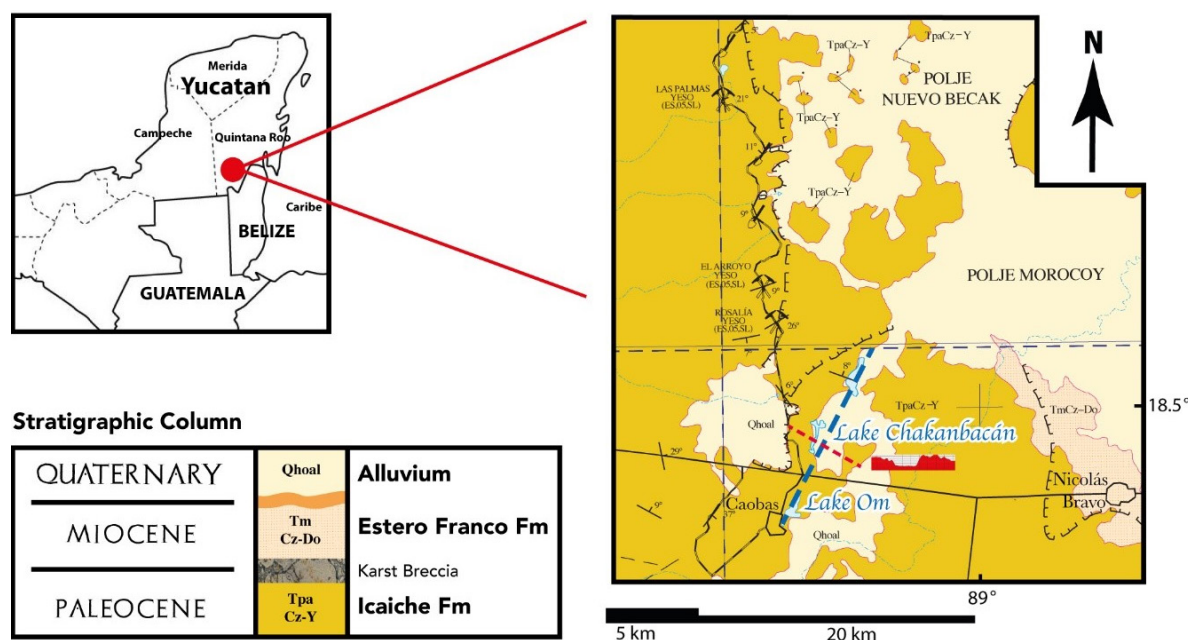


Figure 1 Geologic setting of Lake Chakanbacán. The lake lies in a depression 8.9 km long shown as a gray dashed line in the Figure. This depression extends in a NNE direction from Lake Om (elevation 128mamsl, 18.44°N, 89.1°W) in the south and disappears into the floor of Polje MNB at an unnamed lake (elevation about 100 mamsl) at 18.52°N, 89.06°W in the north. Note that several small exposures (“islands”) of rocks of the Icaiche Formation rise from the floor of Polje Nuevo Becak to the north. These erosional remnants are a typical feature of karst terrains. The depression containing Lake Chakanbacán is most conspicuously developed along the ESE-WNW red line in the Figure. The inset topographic cross section (in red) shows that the depression passes between >30m banks of rocks of the Icaiche Formation. In the partial geologic column (above) rocks are shown using the map symbols of this Figure, which are those used by the Sociedad Geológica Mexicana. “Y” in the symbol for the Icaiche Fm stands for yeso (gypsum). Quarries shown are inactive but once mined gypsum. (Figure 1 is redrafted from a portion of SGM map sheet Chetumal. E16-4-7).

over an estimated area of $>10,000\text{km}^2$ (Perry *et al.*, 2019; Perry *et al.*, 2021). The presence of gypsum in the banks of disappearing Lake Chakanbacán, together with the position of the lake in a probable fault zone at the margins of Polje MNB are significant for two distinct reasons, both of which are related to the high solubility of gypsum relative to other common minerals. 1) Where massive gypsum in earth's shallow subsurface is in contact with flowing groundwater, as is likely here in the karst plumbing system beneath Lake Chakanbacán; the rapid dissolution of the gypsum is likely to result in collapse of overlying rock. That is the mechanism proposed by Perry *et al.*, (2019) for the formation and extension of the poljes of Campeche and southern Quintana Roo. The intimate spatial rela-

tion of Lake Chakanbacán to Polje MNB makes it probable that in observing the disappearance of water from Lake Chakanbacán, we have captured in real-time the process by which numerous large poljes of Campeche and southwestern Quintana Roo have formed and may currently be increasing in area. 2) Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the probable source of most of the high sulfate content of groundwater and surface water in the Mexican Yucatán Peninsula (Perry *et al.*, 2002; Perry *et al.*, 2009; Perry *et al.*, 2019; Bauer-Gottwein *et al.*, 2011; Wagner, 2009). Perry *et al.*, 2021 have proposed that the recharge area for high sulfate groundwater discharging in the Rio Hondo Fault Zone of eastern Quintana Roo lies precisely in the area around Lake Chakanbacán see Figure 2.

Digital Elevation Model (DEM), South of the Yucatán Peninsula

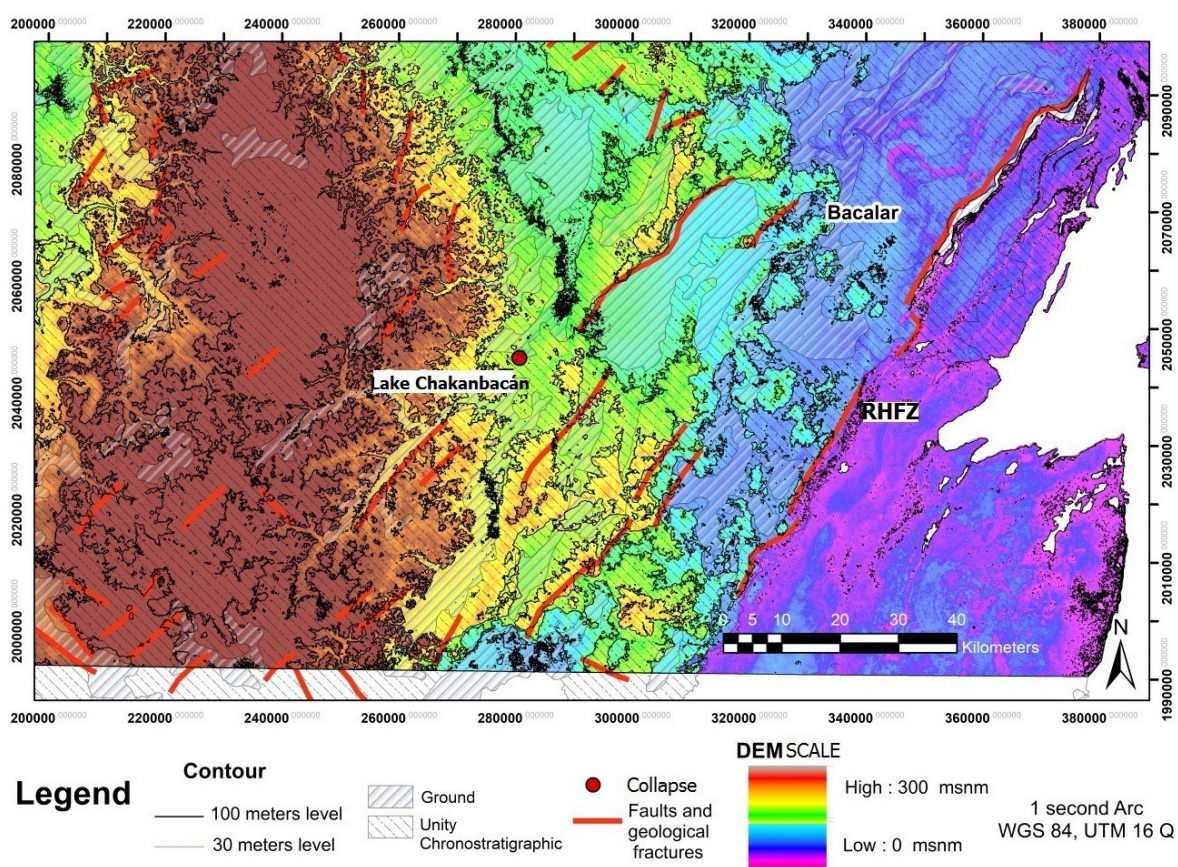


Figure 2 Lake Chakanbacán runs in a direction parallel to the Rio Hondo Fault Zone (RHFZ) as the SGM (2007) indicates and also it is at the west margin of the topographic change from the high to the lowest point of elevation at this Figure. Map made by Dr. José Luis Hernández-Martínez source SGM, (2007).

Obviously, any gypsum dissolved and removed in the formation of poljes reappears as the sulfate (and calcium) found in solution in regional groundwater.

1.2. GEOLOGIC CONTEXT

Stratigraphy and other relevant aspects of the geology of the southern Campeche and southeastern Quintana Roo are discussed in Perry *et al.*, 2019 and in Perry *et al.*, 2021, which this paper accompanies. Lake Chakanbacán is located at the extreme eastern edge of outcrops of the Paleocene-Eocene Icaiche Formation (SGM 1:250,000, Carta Geológico-Minera Chetumal E16-4-7) that, importantly, contains thick beds of gypsum and argillite deposited in a lacustrine environment. The formation was named and is briefly described by Butterlin and Bonet (1960). The depression (polje) Morocoy, floored by Quaternary alluvium lies immediately east of Lake Chakanbacán. Perry *et al.*, 2019, and Perry *et al.*, 2018 have proposed that Polje MNB and several other large depressions in Campeche and southern Quintana Roo formed by subsurface dissolution of gypsum of the Icaiche Formation followed by collapse of overlying rock. We hope that further investigation of the August 2018 Lake Chakanbacán draining event elucidates information about the process by which Polje MNB and other poljes have formed (and apparently are still expanding). Here we discuss the Lake Chakanbacán rapid draining event, the initial phase of lake recovery, and the chemistry of lake water and adjacent surface water after the event.

2. Observation of the Drainage Event

2.1. PRESS REPORTS

Because Lake Chakanbacán is in a remote, forested area, the exact date and time when the lake began to drain is not known. Local resident Francisco Reyes became aware on August 21 that much of Lake Chakanbacán had drained and that in its place was a small stream flowing through

mud banks. An unnamed local resident, reported by Vanguardia on August 23, 2018 and Yucatan Times (August 27), explained that a loud noise they attributed to the disappearance of the lake water had occurred on August 19, and this person recalled that a similar noise had been heard about six years before, presumably indicating that the August draining event was not unique. Also, according to Maleni Marcial (Compendio Quintanarroense, 25 August, 2018), several residents of the neighboring ejido Nicolás Bravo recalled a similar lake drainage fifty years before this event. Ing. José Luis Blanco Pajón, a representative of the Mexican government agency CONAGUA, used the Maya word “xuch” to describe the lake’s disappearance. The use of this regional colloquial term in discussion to the catastrophic lake disappearance suggests that similar events are not uncommon in the region. Blanco Pajón elaborated on what he found at the lake site immediately after the lake disappearance. He stated that “dikes” (sand bars?) had held back water from much of the lake but that about 20 hectares or 40% of the water had drained into three sinkholes of 10m, between 5 and 6m, and 3m diameter.

2.2. FIELD OF INVESTIGATION

On August 26, 2018, 5 days after the Lake Chakanbacán drainage event was discovered, the lake site was visited by a team from the Centro de Investigación Científica de Yucatán (CICY) in company with local residents from ejido Om and by Noé Demetrio Ku from PROFEPA. The group was able to examine lake collapse sites 2 and 3 (Figure 3) but decided the water-saturated ground around site 1 was too unstable to allow safe collection of water from that site. The group noted various indications of mass movement in the bank of Lake Chakanbacán. This evidence included tree trunks leaning toward the lake and small fractures in the ground along paths leading to the collapse zones. The group conducted a reconnaissance toward the southwest, and at point GW (Figure 3) encountered a spring feeding a stream of water that flowed toward the zone of collapse (Leal-Bau-

tista, 2018). Water samples (labelled GW) from that flow were taken from there.

The rapid outflow of groundwater from spring GW and from other sources along the lake bank, such as in the left foreground of the picture, can be seen in Figure 3. This flow confirms the presence of a shallow perched water table separated by lake clay and argillaceous sediment from a deeper karst aquifer into which it is obvious that Lake Chakanbacán must have drained.

2.3. DEEP AND SHALLOW GROUNDWATER IN AND AROUND LAKE CHAKANBACÁN

Water quality analyses of shallow groundwater and surface water from the vicinity of Lake Chakanbacán were made by researchers from CICY and are recorded in Table 1. Temperature, pH, and conductivity measurements of these

waters were made with a multiparameter instrument, and sulfate was determined in the field using an Exact 11 spectrophotometer with a wavelength of 420nm. Alkalinity was determined in the laboratory by Gran titration. The first set of samples shown in Table 1 had been taken as part of a broad regional study in April, 2018, four months before the Lake Chakanbacán drainage event. It consists of 1) water from the municipal well in Nicolás Bravo - drawing groundwater from the Miocene Estero Franco Formation (SGM, 2007), in which gypsum is not an important constituent - and of a very shallow private well in Caobas; and 2) surface water from Lake Om in the town of Caobas (which lies in the same presumptive fault zone as Lake Chakanbacán).

In contrast to the relatively low sulfate ion concentration of surface water and shallow groundwater, water from a municipal well in Caobas

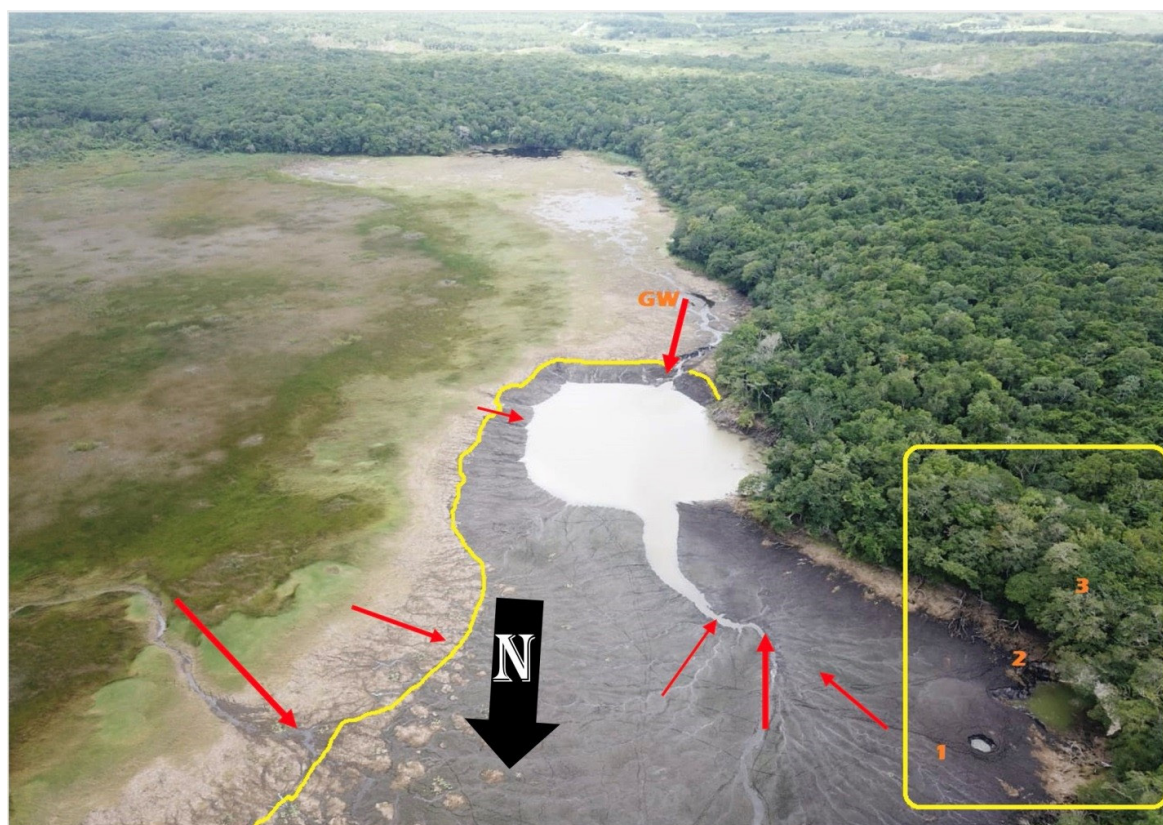


Figure 3 Drone view of bed of drained lake taken on August 20, 2018. Points 1 and 2 are drain sites; Point 3 is the slumped bank where gypsum normally covered by soil is exposed. GW indicates a groundwater seep where water was sampled. Arrows trace direction of surface flow. The major drain appears to have been beneath the water body ponded in the center of the Figure. *Drone photograph courtesy of Noé Demetrio Ku.*

Table 1. Water samples from vicinity of disappearing Lake Chakanbacán, Quintana Roo. Sampling occurred in three occasions, in April, 2018 (before lake drainage), in August 2018 (4 days after the lake drainage) and in September 2018 (when the lake recovered its water).

Date	Name	Latitud	Longitud	pH	Electrical Conductivity (CE) $\mu\text{S}/\text{cm}$	SO_4^{-2} ppm
Surface Water (Lakes)						
April 2018	Caobas Lake	89° 05' 54"	18° 26' 59"	7.41	2,430	1.10
August 2018	Lake Chakanbacán	89° 05' 07.1"	18° 29' 31.9"	7.11	236	1.70
	Collapse Lake Chakanbacán	89° 05' 08.8"	18° 29' 03.7"	7.08	260	8.50
	Caobas Lake	89° 05' 54"	18° 26' 59"	7.52	574	1.00
	Las Palmas Lake	89° 07' 53.2"	18° 39' 44.5"	7.45	685	2.75
September 2018	Lake Chakanbacán	89° 05' 07.1"	18° 29' 31.9"	7.83	426	0.49
	Collapse Lake Chakanbacán	89° 05' 08.8"	18° 29' 03.7"	6.59	290	0.19
	Groundwater arriving to Lake Chakanbacán	89° 05' 09.0"	18° 28' 54.0"	7.88	430	0.19
	Caobas Lake	89° 05' 54"	18° 26' 59"	7.25	473	6.63
	Las Palmas Lake	89° 07' 53.2"	18° 39' 44.5"	7.47	300	0.19
Wells (town supply water)						
April 2018	Caobas Pueblo	89° 06' 22.3"	18° 26' 23.0"	7.48	1,870	7.00
	Nicolás Bravo	88° 55' 50.0"	18° 27' 47.2"	7.69	910	1.46
August 2018	Caobas Pueblo	89° 06' 22.3"	18° 26' 23.0"	7.36	1,377	5.60
	Nicolás Bravo	88° 55' 50.0"	18° 27' 47.2"	7.55	998	1.50
September 2018	Caobas Pueblo	89° 06' 22.3"	18° 26' 23.0"	7.16	1,137	5.02
	Nicolás Bravo	88° 55' 50.0"	18° 27' 47.2"	6.91	1,111	1.55

(drilled into the Icaiche Formation), contained an exceptionally high sulfate ion concentration (1750 ppm) when sampled years earlier by Sanchez Sanchez *et al.*, 2015. This sulfate concentration is more than 4 times the maximum concentration (400 mg/L) considered acceptable by Mexican water quality standards (Proyecto de NOM-127-SSA1-2017). Consequently, CONAGUA had removed the deep Caobas well from service and capped it before the April, 2018 sampling visit

recorded in Table 1. Abandonment of the deep Caobas well by CONAGUA confirms that the high sulfate concentration measured by Sanchez Sanchez *et al.* 2015) is not an anomaly, and their recorded value of 1750 ppm makes Caobas the easternmost example of high sulfate groundwater present over a large region centered near Xpujil, Campeche (18.51°N, 89.39°W) where gypsum of the Icaiche Formation crops out (Sanchez-Sanchez *et al.*, 2015; Perry *et al.*, 2021).

As examples of other groundwater problems associated with high concentrations of sulfate within the region where gypsum of the Icaiche Formation is exposed at the surface, we note that municipal water for Xpujil is delivered from outside the region through two pipelines of 70 and 100km length, and in the nearby village of La Guadalupe, Campeche (18.33°N, 89.48°W) water is delivered by tank truck. (Perry, *et al.*, 2019). Perry *et al.*, 2021 describe the case of a lake and town well at Zoh, Campeche (18.59°N, 89.42°W) where, as in Caobas, lake water with low sulfate ion concentration is present adjacent to a town well whose water has an exceptionally high sulfate ion concentration.

3. Discussion

3.1. KARST DRAINAGE OF LAKE CHAKANBACÁN AND ITS PROBABLE RELATION TO POLJE DEVELOPMENT

From the August 2018 rapid drainage of Lake Chakanbacán we conclude that a karst groundwater system of high discharge capacity is present beneath the lake. The key location of Lake Chakanbacán establishes, with respect to the edges both of Icaiche Formation gypsum and to the western margin of Polje MNB, together with the depression and presumed fault in which it lies, as a probable recharge site for high-sulfate groundwater. These observations support the interpretation of Perry *et al.* (2018) that the Lake Chakanbacán depression is a site where incipient polje formation occurs by dissolution and chemical removal of gypsum of the Icaiche Formation, accompanied by collapse of overlying rock. *In addition, site of the gypsum removal process is consistent with contemporaneous recharge of the deep regional aquifer system that discharges high-sulfate groundwater into the Rio Hondo Fault Zone as proposed by Perry et al., 2021.*

It could be objected that the Lake Chakanbacán depression cannot be a zone of high-sulfate recharge water because all of the water in the lake comes from surface flows and shallow groundwater and is of low sulfate ion concentration as shown by water analyses in Table 1. This is not a valid objection; nor is it a paradox – the rapid

lake drainage of August 2018 was a rare event, *an anomaly*. And the event demonstrates *the capacity of the karst groundwater system for high flow, not its normal mode of operation*. Throughout the extensive parts of Campeche and southern Quintana Roo where gypsum of the Icaiche Formation is present at or near the surface, soil and residual clays of low permeability are also abundant and surface water is almost always characterized by low sulfate concentration. Wagner, 2009; Perry *et al.*, 2011; Perry *et al.*, 2019). At Calakmul and elsewhere in this large area of unpalatable groundwater, the Maya who lived there during the Classic Period established dense population centers supplied by systems for collecting and storing surface water in shallow natural and artificial ponds. These are floored by impermeable local clay, a significant amount of which weathered from the Icaiche Formation (Perry *et al.*, 2019). Focusing on the area around Lake Chakanbacán, it is obvious from the photos the lake is refilling (Figure 3) and a perched surface aquifer is present that is isolated by lake mud and soil from the karst aquifer beneath.

Good circumstantial evidence that the active part of the karst aquifer beneath Lake Chakanbacán is comprised largely of dissolving gypsum; such a study comes from the longitudinal profile of the NNE-SSW depression in which the lake occurs (Figure 1) and of the known occurrence of dissolving gypsum encountered in the now-abandoned well in Caobas. At the southern end of the chain of water bodies, Lake Om at Caobas has an elevation of about 130m and is barely depressed below the surrounding terrain, whereas at the northern end of the depression, the terrain level is about 100m and the depression has merged into the surrounding polje. In a transverse profile in the middle (Figure 1), the banks of Lake Chakanbacán are about 30m below the terrain (topographic cross section inset into Figure 1). We think it reasonable that these observations are consistent with the hypothesis that dissolution of gypsum is proceeding from north to south as the Morcoy portion of Polje MNB expands by dissolution of gypsum and the concurrent collapse of overlying rock.

A question we have not addressed is what was the proximate cause of the August 2018 Lake Chakanbacán event? A reasonable guess would be that as a result of late summer rain, rising lake elevation had acted like a toilet plunger, pushing through abundant mud like that seen in the lake bed (Figure 3) that had clogged the drain. *But we don't know.* We have been unable to obtain local precipitation data for the period.

3.2. A FEASIBILITY TEST: CAN GYPSUM DISSOLUTION REASONABLY EXPLAIN BOTH POLJE FORMATION AND HIGH SULFATE GROUNDWATER IN EASTERN QUINTANA ROO?

The presumed fault depression in which Lake Chakanbacán is located has steep, well-defined banks 2.5 km apart and each about 30 m above lake water. Valley walls here are rocks of the Icaiche Formation (Google Earth accessed, 10 May, 2020; SGM 2007). There is no record of recent tectonic activity in this area, so it seems clear that the valley, which has no surface outlet, was formed by subsidence, and its simple geometry offers a clear opportunity to estimate the amount of subsidence that has occurred. If we assume that subsidence in the area results directly from 1) dissolution of gypsum and chemical transport of calcium and sulfate out of the system, 2) efficient transport occurred through the karst groundwater system responsible for draining Lake Chakanbacán, and 3) groundwater discharge was to the Rio Hondo Fault Zone, then we can calculate whether the process can reasonably explain both the high concentration of sulfate that discharges into the Rio Hondo Fault Zone and the extent of polje formation by gypsum dissolution in Campeche and southern Quintana Roo.

How Rapidly Do Poljes Form? A Calculation of Rate of Chemical Erosion by Groundwater

1) Assume that the 30 m-deep depression in which Lake Chakanbacán lies (Figure 1) was excavated by dissolution of gypsum. (The setting is right; the thickness is right (Perry *et al.*, 2019).)

2) Imagine a regular block of gypsum similar in size to a polje: *Simulated Polje* (SP), a square

block of gypsum 20x20 km and 30 m deep. This represents the amount of gypsum removed to form a basin comparable in size to Polje Morocoy. It contains $1.61E14$ moles of gypsum.

3) Assume that base flow of the Rio Hondo is fed mostly by vigorous springs coming from high-sulfate groundwater draining the western highlands around Lake Chakanbacán. Base flow of the Rio Hondo is estimated to be $25\text{m}^3/\text{second}$ (Conagua, 2018). Our best estimate of the sulfate ion concentration of high-sulfate groundwater nearly saturated with respect to gypsum comes from Cenote Azul (18.65°N , 88.41°W ; Perry *et al.*, 2021), with a SO_4^{-2} concentration of 0.0125 moles/l. Combining river discharge and groundwater/lake sulfate concentration leads to an estimate of annual sulfate discharge by the Rio Hondo of 9.85×10^9 moles of sulfate per year. Using water from Cenote Azul may result in an overestimate of sulfate carried by the Rio Hondo, but the error introduced is probably small compared to uncertainty about past climate. We note here that sulfate ions are direct mole-for-mole counters of gypsum. Even using measurements of sulfate in Rio Hondo water uncorrected for rainwater dilution yield discharge estimates of 6.6 to $7.6E9$ moles per year (Perry *et al.*, 2021).

4) From 2) and 3) above, we calculate that the discharge of the modern Rio Hondo could remove enough gypsum to produce a polje roughly the size of Polje Morocoy in about 16,400 years (at a rate of $9.85E9$ moles/year) to 24,250 years (at a discharge rate of $6.6E9$ moles/year).

The rough calculation here indicates that dissolution of bedded gypsum of the Icaiche Formation could produce Polje Morocoy in about 20,000 years. Poljes in the area range from quite small to several times the size of Polje Morocoy. There is abundant evidence of major changes in regional climate in the past, including times of drought and times of high rainfall accompanied by robust surface drainage (Dunning *et al.*, 2012; Perry *et al.*, 2019). A 20,000-year time estimate seems reasonable.

4. Conclusions

The near-catastrophic drainage of water from Lake Chakanbacán into the local karst aquifer that occurred between 19 and 21 August, 2018 demonstrates the presence of a robust karst groundwater flow system in southeastern Campeche-southwestern Quintana Roo. The water entering the groundwater system in this rare event was diluted surface water atypical of the high-sulfate recharge water generated in the area by dissolving gypsum. Nevertheless, the rapid flow of water through the karst aquifer demonstrated the recharge capacity of the system and confirmed that subsurface dissolution of massive gypsum layers of the Icaiche Formation is a reasonable process for the formation and expansion of large poljes in Campeche and southwestern Quintana Roo, as well as for the generation of high-sulfate groundwater recharging springs and surface water of the Rio Hondo Fault Zone. We suggest that the probable NNE-SSW fault that includes Lake Chakanbacán, together with other fault traces that may lie beneath the Icaiche Formation, comprises the recharge system that furnishes groundwater of high sulfate content that discharges into the Rio Hondo Fault Zone, which is also oriented NNE-SSW.

A simple calculation based on observed subsidence produced by normal drainage into Lake Chakanbacán and surrounding surface water bodies demonstrates that current rate of subsidence in this system could produce a polje comparable in size to Polje Morocoy in about 20,000 years while at the same time feeding sulfate to groundwater at the rate appropriate to maintain the current sulfate concentration of Rio Hondo river water.

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