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Review

The Antarctic Subglacial Hydrological Environment and International Drilling Projects: A Review

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Abstract: Subglacial lakes and hydrological systems play crucial roles in Antarctic subglacial hydrology, water balance, subglacial geomorphology, and ice dynamics. Satellite altimetry has revealed that some recurrent water exchange occurs in subglacial lakes. They are referred to as 'active lakes', which prominently influence a majority of subglacial hydrological processes. Our analysis indicates that active subglacial lakes are more likely to be situated in regions with higher surface ice flow velocities. Nevertheless, the origin of subglacial lakes still remains enigmatic and uncertain. They could have potential associations with geothermal heat, ice sheets melting, and ice flow dynamics. Subglacial lake drilling and water sampling have the potential to provide valuable insights into the origin of subglacial lakes and subglacial hydrological processes. Moreover, they could also offer unique opportunities for the exploration of subglacial microbiology, evolution of the Antarctic ice sheets, and various fundamental scientific inquiries. To date, successful drilling and sampling has been accomplished in Lake Vostok, Lake Mercer, and Lake Whillans. However, the use of drilling fluids caused the water sample contamination in Lake Vostok, and the drilling attempt at Lake Ellsworth failed due to technical issues. To explore more of the conditions of the Antarctic subglacial lakes, the Lake Centro de Estudios Científicos (Lake CECs) and Lake Snow Eagle (LSE) drilling projects are upcoming and in preparation. In this study, we aim to address the following: (1) introduce various aspects of Antarctic subglacial lakes, subglacial hydrological elements, subglacial hydrology, and the interactions between ice sheets and the ocean; and (2) provide an overview and outlook of subglacial lakes drilling projects.

Keywords: antarctic subglacial lake drilling; subglacial hydrology; grounding zone hydrology

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1. Introduction

Subglacial hydrological activities mainly comprise the processes of water storage in subglacial lakes and drainage, as well as the interactions between ice, lakes, bedrock, groundwater, and the ocean. Subglacial hydrology research starts with explorations and discoveries of subglacial lakes. Subglacial lakes are multi-scale in size and are formed at the interface between ice and bedrock [1]. According to modeling results, although over 600 subglacial lakes in Antarctica have been found thus far [1–3], there are still thousands of subglacial lakes that remain to be discovered [4]. Subglacial hydrological processes are crucial for Antarctic ice sheet dynamics, lubrication of ice sheet bases, grounding–line stability, and discharge into the surrounding ocean [5–8]. More importantly, subglacial lakes are considered potential habitats for various microorganisms [9]. Basal aquiferous sediment layers are also potential carriers of paleorecords, which are important for studying topographical evolution and the paleoclimate [10]. Therefore, there has been an international dedication to exploring subglacial lakes that involve drilling and collecting samples from lake water and sediments.

Due to technical difficulties, in situ observations of subglacial hydrologic conditions in Antarctica are very limited. To gather detailed information about Antarctic subglacial hydrology, geophysical and remote sensing techniques are the most efficient approaches. Satellite-based methods enable the real-time monitoring of subglacial hydrological conditions (e.g., the detection of water recharge and discharge events [8]). Also, geophysical methods (e.g., active seismic refraction tomography and ice penetrating radar) can provide measurements of subglacial environments [11,12], as shown in Figure 1.

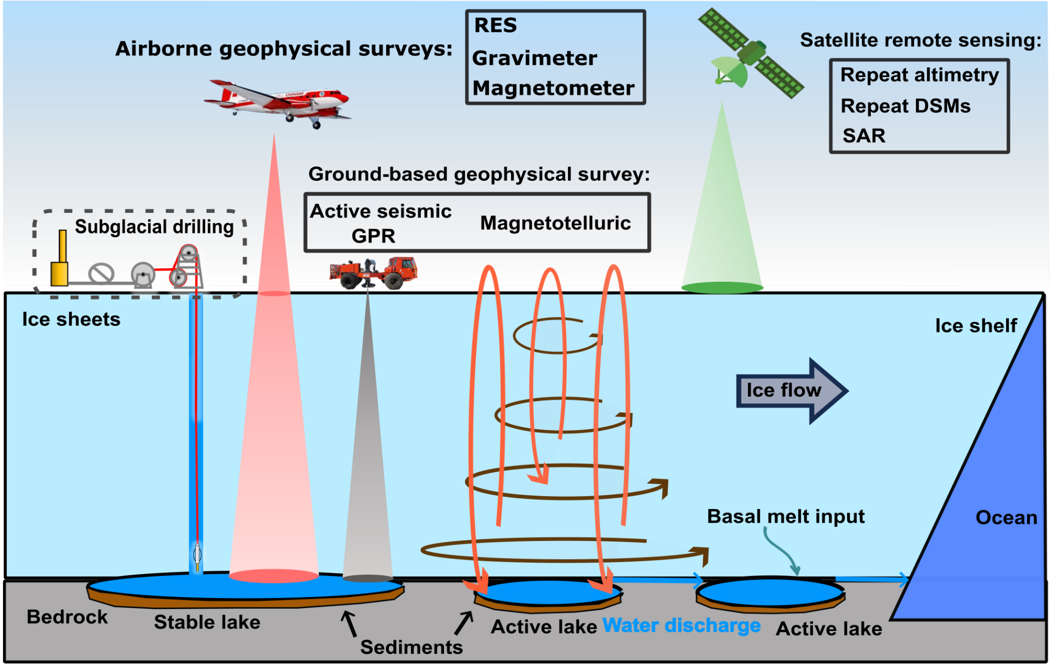

Figure 1. An overview diagram of Antarctic subglacial hydrological systems and related detection methods [3].

Subglacial water can be transfered in large quantities over a long distance in short time scales, which is known as rapid floods [13–15]. Intricate interactions may exist among subglacial lakes within hundreds of kilometers [13,15]. Evidence of terrestrial characteristics has also confirmed that subglacial rapid floods have widely occurred in Antarctica [16,17]. There is an enormous subglacial network in Antarctica, consisting of lakes, rivers, and creeks, thereby covering tens of thousands of square kilometers [18]. Based on experimental evidence and sensitivity analysis, approximately 55% of the subglacial ice–bed interface area is located at the pressure melting point [19], which significantly influences the stability of ice sheets and the movements of ice streams [7]. Also, subglacial lakes have a profound impact on contemporary ice–sheet mass balance and dynamics. They may cause global sea level rise by storing and releasing substantial volumes of meltwater [20]. Furthermore, subglacial drainage to ice shelve cavities accelerates ice shelf basal melting. The freshwater discharge beneath ice shelves intersects with ocean currents, particularly in modified circumpolar deep water (mCDW) and modified ice shelf water (mISW). They influence the ocean current temperature and composition, and subsequently affect diverse ice shelf processes.

Subglacial drainage models encompass water sheets/films, cavities, R-channels, bedrock channels (N-channels), and porous flow, thereby forming a complex hydraulic network [17], as shown in Figure 2. While predictive models have successfully identified a substantial percentage of Antarctic subglacial lakes [4,21], the complexity of the subglacial environment makes it challenging to accurately predict all of the subglacial lakes, especially for small lakes [22]. Recent geophysical modeling suggests a potential underestimation of ice basal melting and a wider area of high heat flux in West Antarctica, thus implying that the number of subglacial lakes may have been underestimated [23].

Subglacial lake drilling offers a direct means to observe subglacial lakes and obtain samples. These samples offer valuable insights into subglacial lake origins, ecosystems, hydrology, and other related topics. Presently, hot water drilling can minimize the risk of contamination. Future research on equipment, protocols, and testing techniques remains an international focus.

In this study, we focused on the recent progress in subglacial environment detection, subglacial hydrological systems, subglacial lake drilling projects, and other related frontier scientific inquiries. Schematic diagrams illustrating the scope discussed in this paper are shown in Figures 1 and 8.

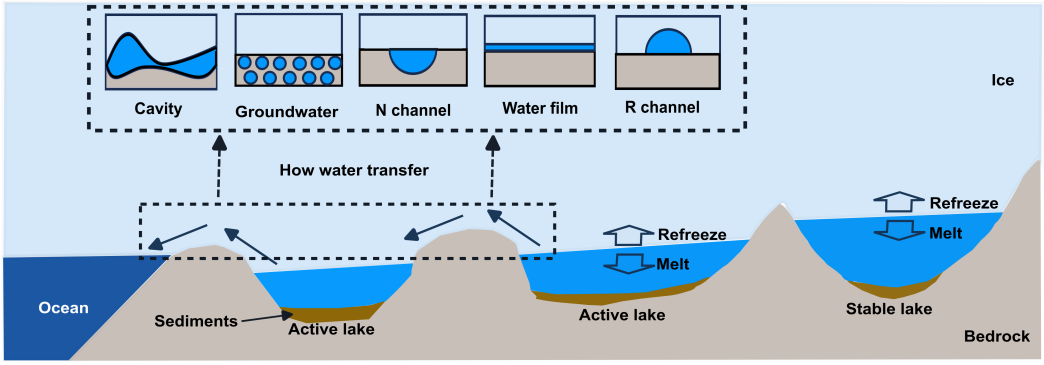

Figure 2. An overview diagram of Antarctic subglacial lakes and subglacial hydrological systems.

2. Subglacial Lakes and Hydrology

2.1. Subglacial Water Detection Methods

Numerous methods have been employed over more than six decades to detect subglacial water in Antarctica. Airborne ice penetrate radar (IPR) is widely used in Antarctica for identifying the ice–rock interface and subglacial lakes [24–26]. IPR has extensively and effectively characterized subglacial water bodies [27] by detecting their brighter reflections compared to the surrounding bedrock [28]. The coherent specular reflections from subglacial water enable the detection of small fractional areas that dominate the radar echo in terms of reflectivity and geometric spreading [29], thereby facilitating the automatic detection of lakes in radar data [30]. Furthermore, lake bottom echoes have been utilized to estimate water thickness and conductivity [31]. With the upgrading of satellite altimetry techniques (e.g., laser altimetry, radar altimetry, and advanced synthetic aperture radar), an increasing number of subglacial lake and hydrological dynamics are being identified. These techniques have been employed on various platforms such as ICESat1-2 [32–35] and CryoSat1-2 [32,35–37]. Space-borne altimetry has the capability to elucidate the connections between basal water flow, ice sheet stability, and marine mass exchange. It can also detect significant volume fluctuations in Antarctic subglacial lakes over decadal timescales, and it has also been used to investigate the correlations between these lakes [14,38,39]. The seismic method, dating back to the pioneering work of Robin (1958) [40], has been crucial in confirming subglacial lake presence, resolving uncertainties, and assessing subglacial water salinity. Recently, with the use of the ground-based transient electromagnetic (TEM) method, Killingbeck et al. (2022) [41] assessed a successful subglacial water salinity characterization. These comprehensive techniques collectively advance our understanding of subglacial hydrology in Antarctica.

2.2. Well-Known Subglacial Lakes

Since the late 1960s, with the discovery of Sovetskaya Lake using IPR [42], the number of discovered subglacial lakes in Antarctica reached 675 in 2022 [3]. For detailed statistics and an extensive overview, please refer to [1–3,43]. Here, we focus on subglacial lakes that have been studied or hold promise for further research as follows:

Vostok Subglacial Lake, discovered in 1974, stands as the world's largest and deepest Antarctic subglacial lake; it is nestled at depths ranging from 3700 m to 4300 m. It spans approximately 280 km in length, 44 km in width, and has an area of 14,000 km^2 [44,45]. Concordia Subglacial Lake, detailed in [46], spans an area of approximately 600–800 km^2, with an estimated water depth of about 1000 m, as suggested by gravity data [47]. Lake Whillans, located beneath Whillans Ice Stream in West Antarctica, was initially discovered in 2007 [13]. It encompasses an area of about 60 km^2 and lies approximately 120 km from the grounding line. South Pole Lake, as reported in [48], stretches to at least 4.2 km in width (possibly up to 10 km) and reaches depths of up to 32 ± 10 m. It occupies a basin formed by thick sedimentary strata and spans an area of approximately 2000 km^2. The 90° E Lake, which was introduced in 2006 by [49], is characterized by a minimum water depth of approximately 900 m, with an estimated volume of approximately 1800 km^3. Subglacial Lake Ellsworth, situated near the Ellsworth Mountains in West Antarctica and about 20 km from the ice divide, is a 10 km-long lake beneath roughly 3.4 km of ice [9,50]. It spans 14.7 km in length and 3.1 km in width, covering an area of 28.9 km^2 with a water volume of 1.37 km^3. Lake Snow Eagle is situated in Princess Elizabeth Land (PEL), East Antarctica, and it boasts dimensions of approximately 42 km in length, 370 km^2 in area, a maximum water thickness exceeding 200 m, and a volume of around 21 km^3 [51].

Subglacial lakes are classified into the following type of active and stable subglacial lakes based on their active level: Stable subglacial lakes, which are typically medium- to large-sized, are primarily located in the central region of Antarctica. Active subglacial lakes, which are generally small- to medium-sized, are situated near the grounding line. Smith et al., 2009 [52] conducted a thorough analysis of "active" lakes, whereby they characterized 124 lakes with activity over the 2003–2008 period using ICESat laser altimetry data. We analyzed surface ice flow velocities (data from [53]) in regions associated with documented subglacial lakes (lake directory from [3]). Results are shown in Figures 3 and 4. We found that areas with active subglacial lakes exhibit significantly higher ice flow velocities than those with stable subglacial lakes, thus highlighting a significant correlation between subglacial lake activity and surface ice flow velocities.

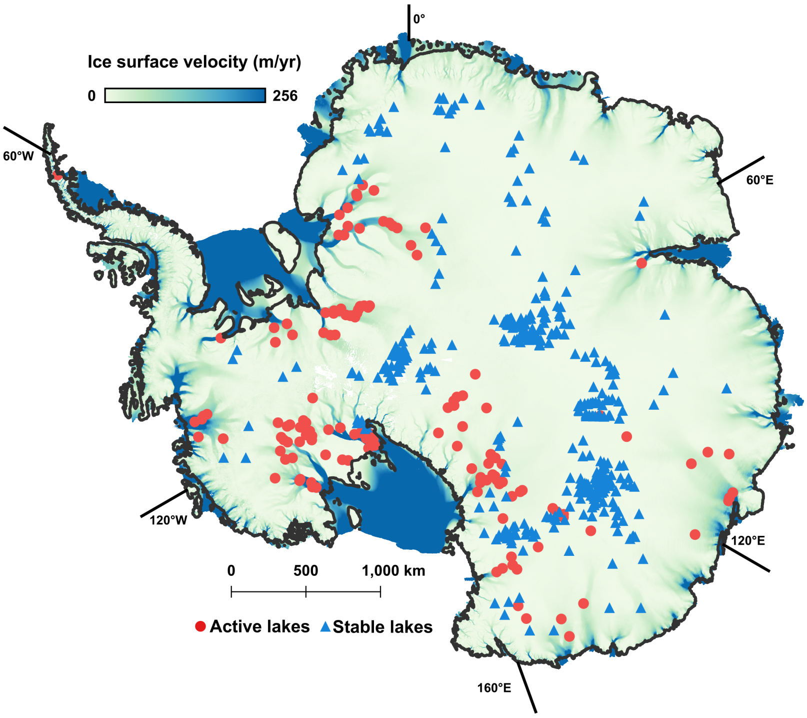

Figure 3. An illustration depicting ice flow velocities for both stable and active subglacial lakes.

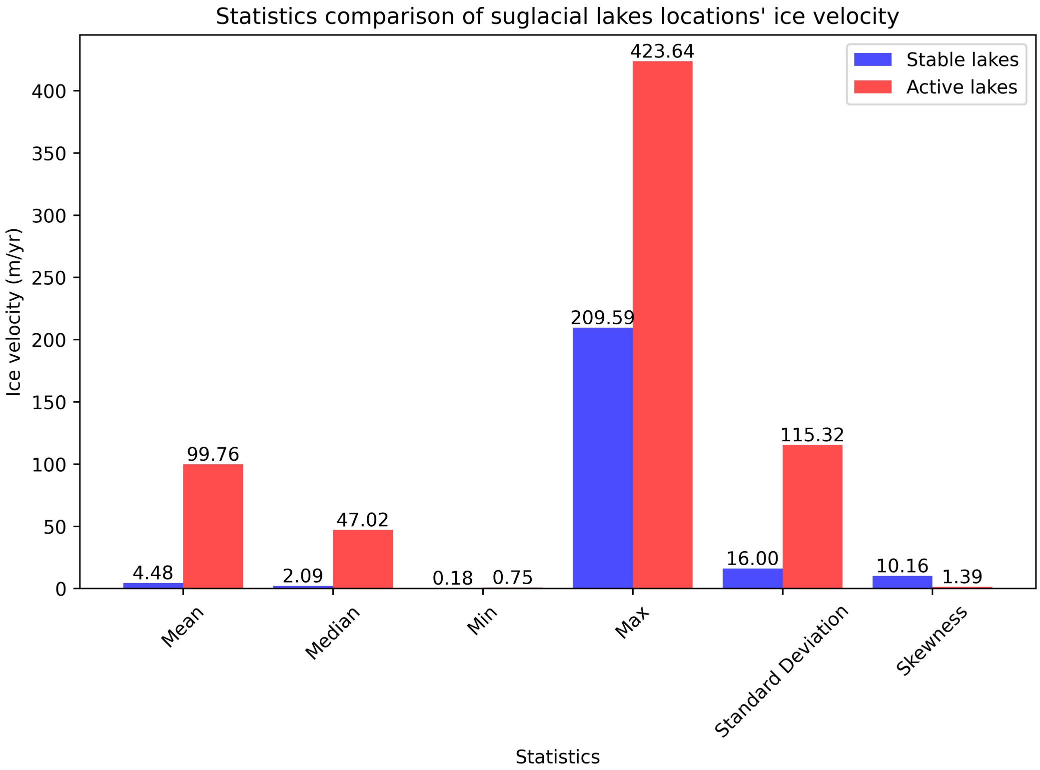

Figure 4. Comparison of data analysis for stable subglacial lake and active subglacial lake locations in relation to ice flow velocity.

2.3. Inland Subglacial Hydrology

Contemporary investigations in Antarctica have notably advanced our understanding of inland subglacial hydrology. In a pioneering work by Wingham et al. [15], observations over 16 months revealed a transfer of 1.8 km^3 of water over 290 km to at least two other subglacial lakes. Fricker and Scambos, 2009 [54] employed laser altimetry data to show the interconnections between subglacial lakes in Mercer and Whillans Ice Streams, West Antarctica. Seismic observations by Leguy et al., 2014 [55] beneath MacAyeal Ice Stream, West Antarctica, unveiled recurring outburst floods in the subglacial water system. In the 2021 study by Neckel et al., 2021 [56], a 6-year time series of differential Sentinel-1 SAR interferometry (DInSAR) data was used to detect the short-term surface subsidence and uplift events in the upstream region of the Jutulstraumen Glacier. These observations suggest episodic subglacial water drainage and fillings, which offer valuable insights for refining subglacial hydrological models. Hodgson et al., 2022 [57] utilized remote sensing and aerogeophysics data to investigate the rapid drainage and gradual refilling of a subglacial lake beneath Mars Glacier in the Antarctic Peninsula, thereby underscoring the influence of climate processes on glacier behavior and their sensitivity to climate change.

2.4. Grounding Zone Subglacial Hydrology

The subglacial hydrology within grounding zones frequently encompasses the discharges of water from inland to the ocean through the grounding line [58]. Space-borne altimetry has been instrumental in detecting the active subglacial lakes adjacent to grounding lines in the past few decades. With space-borne altimetry, Fricker et al., 2007 [13] found Lake Whillans discharged approximately 2.0 km^3 of water into the ocean over about three years, thereby underscoring the dynamic nature of the subglacial water storage. Employing similar methods, Carter et al. (2012) used volume variation estimates of subglacial lakes and an ice flow model to study the spatiotemporal water supply from the grounding line to a coastal ice stream. They found a substantial contribution of freshwater inflows to ice shelf basal melting [5]. With a seismic method, Horgan et al., 2013 [59] conducted a comprehensive analysis of interactions between subglacial hydrology and the ocean, and they suggested that was a possibility of estuaries near the grounding lines in Antarctica. Airborne geophysical surveys, such as ICECAP, have identified the Aurora Subglacial basin as a medium for subglacial lake discharge, with outflows traveling from the Dome C ice divide to the coast through the Totten Glacier [43]. Using geophysical and sedimentological data from the deglaciated western Ross Sea, Simkins et al., 2017 [60] identified a paleosubglacial active hydrological system in the western Ross Sea, thus emphasizing its role as a persistent medium for episodic meltwater drainage events. Numerical modeling and geophysical data analysis have revealed the presence of high-pressure subglacial water systems that stretch from the ice sheet interior to the grounded margin. These systems are now understood to be a critical factor affecting ice sheet stability, ice flow, and the melting of ice shelves at grounding zones [61].

Natural radium isotopes (223 Ra and 224 Ra) analyzed by Null et al., 2019 [62] elucidated the efficiency of submarine groundwater discharge as a medium for exchanging subglacial water with the ocean along the Antarctic coast, thereby bearing critical implications for the understanding of hydrological budgets and solute transport to the ocean. Furthermore, the study of ocean tidal forcing by Warburton et al., 2020 [63] offered insights into the water transport dynamics during the tidal cycle in the grounding zone, thereby revealing nonlinear responses to tidal forcing.

The geophysical evidence of subglacial channels strongly supports the presence of hydrologic activities in the grounding zone [64]. Le Brocq et al., 2013 [65] utilized satellite and airborne remote sensing to confirm the subglacial channels beneath the Filchner–Ronne Ice Shelf in West Antarctica. Additionally, Hager et al., 2022 [66] showed the crucial role of subglacial hydrology in glacier and ice sheet dynamics, where they emphasized the stable channel formation near grounding lines impacting submarine melting and basal friction at glacier termini. Subsequent research has stressed the significance of subglacial discharge contributing to the seasonal melting of ice shelves [5,67]. Finally, Gwyther et al., 2023 [68] underscored the significant impact of subglacial freshwater discharge on Antarctic ice shelves, where they revealing the induced melting that is driven by buoyant plume formation and introduced the far-reaching effects that are often absent from ice–ocean models, as illustrated in Figure 5.

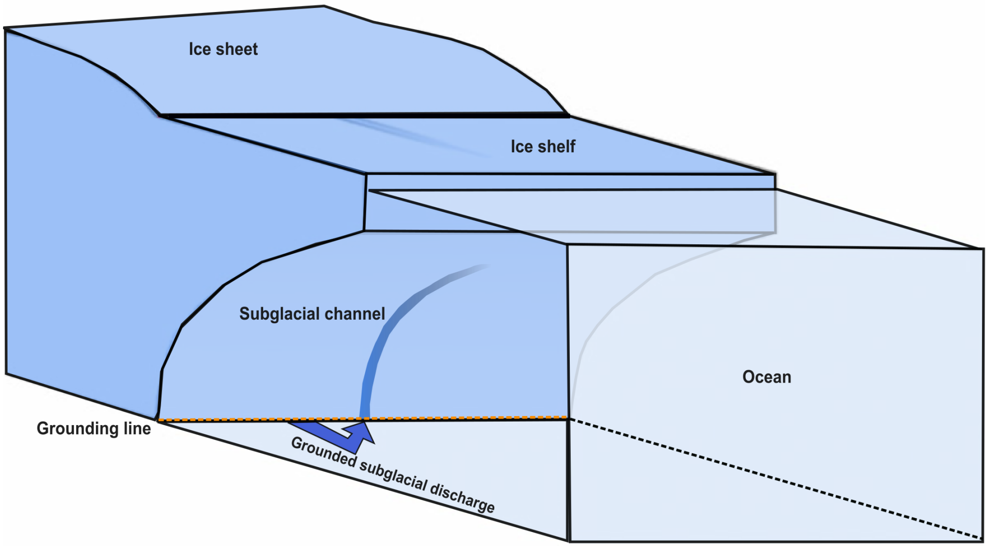

Figure 5. A diagram of subglacially sourced subglacial channels (modified from Alley et al., 2023 [69]).

3. International Efforts on Subglacial Lake Drilling

3.1. Subglacial Lake Drilling History

Antarctic subglacial lakes represent a valuable view for investigating critical scientific inquiries, including the realms of extreme environmental microbiology, astrobiology, and the evolutionary processes within the Antarctic ice sheets. Consequently, conducting contamination-free drilling operations to access subglacial lakes and acquire samples is of utmost importance. They assume a paramount importance in advancing a comprehensive understanding of subglacial environments. Utilizing drilling and logging techniques, comprehensive insights into Antarctic subglacial lakes can be derived with heightened precision [18]. Up 2023, three subglacial lake drilling projects (Lake Vostok, Lake Whillans, and Lake Mercer) were implemented successfully, but one project in Subglacial Lake Ellsworth failed [22]. Regrettably, the drilling project of Lake Vostok, which employed highly toxic drilling fluids, has led to subglacial contamination [18]. The contamination resulting from drilling presents a potential long-term threat to the entirety of subglacial hydrological systems. Therefore, drilling fluids should be cautiously selected [15]. To avoid contamination, Clean Hot Water Drills (CHWDs) is an option, which uses and recycles the melt water from circumambient ice sheets to create scientific access holes [70,71], when attempting to access subglacial lakes. The completed subglacial lake drilling projects can be summarized as follows:

The Lake Vostok project: The Lake Vostok drilling project commenced in 1958. It experienced a significant boost during the 2009/2010 season when drilling resumed at a 3559 m depth with the aid of a new borehole (5G-2). This drilling effort achieved a depth of approximately 3650 m, as documented by [72]. This endeavor marked a substantial achievement in progressively attaining significant drilling depths, and it culminated in a seminal achievement on 5 February 2012. Russian researchers made contact with the subglacial water of Lake Vostok at a depth of 3769.3 m, and they finished the collection of samples within 22 years after the official recognition of the Vostok Subglacial Lake [73]. The Vostok drilling project has supported a series of microbiological and ice age research. Data from the ice 3590 m below the Vostok Station indicate a microbial presence in the accredited ice from Lake Vostok, with bacterial DNA closely related to alpha- and beta-Proteobacteria and Actinomycetes. It suggests a potential for a microbial population in the isolated lake despite undergoing over a million years of isolation from the atmosphere [74,75]. Ice analysis indicates that the biological and chemical properties of the lake are influenced by the differential melting and freezing processes at the ice–water interface, which promote circulation. The estimated age of the lake is approximately to be as old as the ice sheets, approximately 14 million years old [76].

The Lake Ellsworth project: In December 2012, an attempt to access, with a specialized hot water drilling system, Subglacial Lake Ellsworth, which is located 3 km beneath the West Antarctic ice sheet, failed after a decade of planning. The primary reason for the failure was the inability to connect to a subsurface water cavity that is situated 300 m below the ice surface, which led to a shortage of water for the deeper drilling. The more detailed reasons may involve the contribution of non-vertical drilling on one or both drillholes, equipment problems, and an experimental design with drillholes that were only 2 m. Post-failure evaluation and an independent review led to recommendations for equipment and procedural modifications, with a five-year timeframe for implementation. Despite setbacks, the project offered valuable lessons for future subglacial exploration in Antarctica, thereby emphasizing the need for efficient, clean access to subglacial environments. Also, redesigning the hot water drill of Lake Ellsworth could benefit broader Antarctic exploratory research [22]. However, the Lake Ellsworth project is still valuable because a seismic analysis of the subglacial Lake Ellsworth revealed fine-grained sediments that suggested sediment ages of at least 150,000 years, which will also inform future exploration [77].

The Lake Whillans project: In January 2013, the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project utilized a clean hot water drill to access Subglacial Lake Whillans (SLW) [78]. This borehole confirmed the existence of a subglacial water basin, which had only been previously indicated by satellite altimetry and geophysics surveys. Notably, the rapid pressure equilibration between the borehole and SLW suggests unique hydrological conditions. SLW water exhibits lower salinity than seawater but a higher salinity than Subglacial Lake Vostok. During drilling, subglacial water entered the borehole, thus mitigating environmental impact. Sediments in SLW showed no macroscopic evidence of sediment rain out. Future projects should consider heat supply to manage freezing during operations. In parallel, Gustafson et al., 2022 [79] discovered deep subglacial groundwater beneath the Whillans Ice Stream, and they significantly expanded our understanding of subglacial systems and their impacts. The liquid water from Lake Whillans completely sustains diverse aquatic microbial ecosystems [80]. A pristine exploration of Subglacial Lake Whillans in West Antarctica revealed a microbial community utilizing reduced N, S, Fe, and CH_4 as energy sources. These microbes actively participating in biogeochemical cycling emphasized the significance of subglacial environments [81]. Additionally, Lake Whillans also exhibits fill and drain behavior with long water residence times, primarily those sourced from basal–ice melt and a minor seawater contribution. It reveals a distinct weathering regime and ion exchange processes within clay-rich lake sediments [82].

The Mercer Subglacial Lake project: In 2018, the Subglacial Antarctic Lake System Analysis (SALSA) project successfully conducted an environmentally conscious penetration of Mercer Subglacial Lake in Antarctica, where it enabled the collection of a diverse range of samples and data to investigate the complex dynamics of the lake. Through an analysis of the samples, encompassing water, sediment, microbes, and ice, in combination with meticulous measurements and observations, the project ascertained that the melting process had a negligible impact on sediment cores. This finding provides valuable insights into the hydrodynamics and stratigraphy of the lake [83]. Furthermore, the project unveiled a 120 mm subglacial lake–sediment record related to the lake's formation. As such, this project established a link between its origin and the stagnation of the nearby Kamb Ice Stream. This achievement underscores the potential of subglacial sediment archives in deciphering the history of ice [84]. Sediment samples from Mercer Subglacial Lake revealed microbial communities with distinct abundances and compositions at different depths. These communities include chemolithoautotrophic taxa associated with the oxidation of nitrogen, sulfur, and iron oxidation, thus suggesting a sophisticated subglacial metacommunity. The observed variations imply a strong influence of ice sheet dynamics on the structure and function of this metacommunity [85].

A map of the subglacial lake drilling project locations is shown in Figure 6 and a table presenting a brief introduction of the subglacial lake drilling projects is shown in Table 1.

Table 1. Summary of subglacial lake explorations.

Lake	Year	Description	Implementation
Lake Vostok [72]	2012	Successfully reached a new depth of approximately 3650 m.	Russian Antarctic Expedition
Lake Ellsworth [22,86]	2012	Failed, attempt with a hot water drill was halted.	British Antarctic Survey
Lake Whillans [78]	2013	Successfully accessed subglacial lake water.	WISSARD project [1]
Lake Mercer [83,84]	2018	Successfully penetrated and collected samples.	SALSA project [2]
Lake CECs [87]	-	On schedule, with a BEAMISH hot water drilling system [88].	Centro de Estudios Científicos & British Antarctic Survey
Lake Snow Eagle [51]	2025–2027	On schedule, with an RECAS drilling system [89].	CHINARE [3]

Notes: [1] WISSARDproject: the Whillans Ice Stream Subglacial Access Research Drilling project. [2] SALSA project: the Subglacial Antarctic Lake System Analysis project. [3] CHINARE: Chinese Antarctic Research Expedition.

3.2. Future Subglacial Drilling Plans

Several subglacial lake drilling projects have been completed, and their outcomes reveal the shortcomings of the approach, including drilling failures and lake water contamination, as well as the fact that two of the successful drilling projects were focused on active subglacial lakes. Generally, the drilling and sampling of stable subglacial lakes posts serve as crucial scientific challenges. Two potential drilling targets, namely Lake CECs and Lake LSE, are briefly introduced as follows.

Lake CECs: Lake CECs, which is located in the central part of the West Antarctic Ice Sheet, was discovered and mapped in 2014 using grounded ice penetrating radar, which showed unique characteristics comparable to other subglacial lakes. It is a promising candidate for biological exploration [90]. Lake CECs, which is located beneath 2653 m of ice sheet in Antarctica, was found to have a maximum water column thickness of 301.3 ± 1.5 m and an estimated volume of 2.5 ± 0.3 km^3. The central lakebed features were >15 m of high-porosity sediment, thereby signifying a low-energy sedimentary environment. This environment is conducive to the exploration and recovery of sediment records, offering valuable opportunities for scientific research [91]. Successful hot water drilling operations (2021) [87] on Rutford Ice Stream in West Antarctica have demonstrated the feasibility of accessing subglacial environments to depths exceeding 2000 m, and they are also significant for exploring subglacial lakes beneath the thick central West Antarctic Ice Sheet. CECs and the British Antarctic Survey is underway to access Lake CECs (SLCECs) with a focus on ensuring minimal contamination and disturbance to the subglacial environment. They are utilizing systems developed for the Subglacial Lake Ellsworth project and a new clean hot water drill; then, they will dedicate the next step to testing and validation in order to achieve a clean drilling and exploration of SLCECs with a BEAMISH hot water drilling system [88]. In addition, a recent study by [91] involved the investigation of Lago Subglacial CECs(SLC), which is under 2653 m of ice sheet, thereby indicating its potential for better understanding the sediment records of ice and climate history, as well as for microbial life exploration.

Lake Snow Eagle: Jamieson et al., 2016 [92] presented satellite remote sensing and IPR measurements, where they revealed a previously unrecognized extensive subglacial canyon and a large subglacial lake in the interior of Princess Elizabeth Land (PEL) of East Antarctica. These findings highlight the challenges posed by the limited direct ice thickness measurements that have resulted in poor subglacial topography resolution. IPR data [24,25] acquisition utilized the Snow Eagle 601 aerogeophysical platform, which was constructed by the Polar Research Institute of China (PRIC) for the CHINARE program and covers an area of approximately 900,000 km^2. The data, derived from four campaigns that were conducted between 2015 and 2019, have laid a robust foundation for the subsequent discovery of LSE. Subsequently, newly acquired aerogeophysical data have substantiated the presence of one of Antarctica’s largest subglacial lakes: Lake Snow Eagle [51] in Princess Elizabeth Land. This discovery offers valuable insights into the geological characteristics of LSE and its potential for preserving the crucial records of past environmental changes and the evolution of the East Antarctic Ice Sheet. To further explore this subglacial system, a collaborative project led by China is underway. The project’s objectives include integrating logistical capabilities for a Clean Hot Water Drilling system, recoverable thermal sondes, and in situ microbial sample processing devices. This endeavor aims to achieve LSE drilling and water sampling within one or two seasons with a target of obtaining water samples. Additionally, the project will firstly use a Clean Hot Water Drills system to get close to the LSE, where the next step is to then incorporate the use of the recently developed RECoverable Autonomous Sonde (RECAS) (see [89,93] for details) to facilitate subglacial water sampling and analysis while maintaining the isolation of the subglacial lake from the surface environment. A schematic diagram depicting the LSE parameters (modified from [51] and the RECAS drilling system (modified from [89,93]) is shown in Figure 7.

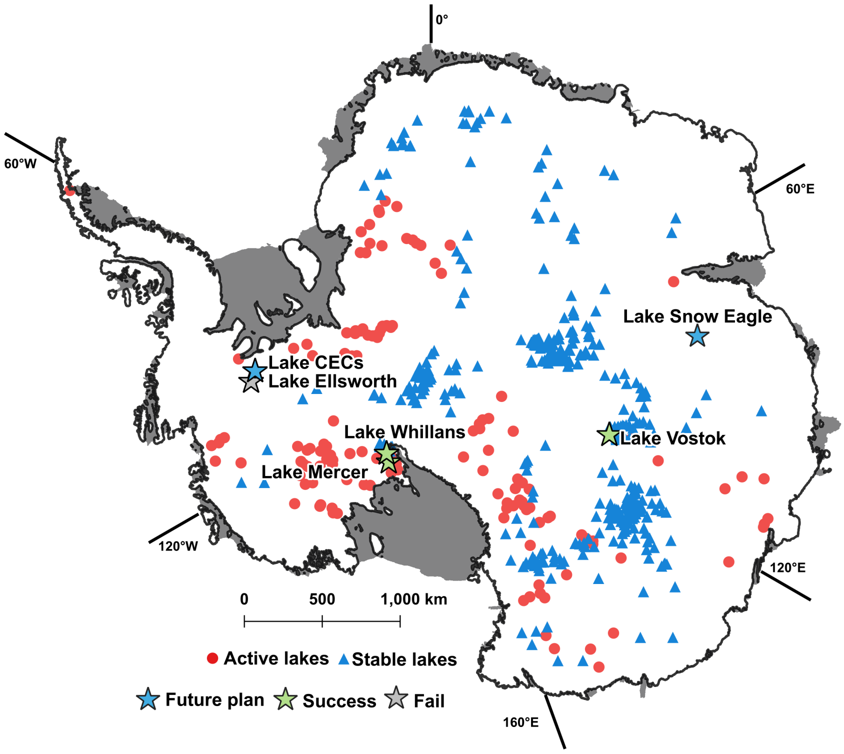

Figure 6. A map of the subglacial lake drilling project locations.

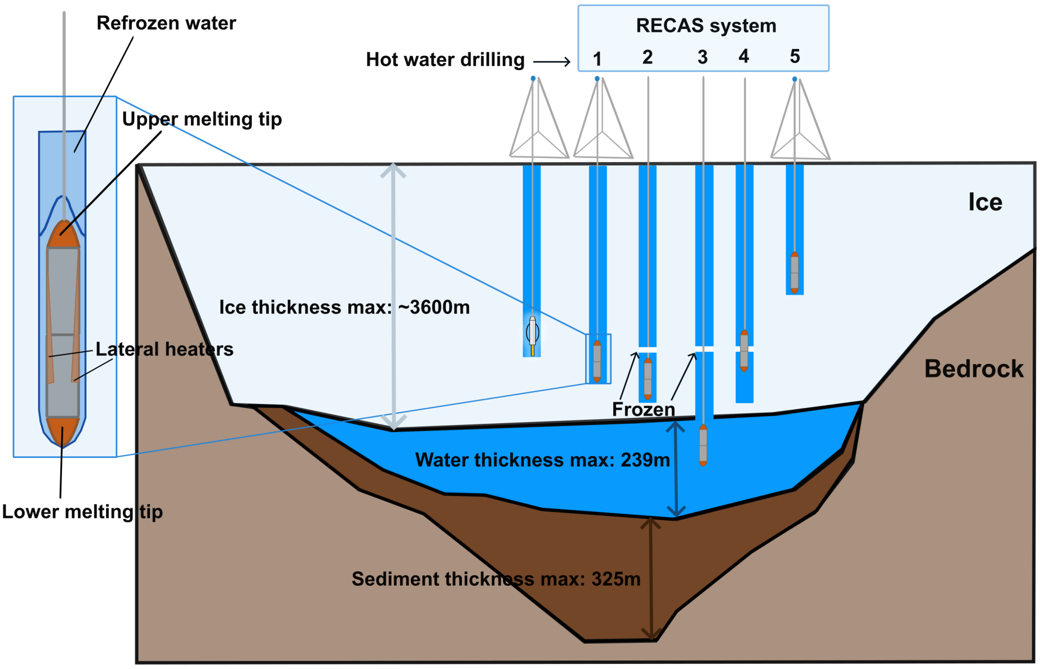

Figure 7. A schematic diagram depicting the LSE parameters (modified from Yan et al., 2022 [51]) and the RECAS subglacial access and sampling operations, specifically Steps 1–5: activation of the sonde, drilling downwards, lake sampling, drilling upwards, and arrival to the surface (modified from Talalay et al., 2014 [89] and Sun et al., 2023 [93]).

4. Conclusions

In this article, we briefly reviewed subglacial lakes, associated subglacial elements, subglacial hydrological processes, and subglacial lake drilling projects (as shown in Figure 8). In conclusion, the various facets of the Antarctic subglacial lakes, regional subglacial hydrology, and hydrological connections among active subglacial lakes and water pathways are integral components of the whole Antarctic system as they influence the region's water balance, geomorphology, and ice dynamics. This review highlights a certain number of critical scientific topics, including subglacial water detection, subglacial hydrologic activities, and the status of subglacial lake drilling projects.

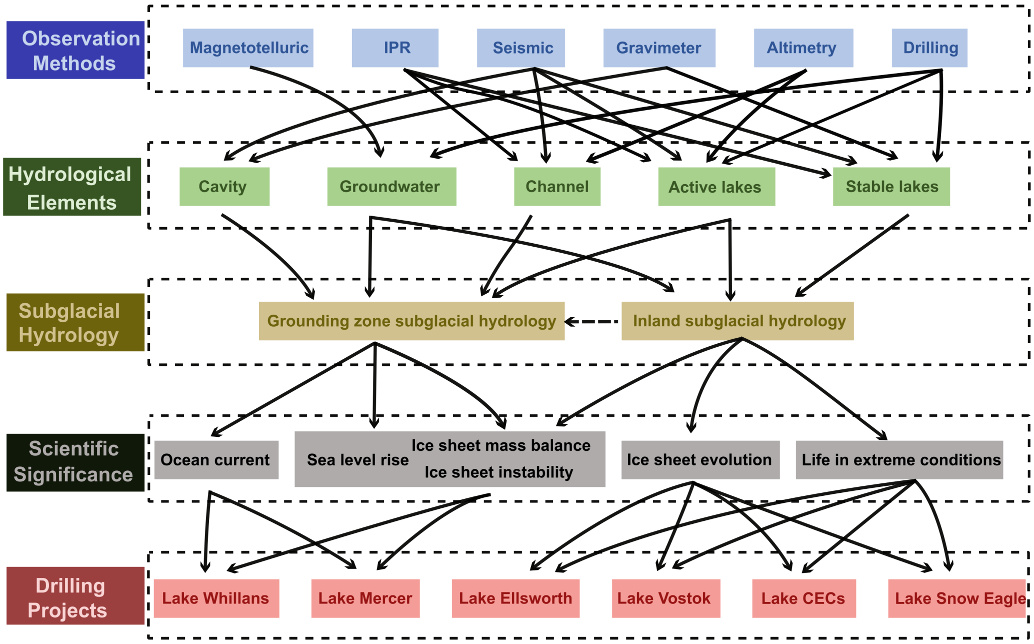

Figure 8. Summary of the scope discussed in this review.

Remote sensing data have unveiled a pivotal discovery—the regular exchange of water between active subglacial lakes. Moreover, grounding zones exhibit intense water exchange and mixing where glacial freshwater converges with sea water. While the potential of drilling and water sample collection from the subglacial lakes offers a view for directly addressing these enigmas, significant technical challenges persist. Current research in subglacial hydrology faces many hurdles, ranging from technology to logistics. To understand the unique phenomena and dynamic behaviors within the Antarctic subglacial system, focused dedications are needed. This dedication will enhance our comprehension of the intricate processes and fill in the gaps of scientific knowledge in this field.

It is worth noting that the subglacial lake drilling project (especially the stable subglacial lakes) is crucial for our understanding of the formation and evolution of subglacial lakes, as well as for deepening our understanding of subglacial hydrological systems. It also provides evidence for microorganisms in extreme environments, as well as provides valuable insights into Antarctic ice sheet evolution or even astrobiology.

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Abbreviations

The following abbreviations are used in this manuscript:

Lake CECs	Lake Centro de Estudios Científicos
LSE	Lake Snow Eagle
mCDW	Modified circumpolar deep water
mISW	Modified ice shelf water
ASAR	Advanced synthetic aperture radar
TEM	Transient electromagnetic
CHWDs	Clean Hot Water Drills
WISSARD	Whillans Ice Stream Subglacial Access Research Drilling
SALSA project	The Subglacial Antarctic Lake System Analysis
CHINARE	Chinese Antarctic Research Expedition
IPR	Ice Penetrating Radar

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