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Dynamics and a Hydraulic-Soil Mechanical Model for Pockmarks in a Mud-draped Lake: Lake Sünnet (NW Anatolia)

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ABSTRACT

The scarcity of bathymetric studies in most Turkish lakes does not allow the documentation and the potential causes of lake bottom irregularities. In this study, relatively high-resolution bathymetric data from Lake Sünnet (NW Anatolia) revealed five deep (5.7 to 9.2m) and narrow (10 to 20m) depressions located along the boundary between the lake bottom and the steep lake margins. Analysis of lake level data belonging to dry seasons hints no leakage through these depressions. However, the negative conical shape and weakly developed levees around the holes suggest an upward episodic groundwater discharge for which direct evidence has been absent up to date. A combined hydraulic and soil mechanical model successfully explains the pockmark activity due to the flow of water through conduits in karstic carbonate bedrock. According to sedimentation rates and average depth of pockmarks in Lake Sünnet, and available regional paleoclimate studies, the onset of pockmark activity might coincide with the transition from the Near East Aridification Phase to the humid Beyşehir Occupation Phase around 300 BCE in SW and NW Anatolia.

KEYWORDS **Groundwater discharge. Hydraulic modelling. Inland lake. Karstic conduits. Pockmarks.**

INTRODUCTION

Continental lakes developed within deep valleys such as glacier and landslide-dammed lakes usually comprise deltaic and coastal sediments in shallow areas while the traction and suspension-laden sediments cover the deeper lake. These horizontal and monotonous sediments may be locally altered by subaqueous landslides, as well as by some enigmatic depressions. The latter might correspond to conduits that drain lake water out of the reservoir through the submerged joint systems and especially karstic cavities. These depressions, also called sinkholes, are serious threats to many man-made reservoirs to be avoided or remediated before the construction of the overlying structure (Crawford *et al.,* 2005; Ertunç, 1999; Günay *et al.,* 2015; Jovanelly, 2014). Another type of subaquatic depression, known as pockmark, is related to the outburst of fluids beneath the stagnant water under favorable conditions (Hovland *et al.,* 2002). These gravity-driven features, which can be exemplified by submarine groundwater discharge, are less common and develop within a complex hydrological framework involving humid climatic conditions, thin fine-grained bottom sediments and high permeability of the host rock (Fleury *et al.,* 2007; Nardelli *et al.,* 2017; Wirth *et al.,* 2020).

This study investigates the characteristics, origin, and dynamics of depressions detected at the bottom of Lake Sünnet which is surrounded by high-elevation hills of carbonate rocks in NW Anatolia. The bathymetric and hydrogeological data and a simple hydrologic model allow us to suggest that these depressions are not water-escape sinkholes, but pockmarks associated with the upward flow of karst groundwater recharged possibly from snowmelt and rainfall, through the dissolution conduits developed within the limestone bedrock. The discovery of pockmarks in an Anatolian inland lake for the first time in this study hints that similar submerged depressions may exist in other lakes surrounded by high-elevation carbonate rocks, and should be investigated for ecological, environmental, and lake management concerns (Descy *et al.,* 2012; Draganits and Janda, 2003; Ionescu *et al.,* 2012).

GEOLOGICAL SETTING AND ORIGIN OF THE LAKE

Lake Sünnet is located between the Mudurnu and Göynük towns west of Bolu province in NW Anatolia at a location 40º 25' 17"N, 30º 57' 23"E and 1040m altitude (Fig. 1A). Due to its transitional position between humid Western Black Sea-Marmara regions and semi-arid Central Anatolia, the region experiences moderate precipitation and evaporation (538mm and 827mm respectively) and has a long-term mean annual temperature of 10.3ºC. The summer and early autumn are generally dry while the rest of the year receives >50mm monthly precipitation. Since the area is mountainous, the number of snowy days is between 5 and 10 (www.meteoblue.com). The local people recall experiencing very heavy snowfall prior to the emergence of global warming in the 1970s. This perspective is supported by the decreasing number of snowfall days and reduced snow cover depth in the mountainous (>1000m) Marmara region since the 1970s (Baltaci *et al.,* 2020).

From a geological viewpoint, the watershed of Lake Sünnet covers Jurassic to Cretaceous limestone and Cretaceous limestone-marl alternations (Fig. 1B). Lower Jurassic to Cretaceous succession consists of thick-bedded limestone with thin marl interlayers. They frequently display decimeter-sized karstic voids partially filled with terra rosa (Ocakoğlu and Tuncay, 2023). In the Cretaceous carbonate succession, the marl beds are thicker and hence the karstic dissolution is weaker. Earlier studies suggested a landslide-dam origin for the lake (Abdüsselamoğlu, 1959). Later studies revealed that the lake formed 8000 years ago by two simultaneous landslides triggered by a very large earthquake in the North Anatolian Fault 20km to the north (Ocakoğlu and Kapan-Yeşilyurt, 2014; Ocakoğlu and Tuncay, 2023). During the instrumental period, earthquakes with magnitudes up to Mw 7.8 were recorded along the North Anatolian Fault (*e.g.* Barka, 1996). Paleoclimatological studies demonstrated that the lake started to be filled quickly

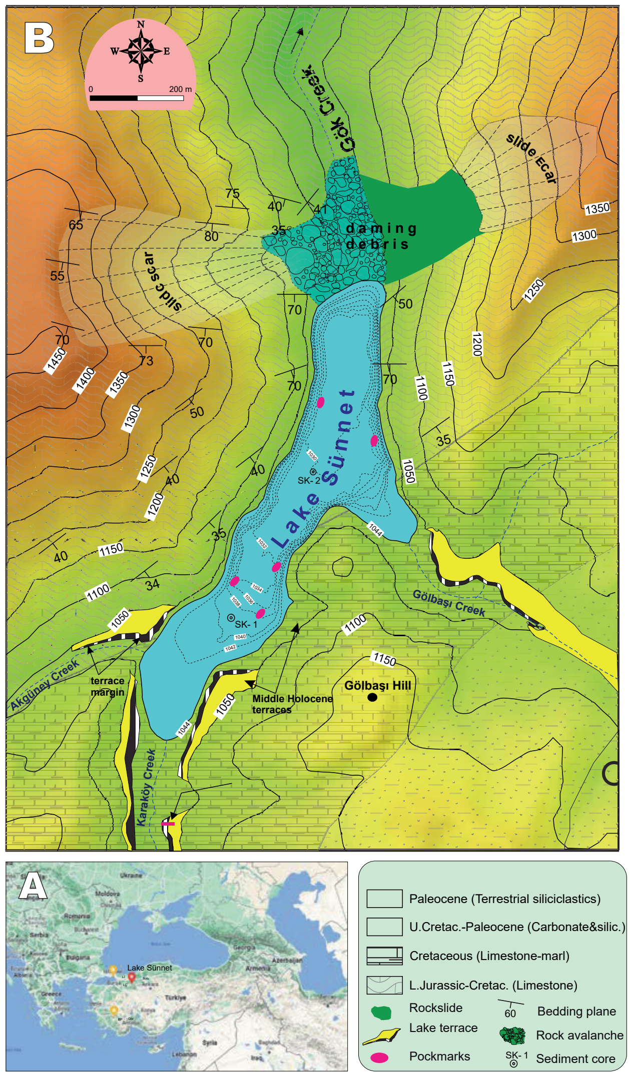

FIGURE 1. A) Location map and B) overview of the morphology and geology of Lake Sünnet. LÇ: Lake Çubuk, Lİ: Lake İznik, BP: Bereket Plain, GW: Gravgaz Wetland.

by the tributaries in the south and east and formed large delta plains. Due to an effective regional drought at around 4.2ka, the lake level dropped substantially and caused the formation of lake terraces at the margins of river courses (Ocakoğlu and Kapan-Yeşilyurt, 2014; Fig. 1B). Analysis of the longitudinal profile of the main Sünnet Valley revealed 60m-thick lake sediments beneath the present lake (Ocakoğlu *et al.*, 2015). The modern bottom sediments are predominantly sandy in the subaqueous delta and mostly clayey and silty in the deeper lake (Erayık, 2011).

METHODOLOGY

The present study is based mainly on the geological findings from the lake infill and the surrounding basement rocks, high-resolution bathymetric data, and several years-long lake level monitoring. The bathymetric data were collected in July 2009 by using an Elac Hydrostar 4300 echosounder which was coupled with a Hemisphere A100 GPS device. The vertical resolution of the echosounder is around 2.5cm in the studied depths (<15m). The average distance between the GPS measurement points is about 2 meters while the total bathymetric survey length is about 10km. Three sediment cores within the lake were collected in 2009 using a Livingstone corer on a 4x4m size modular plastic platform. The retrieved cores were halved, logged, and sampled for multi-proxy analysis in a lake-side laboratory. The grain size distribution of 24 samples across the lake bottom was determined using a hydrometer test (Kır, 2010). One bottom sediment sample was analyzed in further detail using a Malvern Mastersizer instrument with a lower limit of 0.01μm in the Laboratory of the Mining Engineering Department at Eskişehir Osmangazi University. We also profited from the discontinuous lake level monitoring data observed by Balcı (2008) between 2005 and 2006 at 13 different times. The hydraulic and soil mechanical models developed in this study cover parameters such as hydraulic gradient, critical hydraulic gradient, and seepage force. The models and their implications will be discussed separately later for the sake of integrity.

RESULTS

Bathymetry of the Lake and the Pockmarks

Lake Sünnet comprises delta plain sediments that were brought by river networks from the south and east (Fig. 1). The delta plains pass to the deeper lake bottom at 1030m elevation via a relatively high-angle delta front (Fig. 2). The valley margins beneath the lake incline 25-30º and are sharply bounded to the sediment-laden horizontal lake bottom. The bathymetric survey lines locally comprise noticeable highs-and-pits of 20-30cm (max. 100cm) amplitude in sequential measurement points (Fig. 2). These fake features are attributed to the up-and-down motion of the boat having bathymetry instrument due to strong wind action. The horizontal deeper lake bottom comprises five plurimetric depressions up to 9m deep. The depressions are detected mostly along two or more bathymetric lines. Since the number of measurement points across the depressions ranges from 3 to 6, their perception isn't related to any instrumental error.

The location of pockmarks and the profiles perpendicular to the valley margins are shown in Figure 2. All the depressions are located at the boundary between the steep valley margins and the mud-draped horizontal lake bottom, *i.e.* between the basement limestone and lake sediments. The depressions are circular to oval in plan view. Their width ranges between 11m to 20m while their depth is between 5.7m to 9.2m (Table 1). The slope of pockmarks mostly ranges between 62º and 67º. There is an obvious positive correlation between the pockmark volume and the length of the neighboring slope (L_{max}) (Fig. 3). Their cross-sections typically display an ideal polynomial curve, which for example, fits the equation $f(x) = -0.0211x^2 - 0.3279x + 1030.2$ ($r^2 = 0.99$) for the pockmark D. Some of the depressions are bordered by 0-15m wide levee 50-100cm above the flat lake bottom (Fig. 2).

In terms of grain size of bottom sediments, the pro-delta areas are characterized by higher silt and sand ratio (>60%) where fine sands (62-125μm) account for <9% (Appendix, Table I; Fig. 4). In the deeper (>14m) lake bottom far

TABLE 1. Metrics related to the observed pockmarks in Lake Sünnet

Pockmark ID	Hmax (m)	Lake level (m asl)	Pockmark Elevation (m asl)	Pockmark depth (m)	Slope of pockmark (º)	Nearby grain size	Lmax (m)	Pockmark diameter (m)	2D area of the pockmark (m^2)	3D area of the pockmark (m^2)	Volume of the pockmark (m^3)
A	1496	1044	1032.2	8.2	55	CM	794	20	443	514	721
B	1167	1044	1032.2	5.7	62	CM	295	15	130	189	216
C	1167	1044	1031.3	7.5	67	CM	317	11	387	477	539
D	1439	1044	1030.7	9.2	63	CM	1165	20	544	671	1072
E	1493	1044	1030.0	8.5	62	CM	704	20	433	524	522

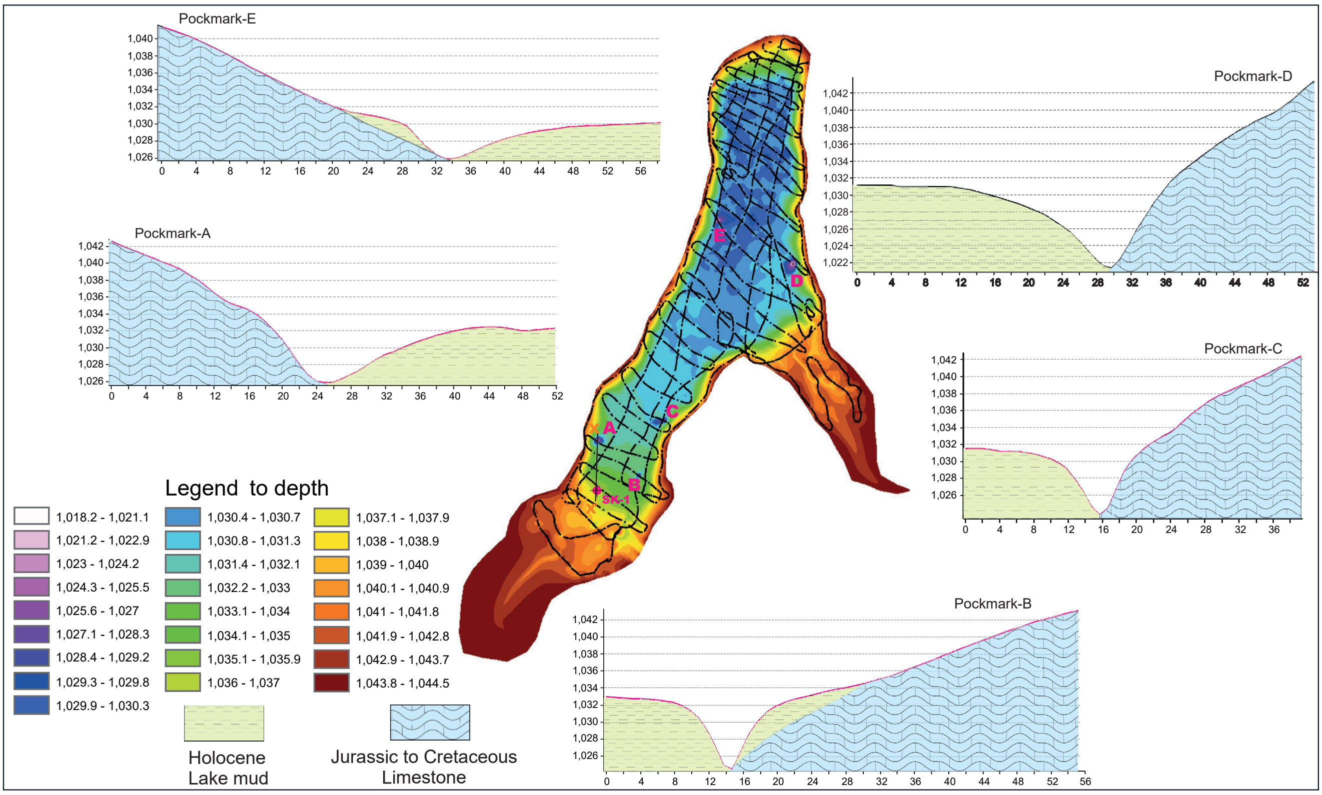

FIGURE 2. Detailed bathymetry of Lake Sünnet and profiles of individual pockmarks (A to E) perpendicular to the lake margins. X-X' is the line of the section shown in Figure 6. Small black circles mark the bathymetric measurement points.

from delta front, the silt+sand ratio is generally smaller than 50%. A precise grain size measurement carried out by a laser-based instrument confirms that only 4% of the sediments is very fine sand (62-125μm) and the mean grain size is fine silt (10μm) (Appendix, Figure I).

The lake monitoring by Balcı (2008) between August 2005 and December 2006 depicts only 1m of lake level drop during the dry period between 30 September and 30 November 2005. Similarly, the maximum lake depth has been fixed at around 9m in the dry period between 4 August and 2 December 2006 (Fig. 5). Based on meteorological data from the Bolu meteorological station (https://www.mgm.gov.tr/), the lowest monthly values of precipitation (<40mm) and the highest values of evaporation (60-160mm) of the year coincide with the lowest lake levels (Fig. 5).

Nature of the Infill of Lake Sünnet

We collected three sediment cores up to 2m thick from different depths of the lake (Figs. 1; 2). SK-1 core was taken from the distal zone of the delta front between the pockmarks A and B. This 215cm-thick core consists of the alternation of sand and mud layers (Fig. 6). Sand layers are dark brown and occasionally 2-3cm thick. They have always sharp basal contact while the upper boundary with mud is frequently gradual. We counted 46sand/silt layers in the core. The interlayered muds are light brown and massive above 160cm whilst they locally display fine lamination in the deeper levels (Fig. 6). Two other cores (SK-2 and SK-4) whose detailed logs are not shown herein were taken from the deeper central and northern part of the lake (Fig. 1). These cores do not include sand layers, yet are composed completely of light brown or grey muds (See

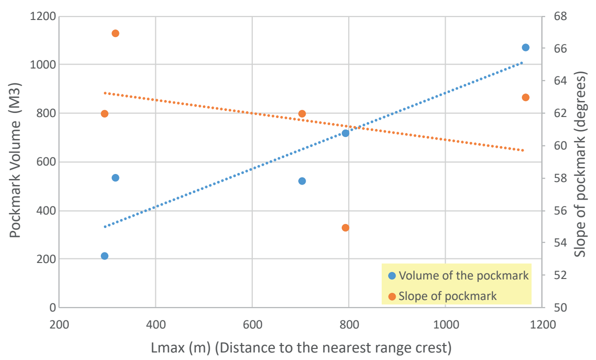

FIGURE 3. Change of pockmark volume and pockmark slope with the length of adjacent slope (L_{max}).

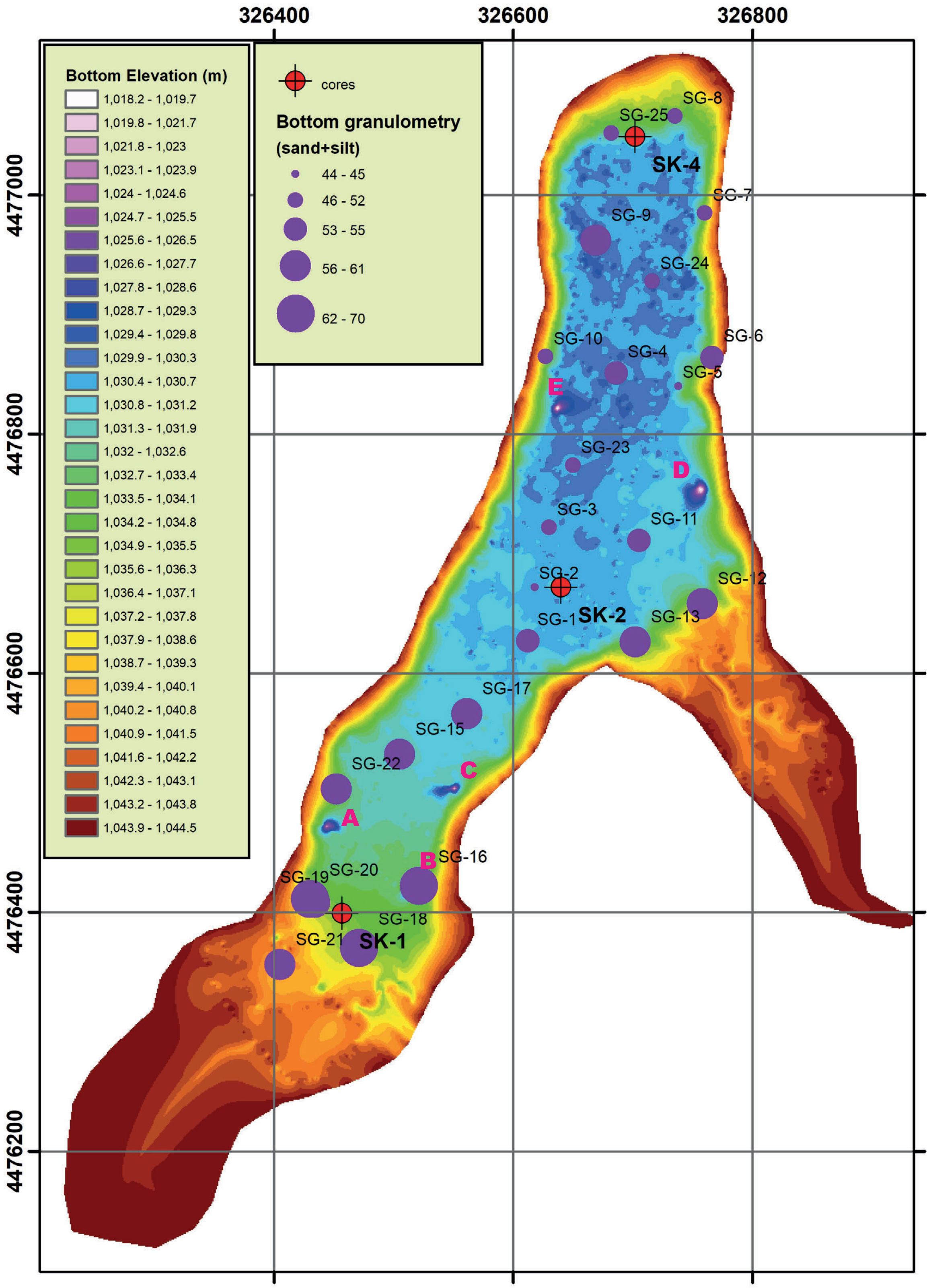

FIGURE 4. Grain-size distribution of the bottom sediments in Lake Sünnet. SK-1 to SK-4 are the cores mentioned in the text.

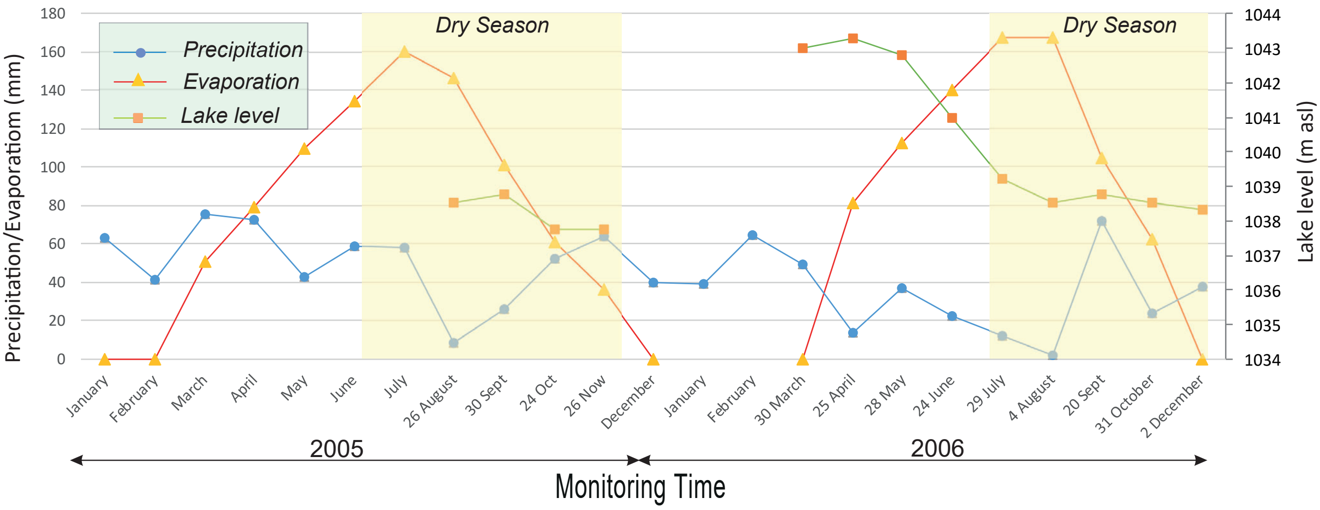

FIGURE 5. Meteorological data (http://www.meteor.gov.tr) and Lake level changes in 2005-2006 (Balcı, 2008) in Lake Sünnet.

Fig. 3 in Ocakoğlu *et al.,* 2022). A detailed radiocarbon-based age-depth model in the SK-4 core revealed an average accumulation rate of 3.4mm/yr in the last 500 years (Ocakoğlu *et al.,* 2022). Taking the overall coarser grain size and the bathymetric profile, the base of the SK-1 core can be attributed to AD 1500.

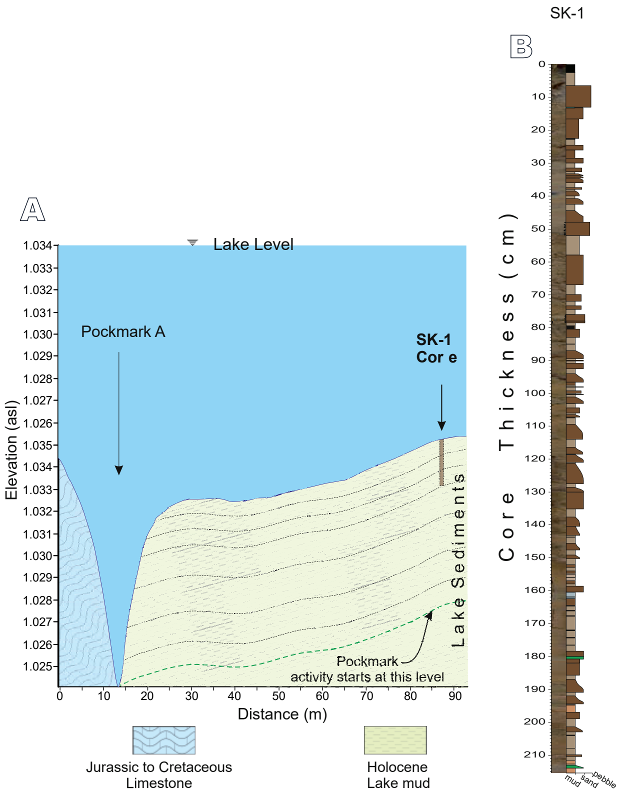

FIGURE 6. A) X-X' profile of the lake floor (see Fig. 2 for the location). B) Lithological log of the SK-1 core.

Hydrological and Soil Mechanical Models

Conceptual model and hydraulic model parameters

The depressions formed at different depths and sizes on the slopes of Lake Sünnet reservoir and the scavenging mechanism of the sediment at the bottom of these depressions are described considering the conceptual hydrogeological model in Figure 7.

This conceptual model comprises geological, hydrogeological, and hydraulic mechanisms. The limestone basement extends from the hillside down to the lake. It hosts many fissures and dissolution voids that enable the infiltration of precipitation. Although the karst cavities/pipes created by dissolution are generally vertical, the larger conduits are assumed to follow the bedding planes between marl and limestone of the L. Jurassic-to-Cretaceous unit dipping grossly towards the lake at the western valley margin (Fig. 1). As a result, these karst pipes terminate at the bottom of the depressions. The hydrogeological scope of the conceptual model assumes that the lake level is essentially controlled by the groundwater level that recharges the former. In addition, the temporary groundwater level or maximum groundwater level (Fig. 4), sustained by the infiltration of precipitation from the multi-crevice slope surfaces, rises above the overall groundwater level, providing the sediment at the bottom of the depressions to be swept. In other words, the establishment of this temporary groundwater level is assumed to fill the karstic cavities/pipes/cracks with the infiltration. The hydraulic mechanism of the conceptual model comprises the groundwater flow in a karstic environment. In karst aquifers, like the carbonate bedrocks of Lake Sünnet, the conductivity of conduits is incomparably higher than the matrix porosity. As a result, the groundwater flow moves toward the conduits which serve as collectors (Fig. 7).

It is agreed that the temporary groundwater level is exposed to atmospheric pressure due to the multiple fissures. Thus, the hydraulic gradient (i), *i.e.* the slope of the line connecting the water levels exposed to the atmosphere, is almost equal to the slope of the hillside (tan β) forming the lake reservoir when drawn between the temporary groundwater level and the lake level. When i>0, the flow occurs conditionally. This condition is that the pressure head, due to the difference in height between the surfaces exposed to atmospheric pressure, is greater than the pressure head loss in the karst pipe where the flow occurs. The loss of pressure head increases with the velocity of the flow. As already stated, the seepage velocity through the matrix is known to be negligible since the groundwater flow that develops in cracks, fissures, and cavities by centering the karst pipe is mainly in the form of seepage. Because of this, even if the temporary groundwater level is slightly above the long-term groundwater level, the flow can reach the lake through holes at the bottom of the depressions with a hydraulic gradient equal to the slope of the hillside.

Soil mechanical model and parameters

The mobilization mechanism of sediments at the bottom of the depressions in Lake Sünnet is explained by the critical hydraulic gradient parameter of traditional soil mechanics (Terzaghi, 1939). Studies conducted in the laboratory have shown that in fully saturated soils (non-plastic soil or cohesionless soil) under the upward seepage flow conditions with the increase of hydraulic gradient, the mean effective stresses that keep the soil grains together decrease, and the intergranular frictional resistance disappears. The hydraulic gradient is determined as the critical hydraulic gradient (i_{cr}) when these mean effective stresses are zero, and this situation is referred to as "static liquefaction" (*e.g.* Budhu, 2010). In other words, this critical hydraulic gradient, which occurs when the seepage pressure acting on any soil surface equals the soil's weight, is presented in Equation 1 (γ_{sat}: saturated unit weight of soil, γ_w =9.81 kN/m^3: unit weight of water. γ_b : buoyant unit weight of soil). Soil grains are swept from the bottom of the depressions when $i \geq i_{cr}$.

$$i_{cr} = \frac{\gamma_{sat} - \gamma_w}{\gamma_w} = \frac{\gamma_b}{\gamma_w} \qquad (1)$$

Static liquefaction, observed in boiling, heaving, piping, and quicksand modes at the downstream toe of levees and mounds constructed on non-cohesive soils, stands out as a problem, threatening the safety of structures that retain water (*e.g.* Pabst *et al.*, 2012). Remarkably, the soil particles are blown towards the surface by the action of the flow in boiling. Sediment sample taken from the top of SK-2 in the vicinity of the depressions at the bottom of the lake dominantly consists of fine-grained soils (average size is 10μm) (Appendix, Figure I). However, the sediments accumulating at the bottom of the depressions are removed by the groundwater discharge at the bottom of the depressions before they gain cohesion or plasticity due to saturation. As another possibility, these colloidal particles can keep floating if the pockmark flow is active enough. The bottom sediment samples collected are mostly classified as CH (high-plasticity clay) (Fig. 4) according to the Unified Soil Classification System (USCS) (average Liquid Limit (LL): 58 and Plasticity Index (PI): 32). The average saturated unit weight was determined as 16.54kN/m^3 as a result of the experiment performed in the laboratory for the sediments of CH soils (*e.g.* ASTM D2937-00, 2018).

The slope of the hillside in the vicinities of the pockmarks is approximately the same and was measured as β=35º. In the conceptual model, the hydraulic gradient evaluated in the hydraulic slope is I= tan 35º = 0.70 (Fig. 7). The critical hydraulic gradient calculated according to Equation 1 is i_{cr}=0.69. The sediments at the bottom of the depression are swept when I= 0.70 > i_{cr} = 0.69 that is, when the groundwater level rises slightly above the lake level due to recharge by the seasonal precipitation.

In the heaving mechanism, which is one of the modes of static liquefaction, the uplift of sediment grains occurs when the seepage forces push sediments upwards, and the static stability of grains is altered. The mobilization of the grains begins under a sufficient hydraulic gradient. Otherwise, sediments within pockmarks will not blow out. This concept can be used for the estimation of minimum

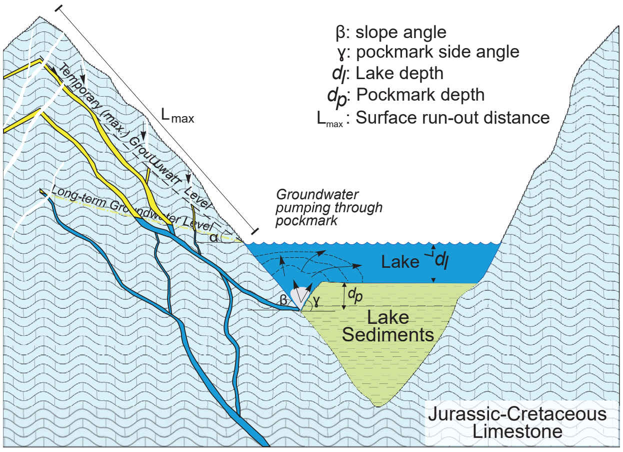

FIGURE 7. Conceptual hydrological and soil mechanical model for Lake Sünnet pockmarks.

sediment thickness that can prevent pockmark activity. The seepage forces (F_s) acting on the unit (*i.e.* $1x1x1m^3$) bulk (sediment plus water in pores) volume at the bottom of the depression can be calculated using Equation 2.

$$F_s = i\gamma_w \qquad (2)$$

The heaving occurs when $F_s \geq \gamma_b$ according to the balance of forces acting vertically on the submerged sediments. According to this approach, the maximum sediment thickness, $t_s = \frac{F_s}{\gamma_b} \times 1 = 1.02m$ is calculated for a successful blowout of the sediments due to upward groundwater pressure through pockmarks. Any thicker sediment cover will cause the fill-up of the pockmarks with the lake sediments.

DISCUSSION

As demonstrated by the lake level data spanning two dry seasons (Fig. 5), the five subaqueous depressions identified at the bottom of Lake Sünnet are not leaking conduits. Contrarily, they are related to hydraulic head in karstic conduits due to the rapid flow of groundwater recharged by flash floods and/or snowmelts, as confirmed by our simple hydraulic model (Fig. 7). Any considerable recharge is expected to raise the local groundwater level in the interconnected conduits and may result in subaqueous groundwater discharge through pockmarks. An indirect validation of this explanation is the positive correlation between adjacent slope length (L_{max}) (*i.e.* the length of route infiltration can occur) (Fig. 7) and the volume of pockmark (Table 1, Fig. 3). As L_{max} increases, the amount of infiltration and hence the hydraulic head will increase (Fig. 6), resulting in the elevated groundwater discharge at the bottom of pockmarks. Higher discharge is expected to form a gentler pockmark slope and increased pockmark volume (Fig. 3).

Previous studies demonstrated a close relationship between pockmark activity and precipitation regime in their karstic recharge area (Serra *et al.,* 2021; Wirth *et al.,* 2020). For instance, the pockmark activity in Lake Banyoles (Spain) coincides well with the seasonal precipitation in the mountainous source area. Still, a delay of two months between the onset of activity and the wet season due to a distant source area was also documented (Colomer *et al.,* 2002). In the Sünnet case, the recharge area of pockmarks is very close (L_{max}<1100m) (Table 1) as demonstrated by our geomorphological studies and the hydraulic model. This implies a short time gap (hours, if not days) between heavy precipitation events and pockmark activity.

There is other indirect evidence for the activity of pockmarks in Lake Sünnet derived from their negative conic shape. This shape suggests that the upward flow of groundwater exponentially decelerates due to friction at the pockmark margins and reduced confinement (*i.e.* enlargement of the pockmark) upward. Similar pockmarks were identified on the Cilento coast (southern Italy) at 12 to 45m water depth, and their activity is confirmed by various monitoring studies (Nardelli *et al.,* 2017). One of the reliable indicators of groundwater flow is the fluidized (or suspended) sediments of varying thickness in pockmarks (Colomer *et al.,* 2001; Colomer *et al.,* 2002; Nardelli *et al.,* 2017; Reusch *et al.,* 2015; Wirth *et al.,* 2020). However, due to the limited monitoring record and the episodic nature of pockmark activity, this indicator is generally not feasible to use, as was the case in Lake Sünnet. The negative conical shape of Lake Sünnet also suggests that the sediments delivered to the lake were not accumulated at the bottom of the pockmarks for an extended period to create a flat surface. Instead, they have temporarily swept away or suspended due to episodic pockmark activity, aligning with the conceptualization in our soil mechanical model. It seems that the fine-grained nature of bottom sediments even in the prodelta areas in the vicinity of pockmarks A, B, and C, do not allow the development of considerable levees around the pockmarks (Fig. 2; 4) as happened in Chez-le-Bart pockmark in Lake Neuchâtel (Reusch *et al.,* 2015). Additionally, the consistent slope angle (~62º) of most of the pockmarks (Table 1) strongly implies that a minimum upward flow velocity of 50cm/s is required based on the Hjulström (1935) diagram, taken the mean fine silt (10μm) mean grain size of the bottom sediments. This rate is very high most probably due to the high hydraulic head induced by the steep slope of the feeding conduits in Lake Sünnet, compared to the well-monitored pockmarks such as Lake Neuchatel (several cm/h) in Europe (Wirth *et al.,* 2020).

Some previous studies demonstrated a close relationship between pockmark activity and climate change events. For instance, pockmarks in Lake Banyoles respond to the ongoing climate shift to drier conditions either by reducing or completely lacking activity in the last decade (Serra *et al.,* 2021). Lacustrine sediments of Lake Banyoles also show a long record of past pockmark activity. The pockmarks in Lake Banyoles (NE Spain) were inactive throughout the dry middle Holocene period (Morellón *et al.,* 2014). However, the increased precipitation has rejuvenated the pockmark activity over the last two millennia, resulting in the formation of 17 distinct homogenite beds due to the reworking of contemporaneous bottom sediments (Morellón *et al.,* 2014). Since the bottom sediments in the deeper part of Lake Sünnet are mostly silt-sized, the past pockmark activity cannot be assessed using grain size. However, the grossly equal depth of five pockmarks (average 8.5m) (Table 1) implies a radical climate change from relatively dry to more humid conditions when the sediments at

8.5m deep were being deposited in the lake record (Fig. 6). Unfortunately, we cannot directly check out this change due to inaccessibility of these deeper stratigraphic levels. However, the average sedimentation rate derived from the core SK-4 (Fig. 4) not far from the pockmarks E and D in the last 500 years (3.4mm/yr) provides some clues. The extrapolation of this sediment rate to the average depth of pockmarks yields 2500 yr Before Present (BP) for the onset of present pockmark activity. This period corresponds to the end of a prolonged drought known as the Near East Aridification Phase, characterized by reduced precipitation and deforestation in Anatolia (Vermoere *et al.,* 2000). By 300 BC, new climatic conditions called the Beyşehir Occupation Phase were established in the stratigraphic records of the Bereket Plain and the Gravgaz Peatland (SW Anatolia), located 300km SW of Lake Sünnet, leading to an increase in population and agricultural activity (Kaniewski *et al.,* 2007; Vermoere *et al.,* 2000). The onset of this wet period is around BC 300 in Lake Çubuk, 20km west of Lake Sünnet, and 2000 BP in Lake İznik further west (Ocakoğlu *et al.,* 2016; Ülgen *et al.,* 2012). According to the paleoclimate record in Lake Çubuk, the last 2300 years have been dominantly wet except for several short-lived dry periods (Ocakoğlu *et al.,* 2016). This dataset confirms the uninterrupted episodic (seasonal) activity of Lake Sünnet's pockmarks since their initiation.

CONCLUSION

Lake Sünnet (NW Anatolia) is a small (1200m-long and 150m-wide), shallow (14m) landslide-dam lake that was developed within a narrow valley of Mesozoic carbonate rocks. Bathymetric investigation of the lake revealed five deep (average 8.5m) and narrow (20m) depressions developed along the lake margins. According to data from a previous lake level monitoring study covering two dry periods, these depressions are not leaking structures, but subaqueous outlets of karstic conduits attached to the hillslopes of the lake. Their perfect negative conical shape and the weakly developed levees in some of these pockmarks, as well as the positive correlation between the volume of pockmarks and the maximum height of the adjacent hillslope, further support this hypothesis. A simple hydraulic model shows the adjacent pockmark activity when the hydraulic gradient of the flow between the temporary and long-term levels of groundwater is equal to the slope of the hill. Furthermore, the soil mechanical model confirms the static liquefaction of lake bottom sediments due to flow in pockmark. In this regard, the average depth (~8.5m) of the pockmarks which represent a site of non-deposition due to episodic liquefaction hints about the onset of pockmark activity. Based on the previous sedimentation rates in Lake Sünnet, the earliest pockmark activity might have started at 2500 BP. This time seems to match fairly well with a climate shift from the Near East Aridification Phase to the more humid Beyşehir Occupation Phase around 300 Before Common Era in the SW and NW Anatolian paleoclimate records. New pioneering monitoring investigations are required to validate the activity of Sünnet pockmarks and to assess their impact on the hydrology and ecosystem of the lake.

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APPENDIX

TABLE I. Granulometry of grab samples

Örnek No:	X	Y	Z	kum	silt	kil
SG-1	326612	4476627	1030.9	11	44	45
SG-2	326618	4476672	1030.5	8.15	36.85	55
SG-3	326630	4476722	1030.7	8	43	49
SG-4	326686	4476851	1030.7	10	43	47
SG-5	326738	4476840	1031.0	10	34	56
SG-6	326766	4476864	1036.42	8	46	46
SG-7	326760	4476985	1033.3	8	42	50
SG-8	326735	4477066	1034.6	8	44	48
SG-9	326669	4476962	1030.0	8	49	43
SG-10	326627	4476865	1036.2	9	42	49
SG-11	326705	4476711	1030.7	10	43	47
SG-12	326758	4476658	1037.7	6	54	30
SG-13	326702	4476626	1034.5	7	51	42
SG-14	326709	4476564	1042.0	-	-	-
SG-15	326505	4476532	1031.45	8	50	42
SG-16	326521	4476422	1032.9	8	55	47
SG-17	326561	4476566	1031	10	48	42
SG-18	326471	4476370	1035.2	9	55	46
SG-19	326434	4476408	1036.4	9	52	39
SG-20	326430	4476411	1038	8	62	30
SG-21	326405	4476356	1041	6	51	43
SG-22	326452	4476503	1032	8	50	52
SG-22A	326452	4476503	1032	7	36	57
SG-23	326650	4476774	1030.6	7	43	50
SG-24	326716	4476928	1030.3	8	43	49
SG-25	326682	4477052	1032.8	8	44	48

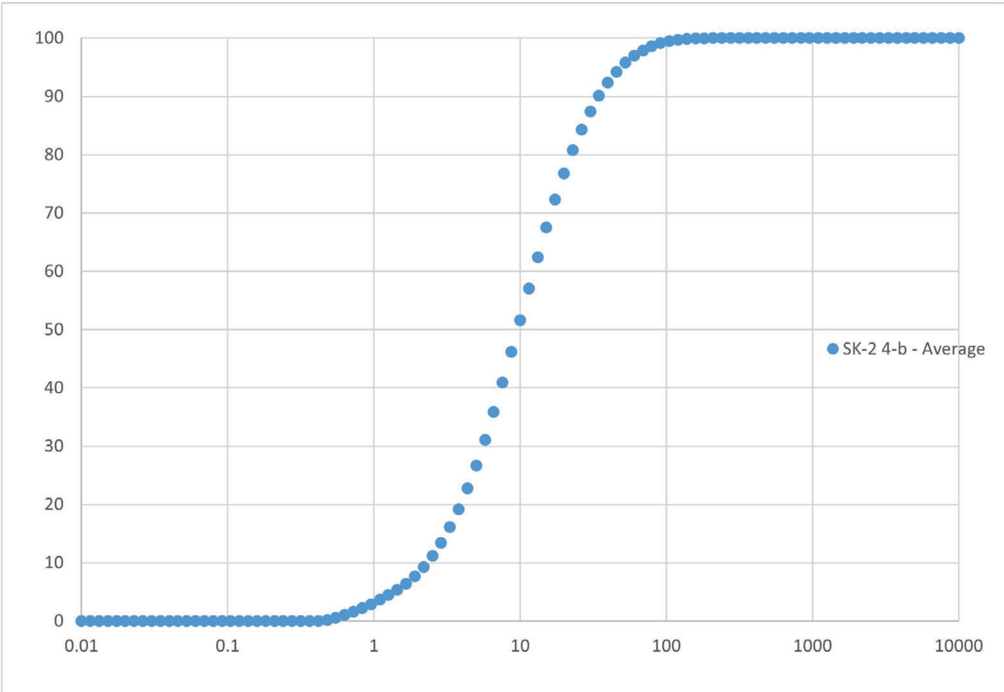

FIGURE I. Granulometry of SG-2 grab.